

EUV

Lithography

EUV Lithography

Vivek Bakshi, *Editor*

SPIE
PRESS

Bellingham, Washington USA

Library of Congress Cataloging-in-Publication Data

Bakshi, Vivek.

EUV lithography / Vivek Bakshi.

p. cm. -- (Press monograph ; 178)

ISBN 978-0-8194-6964-9

1. Ultraviolet radiation--Industrial applications. 2. Photolithography. 3. Optical coatings. I. Title.

QC459.B35 2007

621.3815--dc22

2008018045

Published by

SPIE

P.O. Box 10

Bellingham, Washington 98227-0010 USA

Phone: +1 360.676.3290

Fax: +1 360.647.1445

Email: Books@SPIE.org

Web: <http://spie.org>

ISBN: 9780819469649

and

John Wiley & Sons, Inc.

111 River Street

Hoboken, New Jersey 07030

Phone: +1 201.748.6000

Fax: +1 201.748.6088

ISBN: 9780470471555

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Printed in the United States of America.



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To the technologists who have made EUVL a reality

Contents

Preface	xiii
Introduction	xvii
List of Contributors	xix
List of Abbreviations	xxi
Chapter 1 EUV Lithography: An Historical Perspective	1
<i>Hiroo Kinoshita and Obert Wood</i>	
1.1 Introduction	1
1.2 The Early Stage of Development—1981 to 1992	3
1.3 The Second Stage of Development—1993 to 1996	10
1.4 Other Developments in Japan and Europe	18
1.5 The Development of Individual Technologies	20
1.6 EUVL Conferences	40
1.7 Summary	42
Acknowledgments	44
References	46
Chapter 2 EUV LLC: An Historical Perspective	55
<i>Chuck Gwyn and Stefan Wurm</i>	
2.1 Introduction	56
2.2 Formation of the LLC	59
2.3 Program Structure	66
2.4 Program Results	72
2.5 Retrospective Observations	79
2.6 Status of EUV Development at the End of LLC	84
2.7 Summary	85
Appendix A: Major Accomplishments of the EUV LLC Program	87
Appendix B: EUV LLC Program Patents	92
Acknowledgments	96
References	99

Chapter 3	EUV Source Technology	103
<i>Vivek Bakshi</i>		
3.1	Introduction	104
3.2	EUV Source Requirements	106
3.3	DPP and LPP Source Technologies	109
3.4	EUV Source Performance	112
3.5	Summary and Future Outlook	126
	References	127
Chapter 4A	Optics and Multilayer Coatings for EUVL Systems	133
<i>Regina Soufli, Saša Bajt, Russell M. Hudyma and John S. Taylor</i>		
4A.1	Introduction	133
4A.2	Properties of EUVL Systems	133
	References	134
Chapter 4B	Projection Systems for Extreme Ultraviolet Lithography	135
<i>Russell M. Hudyma and Regina Soufli</i>		
4B.1	General EUVL Optical Design Considerations	135
4B.2	EUV Microsteppers	138
4B.3	Engineering Test Stand (ETS)	147
4B.4	Six-Mirror EUVL Projection Systems	149
	Acknowledgments	156
	References	157
Chapter 4C	Specification, Fabrication, Testing, and Mounting of EUVL Optical Substrates	161
<i>John S. Taylor and Regina Soufli</i>		
4C.1	Introduction	161
4C.2	Specification	162
4C.3	Projection Optics	163
4C.4	Effect of Substrate Errors on Imaging Performance	164
4C.5	Low-Frequency (Figure) Errors	165
4C.6	Mid-Spatial-Frequency Errors	169
4C.7	High-Spatial-Frequency Errors	170
4C.8	Influence of Coatings on Roughness Specification	171
4C.9	Calculation of Surface Errors	171
4C.10	Uniformity	173
4C.11	Substrate Materials	173
4C.12	Fabrication	174
4C.13	Metrology	176
4C.14	Mounting and Assembly	177
4C.15	Alignment	179
4C.16	Condenser Optics	179

Acknowledgments	181
References	181
Chapter 4D Multilayer Coatings for EUVL	187
<i>Regina Soufli and Saša Bajt</i>	
4D.1 Overview and History of EUV Multilayer Coatings	187
4D.2 Choice of ML Materials and Wavelength Considerations	188
4D.3 Multilayer Deposition Technologies	189
4D.4 Theoretical Design	190
4D.5 High Reflectivity, Low Stress, and Thermal Stability Considerations	191
4D.6 Optical Constants	192
4D.7 Multilayer Thickness Specifications for Imaging and Condenser EUVL Mirrors	193
Acknowledgments	197
References	197
Chapter 5 EUV Optical Testing	205
<i>Kenneth A. Goldberg</i>	
5.1 Introduction	205
5.2 Target Accuracy	207
5.3 Techniques for Angstrom-scale EUV Wavefront Measurement Accuracy	208
5.4 Intercomparison	218
5.5 Future Directions	219
References	222
Chapter 6A Optics Contamination	227
<i>Saša Bajt</i>	
6A.1 Introduction	227
6A.2 Fundamentals of Optics Contamination	234
6A.3 Optics Contamination Control	241
6A.4 Summary and Future Outlook	250
References	251
Chapter 6B Grazing Angle Collector Contamination	261
<i>Valentino Rigato</i>	
6B.1 Introduction	261
6B.2 Collector Lifetime Status and Challenges	269
6B.3 Summary	281
Acknowledgments	281
References	281

Chapter 6C Normal Incidence (Multilayer) Collector Contamination	285
<i>David N. Ruzic and Shailendra N. Srivastava</i>	
6C.1 Introduction	285
6C.2 Overview of Normal-Incidence Collector Mirrors	287
6C.3 Collector Performance	290
6C.4 Summary	317
Acknowledgments	318
References	318
Chapter 7 EUV Mask and Mask Metrology	325
<i>Han-Ku Cho and Jinho Ahn</i>	
7.1 Introduction	326
7.2 EUV Mask Structure and Process Flow	327
7.3 Mask Substrate	328
7.4 Mask Blank Fabrication	332
7.5 Absorber Stack and Backside Conductive Coating	349
7.6 Mask Patterning	355
7.7 Mask Cleaning	361
7.8 Advanced Mask Structure	363
7.9 Summary and Future Outlook	372
Acknowledgments	373
References	373
Chapter 8 Photoresists for Extreme Ultraviolet Lithography	383
<i>Robert L. Brainard</i>	
8.1 Introduction	384
8.2 Earliest EUV Resist Imaging	385
8.3 Absorption Coefficients of EUV Photoresists	391
8.4 Multilayer Resists and Pattern Transfer	394
8.5 Resist Types	403
8.6 PAGs and Acids	426
8.7 Line Edge Roughness	428
8.8 Summary and Future Outlook	435
Acknowledgments	435
References	437
Chapter 9 High-Resolution EUV Imaging Tools for Resist Exposure and Aerial Image Monitoring	449
<i>Malcolm Gower</i>	
9.1 Introduction	450
9.2 EUV Tool Design Considerations	450
9.3 EUV Microstepper	453
9.4 Reticle Imaging Microscope	470

9.5 Summary and Future Outlook	488
Acknowledgments	490
References	490
Chapter 10 Fundamentals of EUVL Scanners	493
<i>Kazuya Ota</i>	
10.1 Introduction	494
10.2 Illumination Optics	494
10.3 Projection Optics	498
10.4 Stages	502
10.5 Sensors	506
10.6 Handling Systems	508
10.7 Vacuum and Environment System	508
10.8 Budgets	509
10.9 Summary	511
Acknowledgments	511
References	512
Chapter 11 EUVL System Patterning Performance	515
<i>Patrick Naulleau, John E. Bjorkholm, and Manish Chandhok</i>	
11.1 Introduction: The Benefits of EUV Imaging	516
11.2 Imaging with the 0.1-NA ETS Optic	517
11.3 Imaging with the 0.3-NA MET Optic	530
11.4 System Contributors to Line Edge Roughness	539
11.5 Flare in EUVL Systems	551
11.6 Summary	576
Acknowledgments	577
References	577
Chapter 12 Lithography Cost of Ownership	585
<i>Phil Seidel</i>	
12.1 Cost of Ownership Overview	586
12.2 Lithography: Historical Cost and Price Trends	599
12.3 Major Lithography CoO Parameter and Productivity Drivers	604
12.4 General Observations on Lithography Cell and CoO Improvements (Past Decade)	622
12.5 CoO Considerations for Future Lithography Technologies	629
12.6 Summary	635
12.7 Appendix: Example Case Studies of Lithography CoO Calculations	635
Acknowledgments	638
References	639

Appendix Reference Data for the EUV Spectral Region	643
<i>Eric M. Gullikson and David Attwood</i>	
A.1 Introduction	643
Table A.1 Optical constants and absorption data for extreme ultraviolet wavelengths	643
Table A.2 Physical constants	652
Table A.3 Electron binding energies in electron volts for the elements in their natural forms	653
Table A.4 Photon energies in electron volts of principal K- and L-shell emission lines	659
References	663
Index	665

Preface

Extreme ultraviolet lithography (EUVL) is the leading patterning technology for the production of computer chips beyond the current 193-nm-based optical lithography. EUVL has been in development since the 1980s; today, alpha-level EUVL scanners are in the field, and beta-level scanners are expected to be deployed in a few years. EUVL uses photons of 13.5-nm wavelengths for patterning. Because photons are absorbed heavily by all materials at this wavelength, the entire EUVL scanner is in vacuum, and reflective optics—mostly multilayer (ML) mirrors—are used. To develop EUVL as a patterning technology for high-volume manufacturing (HVM) of computer chips, progress has been made on several fronts: EUV light sources, optics, optics metrology, contamination control, masks and mask handling, and resists. In addition, learning from microexposure tools (METs) has been invaluable in the development of EUV resists and full-field EUVL scanners.

This reference book contains 12 chapters contributed by leading researchers and suppliers in the EUVL field. It also contains a detailed appendix with EUVL reference data. The chapter topics are intended to cover the needs of practitioners of the technology as well as readers who want an introduction to EUVL.

This book starts with two chapters on the history of EUVL development. The first chapter covers pioneering work from the earliest days until the EUV Limited Liability Corporation (LLC) was formed to consider the commercial feasibility of EUVL. The contributions of the EUV LLC are covered in the second chapter. Chapter 3 presents an overview of EUV source technology (requirements, technology status, and metrology). Chapters 4a–4d cover EUV optics (substrate, ML deposition, and optical design). Chapter 5 describes and compares different EUV wavefront measurement techniques for EUV optics testing. Chapters 6a–6c explain contamination and its control in EUVL scanners. In today's EUVL scanners, the collector optics in EUV sources are subject to the most serious contamination. Chapter 6 addresses this issue as well as the contamination of scanner optics. Chapter 7 discusses EUV mask technology (substrate, blank fabrication, absorber stack and backside conductive coating, patterning, cleaning, and phase shift masks). Chapter 8 covers the fundamentals and development of EUV resist technology and addresses line edge roughness (LER). Chapter 9 describes the design and components of the first METs, which have enabled resist development. Two of these METs are in the field today. Chapter 10 presents the fundamental design considerations for an EUVL scanner and describes various components of

a full-field scanner, including illumination and projection optics, stages, sensors, and handling systems. Chapter 11 covers the benefits of patterning with 13.5 nm and presents the results of patterning with MET optics; LER and flare in EUVL systems are also discussed in this chapter. Finally, Chapter 12 explains the cost of ownership (CoO) fundamentals and lithography cost trends for future lithography techniques. The appendix contains reference data for the EUV spectral region, information relevant for practitioners of EUVL.

As EUVL technology has continued to develop, I have worked with authors and referees to identify topics that could be covered by a reference book. For detailed information on EUV source technology, readers are encouraged to consult the previously published text, *EUV Sources for Lithography*. Also, because EUVL technology continually evolves, an overview of its status has been omitted from this volume. I expect many readers will be interested in one particular topic and thus go straight to that chapter; for this reason, we have tried to make each chapter as complete in itself as possible.

Over the last two decades, researchers, commercial suppliers, and end users around the world have published several hundred papers per year on EUVL, and the amount of technical data on EUVL technology just continues to increase. My effort as volume editor has been to produce an authoritative reference book on EUVL technology, which until now has not existed. Today, EUV source technology is the leading challenge for implementing EUVL in HVM. EUV mask technology has made significant progress; however, defect-free masks that satisfy defectivity requirements remains a challenge. EUV resist, which will simultaneously satisfy the requirements of resolution, sensitivity, and LER, is another leading challenge for EUVL. As we see continued progress in addressing these three critical technical challenges, through publications and technical conferences, this book will continue to provide the in-depth technical background information relevant to source, mask, resist, scanners, and other technology areas.

The primary strength of this book is that the contributions come from leading experts in each technical area. My initial call for contributions went to authors around the world (Asia, Europe, and the U.S.). Due mostly to time constraints, more U.S. authors are represented in this volume. I am happy to report, however, that each chapter was still reviewed by experts worldwide, who adjusted their busy schedules to review the work of their colleagues and suggest many changes. In this sense, the entire global EUVL community has participated in the generation of this volume. This project has been successful because of the authors' dedication and hard work. This book is the fruit of their labor. During the editing of this volume, I realized that EUVL is a reality today due to the labor of hundreds of technologists around the world. For this reason, I have dedicated this book to these technologists who have made EUVL a reality.

I would also like to acknowledge the contributions of my family, whose influence, encouragement, and support have allowed me to undertake such a project. First of all, my father, Mr. Om Prakash Bakshi, MA, set a very high standard for written communication and the pursuit of excellence, which still today I can only

strive to meet. My mother, Mrs. Pushpa Bakshi, MA, retired lecturer of the Punjabi language, always set an example of hard work and taught me a pragmatic approach toward solving everyday problems, which still guides me. Without the support of my family, Laura and Emily, I would not have been able to complete this project. I very much appreciate their tolerance of my absences in the evenings, on week-ends, and at vacation time, while I labored to complete this volume.

Finally, I would like to thank SPIE Press manager, Timothy Lamkins; SPIE editor, Scott Schrum; and copyeditor, Margaret Thayer. Their teamwork made this project possible. I very much appreciate their support and hard work for making this book project a reality.

Vivek Bakshi, PhD
President, EUV Litho, Inc.
September 2008
vivek.bakshi@euvlitho.com
<http://www.euvlitho.com>

Introduction

The semiconductor industry continues to derive profit and revenue from device scaling, so any technique that promises to extend dimensional scaling receives great attention from the industry. Each new technology node means a lower cost per device and tens of billions of dollars in additional revenue to the industry. As current techniques of extending optical lithography become ever more difficult and costly, each opportunity to introduce a new lithography method opens the door for further cost-effective dimensional scaling.

However, introducing nonoptical lithography techniques requires coordination and resources that no one company can muster on its own. New infrastructure must be created, new supply chains must be established, and new standards must link all of these together. The cost of establishing the infrastructure and developing the tools and processes is usually measured in billions of dollars. Only through the coordination of multiple stakeholders can these dramatic changes occur in a timely manner. Each component of the lithography solution will only be profitable if all of the necessary components are in place. The perfect tool is useless without the right light source, masks, and resists; similarly, the mask, resist, and light source suppliers will not be successful without each other. Risk must be taken, and shared, among all of the parties. In particular, the semiconductor companies will not be successful unless all of the components are ready and manufacturable.

Extreme ultraviolet lithography (EUVL) is one of those non-optical methods that promises extendibility by addressing not only the 32-nm half-pitch nodes, but several nodes beyond that. EUVL provides a photon-based, single-exposure technique that resembles current optical lithography techniques. With a $14\times$ reduction in wavelength compared to 193-nm optical lithography, EUVL provides a significant advantage in diffraction-limited resolution. To ensure a cost-effective, manufacturable solution for EUVL, performance targets have been set that can deliver a very cost-effective, attractive lithography solution.

However, the very short wavelength of EUVL that provides tremendous resolution scalability also hinders the readiness of EUVL technology. The many challenges of using EUV photons to manufacture wafer lithography are reflected in the current EUVL technology challenges. Generating EUV photons from hot and somewhat dirty plasma sources requires new developments in materials for long lifetime and new optics for efficient collection of the clean in-band EUV light. The need for reflective optics places a major burden on the mask blank industry

by requiring the defect-free generation of cost-effective, multilayer-coated mask blanks. Low-projection-optics aberrations for EUV light require polishing to small fractions of the 13.5-nm exposure wavelength. And the high exposure energy can make the generation of low line edge roughness patterns at small dimensions and at low-exposure doses very difficult. These are the challenges and solutions that are discussed in this volume.

As a global consortium of leading-edge semiconductor companies, SEMATECH has been coordinating and leading the EUVL development effort for more than five years. Bringing together semiconductor companies and suppliers through research projects, technical workshops, and broadly scoped lithography symposia has helped catalyze the development of technical results that could make EUVL a manufacturable technology. This volume represents SEMATECH's consensus-building efforts and includes contributions from researchers worldwide. Achieving success in EUVL is truly a global effort, as demonstrated in this volume. Only if we work together can we bring together all of the pieces needed to make EUVL a cost-effective, manufacturable technology.

Michael Lercel
Director, Lithography Division
SEMATECH

List of Contributors

Jinho Ahn
Hanyang University, South Korea

David Attwood
Lawrence Berkeley National Laboratory,
USA

Saša Bajt
Deutsches Elektronen-Synchrotron,
Germany

Vivek Bakshi
EUV Litho, Inc., USA

John E. Bjorkholm
Intel Corporation (Retired), USA

Robert L. Brainard
University of Albany, USA

Manish Chandhok
Intel Corporation, USA

Han-Ku Cho
Samsung, South Korea

Kenneth A. Goldberg
Lawrence Berkeley National Laboratory,
USA

Malcolm Gower
Exitech Ltd, UK

Eric M. Gullikson
Lawrence Berkeley National Laboratory,
USA

Chuck Gwyn
Intel Corporation (Retired), USA

Russell M. Hudyma
Hyperion Development LLC, USA

Hiroo Kinoshita
University of Hyogo, Japan

Michael Lercel
SEMATECH, USA

Patrick Naulleau
Lawrence Berkeley National Laboratory,
USA

Kazuya Ota
Nikon Corporation, Japan

Valentino Rigato
Media Lario Technologies, Italy

David N. Ruzic
University of Illinois at Urbana-
Champaign, USA

Phil Seidel
SEMATECH, USA

Regina Soufli
Lawrence Livermore National
Laboratory, USA

Shailendra N. Srivastava
University of Illinois at Urbana-
Champaign, USA

John S. Taylor
Lawrence Livermore National
Laboratory, USA

Obert Wood
Advanced Micro Devices, USA

Stefan Wurm
SEMATECH, USA

List of Abbreviations

AES	Auger electron spectroscopy
AFM	atomic force microscopy
ALD	atomic layer deposition
ALS	Advanced Light Source
AMHS	automated material handling systems
APC	automated process control
APSM	alternating phase shift mask
AR	action required
ARC	antireflective coating
ASET	Association for Super-Advanced Electronics Technologies
ASIC	application specific integrated circuit
BARC	bottom antireflective coating
BCA	binary collision approximation
BIN	COG binary chrome on glass
BNL	Brookhaven National Laboratory
BW	bandwidth
CA	clear aperture
CAR	chemically amplified photoresist
CCD	charge-coupled device
CCOS	computer-controlled surfacing
CD	critical dimension
CE	conversion efficiency
CGH	computer-generated hologram
CMM	coordinate measuring machine
CMP	chemical-mechanical polishing
CoO	cost of ownership
CP	cell projection
CPMI	Center for Plasma Material Interactions
CRADA	cooperative research and development agreement
CTE	coefficient of thermal expansion
CTF	contrast transfer function
CVD	chemical vapor deposition
CW	continuous wave
CXRO	Center for X-ray Optics

DARPA	Defense Advanced Research Projects Agency
dc	direct current
DDR&E	Director of Defense Research & Engineering
DLS	damped least squares
DMAP-MDS	dimethylaminopentamethyldisilane
DMT	debris mitigation tool
DOC	Department of Commerce
DOD	Department of Defense
DOE	Department of Energy
DOE	design of experiments
DOF	depth of focus
DP	double patterning
DPF	dense plasma focus
DPP	discharge-produced plasma
DRAM	dynamic random access memory
DSP	digital signal processor
DUV	deep ultraviolet
E-D	exposure-defocus
EIPBN	Electron, Ion, and Photon Beam Technology and Nanofabrication
EIT	extreme ultraviolet imaging telescope
EL	exposure latitude
EPL	electron-beam projection lithography
ePSM	embedded phase shift mask
ESA	energy sector analyzer
ESCAP	environmentally stable chemically amplified photoresists
ESL	etch stop layer
ETS	Engineering Test Stand
EUCLIDES	Extreme UV Concept Lithography Development System
EUV	extreme ultraviolet
EUVA	Extreme Ultraviolet Lithography System Development Association
EUVL	extreme ultraviolet lithography
EUV LLC	EUV Limited Liability Corporation
EXTATIC	Extreme UV Alpha Tools Integration Consortium (MEDEA+)
FC	Flying Circus
FEA	finite element analysis
FEL	free electron laser
FEM	focus exposure matrix
FF	far field
FIA	field image alignment
FAB	fabrication facility
FIB	focus ion beam
FOM	Fundamenteel Onderzoek der Materie Institute
FOUP	front-opening unified pod

FTE	full-time equivalent
FTIR	Fourier transform infrared spectroscopy
FVC	flare variation compensation
FWHM	full-width half maximum
GAE	gas-assisted etching
GI	grazing incidence
GUI	graphical user interface
GWLE	good wafer level exposure
H	horizontal
HIT	Himeji Institute of Technology
HMDS	hexamethyldisilazane
HP	half-pitch
HPFS	high-purity fused silica
HSFR	high-spatial-frequency roughness
HSQ	hydrogen silsesquioxane
HV	horizontal/vertical
HVM	high-volume manufacturing
HWS	Hartmann wavefront sensor
IBSD	ion beam sputter deposition
IBA	inverse bremsstrahlung absorption
IBF	ion beam figuring
IL	imaging layer
IC	integrated circuit
ICA	instantaneous clear aperture
IF	intermediate focus
ILS	image log slope
INERT	Illinois ion energy reduction technique
IP	intellectual property
IPD	in-plane distortion
IPE	image placement error
IPL	ion-beam projection lithography
IPS	integrated product scheduling
ISMI	International SEMATECH Manufacturing Initiative
ISMT	International SEMATECH
ITRS	International Technology Roadmap for Semiconductors
JDA	joint development agreement
JDP	joint development program
JSPE	Japan Society for Precision Engineering
LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkeley National Laboratory
LDD	low defect deposition
LiEDA	lithium salt of ethylenediamine
LER	line edge roughness
LLNL	Lawrence Livermore National Laboratory

LOCOS	local oxidation of silicon
LPCVD	low-pressure chemical vapor deposition
LPP	laser-produced plasma
L/S	line/space
LSC	laser shock wave cleaning
LSI	large-scale integration
LSM	layered synthetic microstructure
LTEM	low thermal expansion material
LTF	line edge roughness transfer function
LTO	low-temperature oxide
LTR	LER transfer function
LWR	line width roughness
MBDC	Mask Blank Development Center (SEMATECH)
MBE	molecular beam epitaxy
MCP	microchannel plate
MEDEA+	Microelectronics Development for European Applications+
MEEF	mask error enhancement factor
MET	microexposure tool
MFS	minimum feature size
MHD	magnetohydrodynamics
ML	multilayer
ML2	maskless lithography
MLM	multilayer mirror
MOPA	master oscillator–power amplifier
MOS	metal-oxide semiconductor
MPU	microprocessing unit
MRF	magnetorheological finishing
MSFR	mid-spatial-frequency roughness
MTF	modulation transfer function
MTBF	mean time between failure
MTTR	mean time to repair
MTTT	mean time to test
Mw	molecular weight
NA	numerical aperture
NGL	next-generation lithography
NI	normal incidence
NIL	nano imprint lithography
NILS	normalized image log slope
NIST	National Institute of Standards and Technology
NMOS	n-type metal-oxide semiconductor
NSLS	National Synchrotron Light Source
NSR	Nikon Step and Repeat System
OAI	off-axis illumination
OH	overhead

OL	overlay
OOB	out-of-band
OPC	optical proximity correction
OPD	out-of-plane distortion
OSA	Optical Society of America
OTF	optical transfer function
PACE	plasma-assisted cleaning by electrostatics
PAG	photo acid generator
PBS	polybutene-1 sulfone
PDI	point-diffraction interferometry
PEB	post-exposure bake
PECVD	plasma-enhanced chemical vapor deposition
PEEM	photoelectron emission microscopy
PHS	polyhydroxystyrene
PM	preventative maintenance
PMI	phase-measuring interferometer
PMM	phase-measuring microscopy
PMMA	poly (methyl methacrylate)
PO	projection optics
POB	projection optics box
PPL	planarization layer
PREUVE	PRogramme Extreme UV
PSI	Paul Scherrer Institut
PS/PDI	phase-shifting point-diffraction interferometer
PSD	power spectral density
PSDI	phase-shifting diffraction interferometer
PSF	point-spread function
PSL	polystyrene latex
PSM	phase shift mask
PSPDI	phase-shifting point-diffraction interferometer
PTB	Physikalisch-Technische Bundesanstalt
PV	peak to valley
PVD	physical vapor deposition
QCM	quartz crystal microbalance
RAM	reliability, availability, and maintainability
RDC	Research Development Center (of the VNL)
RES	resolution
RET	resolution enhancement technique
RGA	residual gas analyzer
RH	relative humidity
RIM	reticle imaging microscope
RIE	reactive ion etch
RLS	resolution, LER, sensitivity
RM	reflection mask

ROFR	right of first refusal
ROI	return on investment
ROMP	ring-opening metathesis polymerization
RP1	Ronler Processing 1
SAHD	send-ahead
SB	soft bake
SEM	scanning electron microscopy
SEMI	Semiconductor Equipment and Materials International
SES	Subfield Exposure Station
SHC	supersonic hydrocleaning
SHWS	Shack-Hartmann wavefront sensor
SIA	Semiconductor Industry Association
SIMS	secondary-ion mass spectroscopy
SLR	single-layer resist
SMIF	standard mechanical interface
SNL	Sandia National Laboratories
SOHO	solar and heliospheric observatory
SOW	statements of work
SPC	statistical process control
SPF	spectral purity filter
SPP	silicone-based positive photoresist
SRAF	sub-resolution assist features
SRC	Semiconductor Research Corporation
STM	scanning tunneling microscopy
SVGL	Silicon Valley Group Lithography
SXPL	soft x-ray projection lithography
TEG	test elements group
TEM	transmission electron microscope
TIS	total integrated scatter
TM	transmission mask
TMAH	tetramethylammonium hydroxide
TPT	throughput
TRACE	transition region and coronal explorer
TSI	top surface imaging
UHV	ultrahigh vacuum
ULE	ultra-low-expansion (Corning glass)
UPW	ultra-pure water
USAL	United States Advanced Lithography
UFTL	unexposed film thickness loss
UTR	ultrathin resist
VNL	Virtual National Laboratory
VUV	vacuum ultraviolet
VSB	vector-shaped beam
WPM	wafers per mask

WFE	wavefront error
WPH	wafers per hour
XPL	x-ray proximity lithography
XPS	x-ray photoelectron spectroscopy
XRD	x-ray diffraction
YAG	yttrium aluminum garnet

Chapter 1

EUV Lithography: An Historical Perspective

Hiroo Kinoshita and Obert Wood

Contents

1.1	Introduction	1
1.2	The Early Stage of Development—1981 to 1992	3
1.3	The Second Stage of Development—1993 to 1996	10
1.3.1	Two-mirror imaging system development	12
1.3.2	Three-mirror imaging system development	15
1.3.3	MOS device demonstration using EUVL	16
1.4	Other Developments in Japan and Europe	18
1.5	The Development of Individual Technologies	20
1.5.1	Selection of the exposure wavelength	21
1.5.2	Design of reflective imaging systems	23
1.5.3	Fabrication and evaluation of aspherical mirrors	27
1.5.4	Multilayer coatings and reflection masks	31
1.5.5	EUV resist development	36
1.5.6	EUV light source development	37
1.6	EUVL Conferences	40
1.7	Summary	42
	Acknowledgments	44
	References	46

1.1 Introduction

For more than three decades, the number of transistors on a chip has grown exponentially, doubling on the average of every 18 months. With each new technology generation, the role of lithography has increased in importance not only because of the requirements for smaller feature sizes and tighter overlay, but also because of the increasing costs of lithography tools. Optical projection lithography and its extensions, e.g., water immersion, are expected to remain the lithographic technologies of choice until at least 2010. Extreme ultraviolet lithography (EUVL) extends

optical lithography to a higher resolution and provides a larger depth of focus because it utilizes a shorter imaging wavelength (13.5 nm versus 193–248 nm) and employs a smaller numerical aperture (NA) imaging system (0.25–0.45 NA versus 0.93–1.35 NA). This chapter recounts the early years of EUVL development, from the first imaging with normal incidence multilayer (ML)-coated mirrors in 1981 to the beginning of EUVL commercialization efforts at the end of 1996.

Early concepts for EUVL emerged from research in Japan and the U.S. during the 1980s using soft x-rays in the 4-nm to 40-nm wavelength range.^{1–4} The results of the first demonstration of soft x-ray reduction lithography using multilayer-coated Schwarzschild optics were made public in 1986.¹ The first demonstration of the technology's potential and of nearly-diffraction-limited imaging took place in 1990.⁵ Because of EUV lithography's potential to be utilized at ever-smaller feature sizes, a consortium of U.S. national laboratories, integrated device manufacturers, and private commercial companies combined to form the EUV Limited Liability Company (EUV LLC) in 1997 to guide and fund its commercialization. (For details, see Chapter 2 of this book.) Today, commercial EUV exposure-tool development is underway at ASML, Canon, and Nikon, and EUVL infrastructure development is under active development worldwide at a number of universities, national laboratories, and semiconductor consortia.

Most of the basic concepts needed for EUVL were demonstrated, and most of the EUV-specific critical issues were identified during the early years. Sufficient progress was made on all of the critical issues during this time period that none thereafter were regarded as a “show stopper”; several critical issues were resolved entirely. Two early success stories were in the fabrication and metrology of aspheric surfaces and in the application and metrology of reflective ML coatings. In the beginning, aspheric surfaces were not much more than laboratory curiosities, but eventually they could be fabricated with a controlled spectrum of surface heights spanning spatial wavelengths from the clear aperture of the part down to ~ 1 nm. Reflective ML coatings initially provided only marginally larger reflectances than a grazing incidence mirror, but later could provide normal-incidence reflectances close to the theoretical maximum. The work done on ML coatings for EUVL has spawned important research on the processes by which a single atomic layer can be formed and on the quality of the interface between materials. While some EUV-specific critical issues still have not been completely resolved, the questions that remain tend to involve cost and reliability rather than technical issues.

The major historical developments that took place from 1981 to 1992 are summarized in Sec. 1.2 and from 1993 to 1996 in Sec. 1.3. Other relevant developments that took place in Japan and Europe are summarized in Sec. 1.4. The development of the most important components and subsystems are described in Sec. 1.5, including the selection of the exposure wavelength, the design of reflective imaging systems, the fabrication and evaluation of aspherical mirrors, and the development of ML coatings and reflection masks, EUV resists, and EUV light sources. The most important EUVL conferences that took place during the early years, together

with a list of the conference proceedings and technical journals that contain the majority of papers on EUVL from its beginning in the mid-1980s through 1996, are described in Sec. 1.6 and in Tables 1.1 and 1.2. A short summary of the current status of EUVL is presented in Sec. 1.7, followed by an extensive list of references.

1.2 The Early Stage of Development—1981 to 1992

The use of normal-incidence reflective optics for x-ray microscopes and x-ray telescopes was proposed in the early 1980s,^{6–8} but the key enabling technology—efficient ML reflective coatings—was not sufficiently advanced at that time to be of much use. Nevertheless, in 1981, J. Henry, E. Spiller, and M. Weisskopf succeeded in measuring the imaging performance of a normal-incidence x-ray telescope at a wavelength of 6.76 nm.⁶ The test was performed at a 1000-foot-long x-ray test and calibration facility at the Marshall Space Flight Center in Huntsville, Alabama. The primary mirror was 3 inches in diameter and 0.5-inch thick. The Zerodur mirror substrate was figured to better than $\lambda/100$ ($\lambda = 632.8$ nm) and smoothed to x-ray tolerances using a proprietary technique. A ML coating consisting of 124 alternating layers of a rhenium-tungsten (Re-W) alloy and carbon (C) was deposited directly on the Zerodur substrate. The measured resolution was ~ 1 arcsec full-width at half maximum (FWHM), and the integrated reflectivity at the half-power point was 2.8%.

In 1981, J. Underwood and T. Barbee, Jr. constructed a layered synthetic microstructure (LSM) that reflected the first-order K-band emissions of C ($\lambda = 4.48$ nm) at normal incidence, then used it to obtain images of a grid illuminated with a C target x-ray tube.⁸ The LSM consisted of 76 layer pairs of W ($d_W = 7.65$ Å) and C ($d_C = 15.10$ Å) deposited on a 76.2-mm diameter, 0.38-mm-thick silicon (Si) wafer. The integrated reflectivity of the LSM-coated mirror was estimated to be about 6%. The mirror was set up on an optical bench in a vacuum chamber in the configuration shown in Fig. 1.1 and was illuminated using an x-ray tube with a colloidal graphite-coated target. The detector, a special fine-grained film sensitive to soft x-rays (Eastman Kodak SO-212), was exposed for one hour; when developed, the film revealed a 5-line/mm pattern. This experiment is believed to be the first normal-incidence imaging using a ML-coated optic.

In 1982, when lithographic exposure tools illuminated with the g-line of mercury (Hg) were just becoming available, few lithographers were paying much

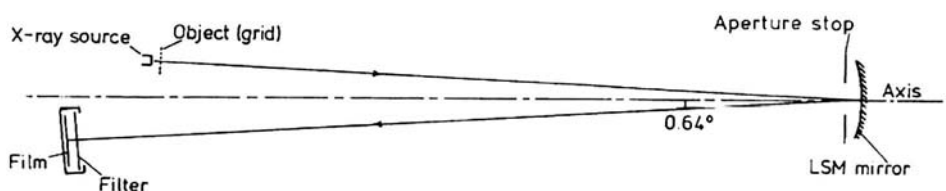


Figure 1.1 Experimental arrangement for normal incidence imaging with carbon K x-rays. (Reprinted from Ref. 8 with permission from Nature Publishing Group.)

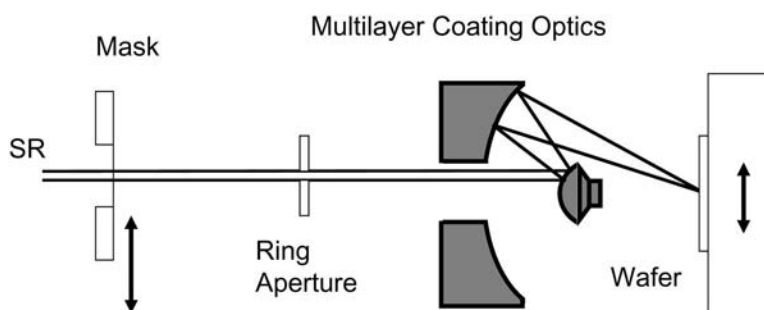


Figure 1.2 Experimental arrangement used by NTT for the first demonstration of soft x-ray projection imaging.

attention to the possibility of x-ray reduction imaging. In fact, the leading alternative lithographic technology at that time was x-ray proximity lithography (XPL). The target resolution for XPL was $0.5\ \mu\text{m}$, a feature size that was difficult to print at that time using optical projection lithography. IBM in the U.S., NTT in Japan, and others were actively engaged in the development of XPL and were using it for the trial production of semiconductor devices. The performance of XPL steppers and x-ray resists seemed adequate, but there were too many manufacturing problems with the x-ray proximity masks.

In 1984, H. Kinoshita of NTT began to consider seriously x-ray reduction lithography as a viable alternative to XPL. Figure 1.2 shows the configuration of the first experimental setup for x-ray reduction lithography.¹ Since the first imaging-system was designed to image a ring-shaped field, the mask and wafer stages were expected to move in sync to extend the exposed area. Initially, the mirrors consisted of a tungsten-carbon ML⁹ deposited on a SiC blank, and the mask was a transparent Si stencil. Later, an imaging system designed to work near the absorption edge of Si was built at the High Energy Physics Laboratory in Tsukuba, Japan, and the initial experiments were carried out at that location. In the beginning, the alignment accuracy of the imaging-system mirrors was very poor because the alignment was carried out with a visible microscope, and all of the replicated patterns were severely distorted. An image of a $4\text{-}\mu\text{m}$ line and space pattern was finally produced in 1985 (see Fig. 1.3), and the results of the early experiments were first presented at the annual meeting of the Japan Society of Applied Physics in 1986. Unfortunately, the response to the paper was rather negative; the audience seemed unwilling to believe that an image had actually been made by bending x-rays.

In 1985, T. Barbee, Jr., S. Mrowka, and M. Hettrick reported the development of molybdenum-silicon (Mo-Si) ML coatings that yielded a high normal-incidence reflectivity at wavelengths around $20\ \text{nm}$.¹⁰ This was the first report of a normal-incidence reflectivity beyond the theoretically predicted value that had ever been obtained experimentally (Fig. 1.4).

In 1986, at the end of a presentation on photoionization-pumping of short-wavelength lasers at the Short Wavelength Coherent Radiation: Generation and Applications Conference in Monterey, California, W. Silfvast and O. Wood of AT&T

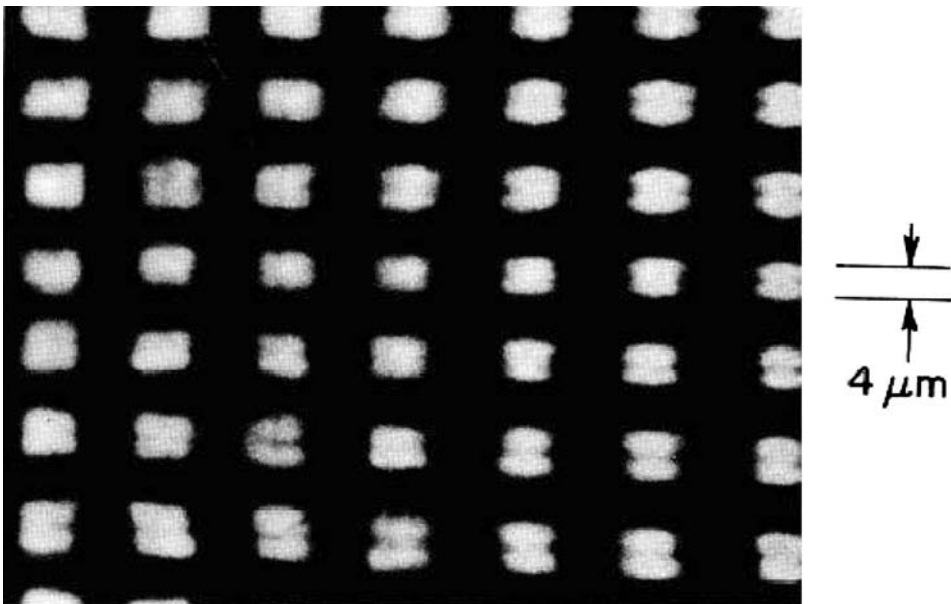


Figure 1.3 Photograph of a 4-μm pattern of dots in a PMMA resist produced by imaging with Schwarzschild optics in 1986.

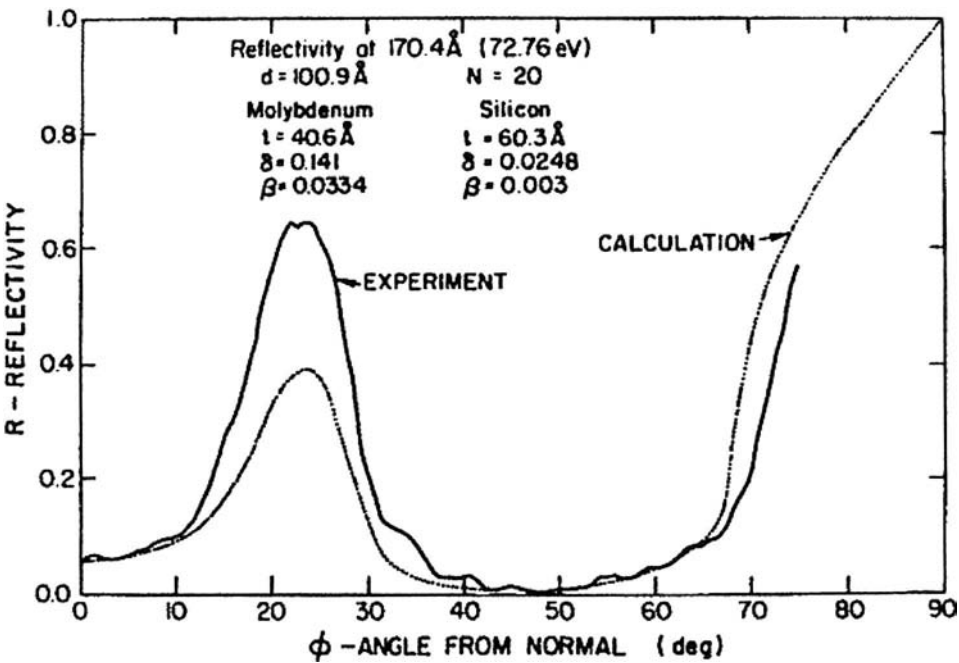


Figure 1.4 Reflectivity of a Mo/Si multilayer film at a wavelength of 170.4 Å. (Reprinted from Ref. 10 with permission from the Optical Society of America.)

Bell Labs suggested to a representative of a U.S. government funding agency that “the development of soft x-ray lasers when taken together with the possibility of multilayer reflectors in this spectral region could lead to a practical system for lithography.”³ The reviews of the subsequent funding proposal, entitled “Tenth micron lithography with a 10 Hz 37.2 nm sodium laser,” were extremely negative. The reviewers maintained that “even if each of the components and sub-systems could be fabricated, the complete lithography system would be so complex that its uptime would be negligible,” and “the printing of 0.1 μm features might be of use for a few high-speed GaAs circuits, but would never be needed for Si integrated circuits.” Because the authors remained convinced that the ideas put forward in their proposal were ones that needed to be explored, the technical parts of the proposal were submitted to a technical journal and subsequently appeared in the first issue of the 1988 volume of *Microelectronic Engineering*.³

In 1988, A. Hawryluk and L. Seppala of Lawrence Livermore National Laboratory (LLNL) proposed soft x-ray projection lithography (SXPL) using a two-mirror imaging system at the 32nd International Symposium on Electron, Ion, and Photon Beams (EIPB) in Ft. Lauderdale, Florida, in a paper entitled, “Soft x-ray projection lithography using an x-ray reduction camera.”⁴ The design of their 5 $\times$ reduction camera, shown in Fig. 1.5, was based on an inverse Cassegrain. Taking into account the penetration depth of the resist materials, the exposure wavelength was set to the absorption edge of C (4.48 nm); a concave spherical mask was used to correct for the curvature of the image field.⁴ In 1989, A. Hawryluk, N. Ceglio, and D. Gaines changed the design wavelength to 13 nm and proposed a system that employed a flat mask and a flat wafer in combination with a scanning stage for the mask and wafer so a larger area could be exposed.¹¹ The authors of these proposals, all members of the Advanced Diagnostics Group in the Laser Fusion Program

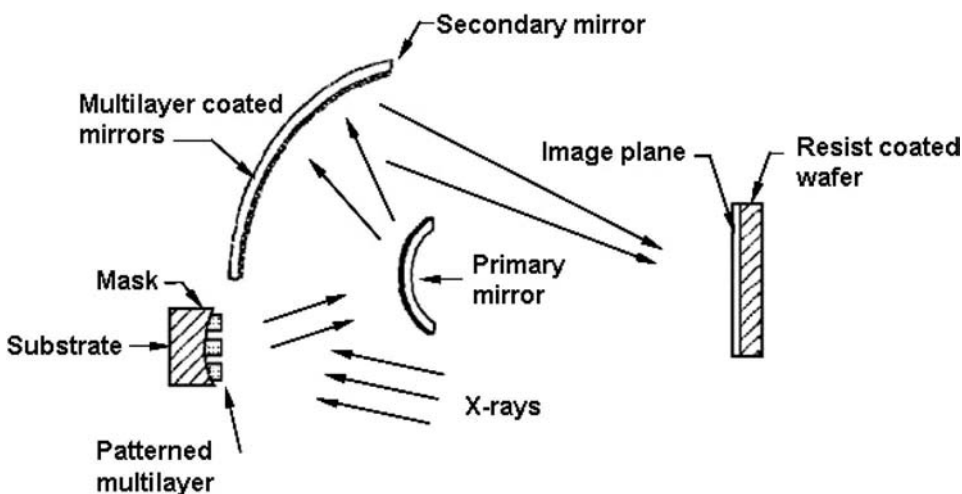


Figure 1.5 X-ray reduction camera with corrected field curvature and uniform illumination developed by LLNL. (Reprinted from Ref. 4 with permission from AVS—The Science & Technology Society.)

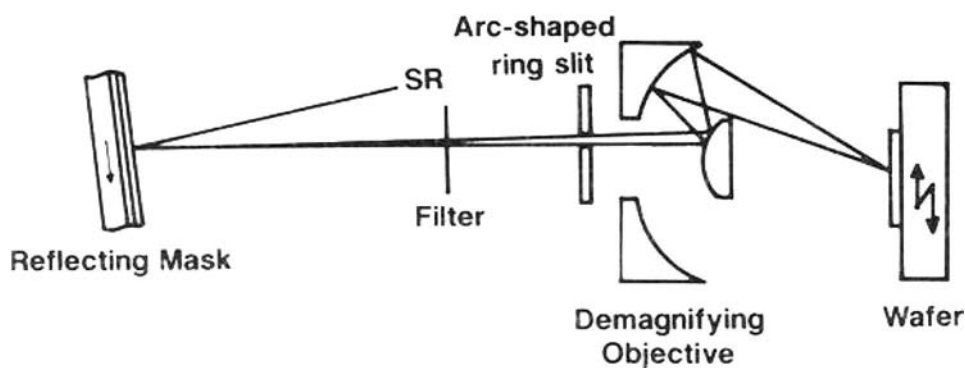


Figure 1.6 Schematic illustration of the experimental set-up to evaluate the image-forming characteristics of Schwarzschild optics and a flat reflective mask. (Reprinted from Ref. 12 with permission from AVS—The Science & Technology Society.)

at LLNL, were actively developing the components and techniques needed for soft x-ray plasma diagnostics (e.g., grazing incidence optics, ML-coated optics, Fresnel zone plates, transmission gratings, etc.); hence, they were able to make important contributions to the development of SXPL from the very start.

In 1989, H. Kinoshita et al. of NTT described early work in Japan at the 33rd International EIPB Symposium in Monterey, California, in a paper entitled, “Soft x-ray reduction lithography.” The paper described the first replication of a 0.5- μm pattern with a Schwarzschild imaging system and a reflection-type mask (Fig. 1.6).¹² The paper also included suggestions on (1) the optimum exposure wavelength, (2) the structure and fabrication of reflective masks, and (3) the characteristics of a practical soft x-ray resist. At the EIPB symposium banquet in the Monterey Aquarium, a Russian scientist, Dr. Tanya Jewell of AT&T, cornered Dr. Kinoshita and proceeded to deluge him with questions. The combination of poor Japanese English and poor Russian English made conversation extremely difficult, so the discussion continued for a long time with Obert Wood of AT&T acting as interpreter. The following year, AT&T announced the printing of a 0.05- μm pattern using SXPL. The authors of this chapter regard the discussion that night in Monterey in 1989 as having been “the dawn of EUVL.”

In 1990, D. Berreman et al. of AT&T Bell Labs described the printing of 0.2- μm features using a 20:1 reduction iridium (Ir) coated Schwarzschild optic at a wavelength of 36 nm (Fig. 1.7).¹³ Later that year, J. Bjorkholm et al. of AT&T demonstrated diffraction-limited imaging at a 14-nm wavelength using a Mo/Si ML-coated Schwarzschild camera by printing features as small as 0.05 μm in photoresist,⁵ as shown in Fig. 1.8. In 1991, A. MacDowell et al. of AT&T described an iridium-coated 1:1 Offner ring-field imaging system for use at a wavelength of 42 nm (Fig. 1.9).¹⁴ Although the group at AT&T specialized in lasers and optical devices, they were also thinking about how to apply laser technology to lithography. Their main goal was to obtain proof of diffraction-limited imaging using an on-axis Schwarzschild camera without distortion. That goal was different from H. Kinoshita’s initial goal of obtaining a large exposure field. Nevertheless,

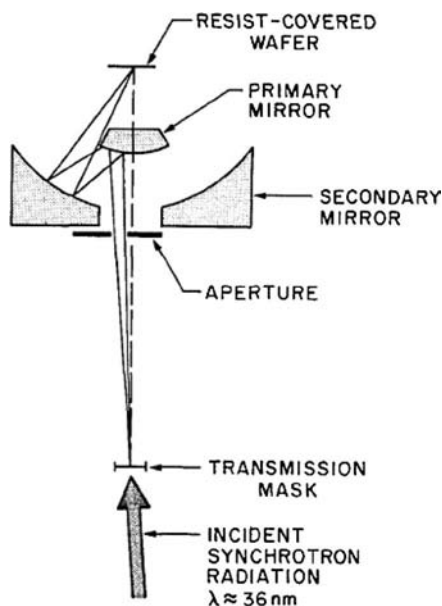


Figure 1.7 Schematic diagram of the experimental arrangement for soft x-ray projection imaging with a Schwarzschild objective used by AT&T Bell Labs. (Reprinted from Ref. 13 with permission from the Optical Society of America.)

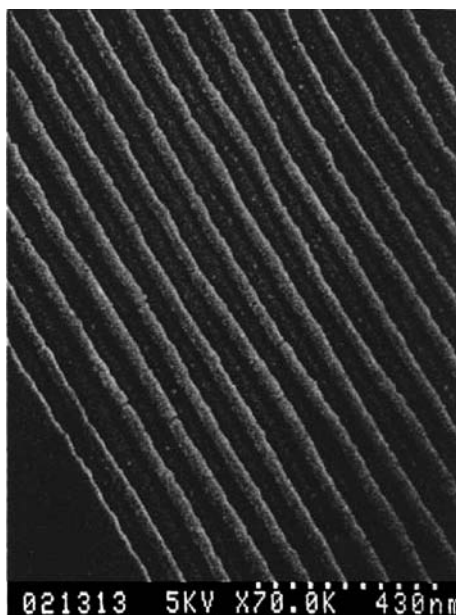


Figure 1.8 SEM micrograph showing a closeup of $0.05\text{-}\mu\text{m}$ lines and spaces printed by AT&T Bell Labs using a Mo/Si ML-coated Schwarzschild optic. (Reprinted from J. Bjorkholm et al., *J. Vac. Sci. & Tech. B* **8**, 1509, 1990, with permission from AVS—The Science & Technology Society.)

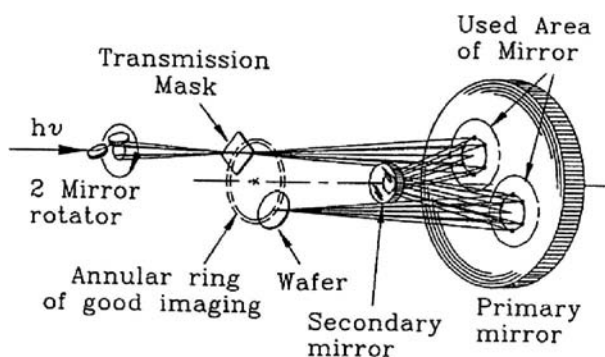


Figure 1.9 Experimental arrangement for soft-x-ray imaging utilizing a 1:1 Offner relay. (Reprinted from Ref. 75 with permission from the Optical Society of America.)

the demonstration of diffraction-limited imaging by AT&T helped pave the way for the development of reduction lithography at short wavelengths.

In 1991, the first Optical Society of America (OSA) Topical Meeting on Soft-X-ray Projection Lithography took place in Monterey, California. At this conference, a group from Sandia National Laboratories (SNL) and AT&T reported the first SXPL system with a laser plasma source (Fig. 1.10).¹⁵ The laser plasma source consisted of a 1.25 J/pulse KrF excimer laser operating at repetition rates up to 100 Hz focused to a 150- μm diameter spot on a rotating gold-coated cylindrical target. At an intensity on the target of $7 \times 10^{10} \text{ W/cm}^2$, the measured total conversion efficiency (CE) in a 4.5% spectral band centered at 13.9 nm was 0.5%. Images of a transmission mask were made in spin-cast films of poly (methyl methacrylate) (PMMA) 50- to 60-nm thick using a 0.08-NA Schwarzschild optic. An atomic force micrograph (AFM) of a portion of the resist image reproduced in Fig. 1.11 shows that 0.1- and 0.15- μm features were clearly resolved.

At the 1992 OSA Topical Meeting on Soft X-ray Projection Lithography, NTT presented exposure results for a two-aspherical-mirror imaging system¹⁶ (Fig. 1.12) designed by K. Kurihara, et al.¹⁷ The experiment utilized a synchrotron source, a two-mirror illumination system, a C filter to eliminate wavelengths longer than 400 Å, a reflecting mask, a two-aspherical-mirrors imaging system, and a resist-coated wafer. The illumination system, employing a Köhler-design and consisting of two toroidal mirrors, illuminated a 100-mm-wide ring-shaped field on a reflecting mask. The incident angle on the optics was nearly normal ($\sim 2^\circ$), and the imaging system was telecentric with respect to the plane of the wafer. To expose a large square field on the wafer, the mask and wafer stages were made to move in sync. The optics for the first experiment were fabricated by Hidaka Kougaku of Japan, but the measurement of their performance with a Fizeau interferometer revealed that they did not meet the required specifications. Subsequently, NTT had more precise mirrors fabricated by Tinsley Laboratories (Fig. 1.13) and two years later succeeded in replicating patterns over a 10-mm² field using the improved optics.¹⁸

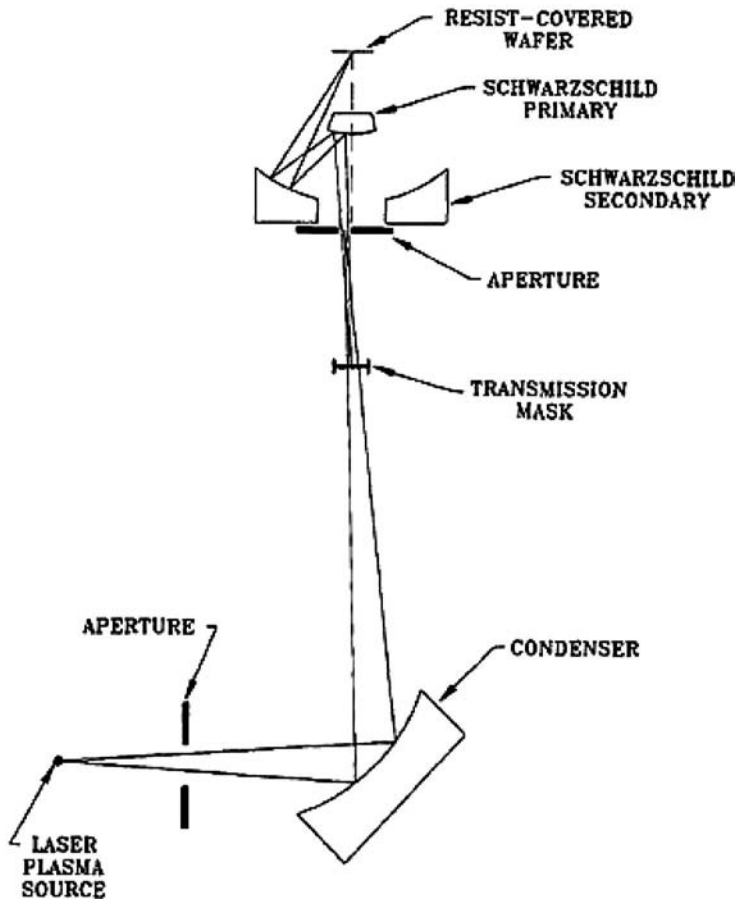


Figure 1.10 Soft-x-ray projection imaging system using Schwarzschild optics and a laser plasma source. (Reprinted from G. Kubiak et al., *J. Vac. Sci. & Tech. B* **9**, 3187, 1991, with permission from AVS—The Science & Technology Society.)

1.3 The Second Stage of Development—1993 to 1996

During the second stage of EUVL development from 1993 to 1996, the focus of R&D work worldwide shifted from demonstrations of EUV imaging to the development of EUV imaging systems that could provide larger image fields and smaller wavefront errors, and to EUVL system integration. The start of this second stage of development coincided with a change in the name of the technology from “soft x-ray projection lithography” to “extreme ultraviolet lithography.” The name change was proposed in May 1993 at the OSA Topical Meeting on Soft X-ray Projection Lithography in Monterey by Richard Freeman of AT&T, ostensibly to avoid confusion with “x-ray proximity lithography,” which was also under development at that time. “EUV lithography” sounded like a natural extension of deep ultraviolet (DUV) lithography, the type of optical lithography widely used commercially in 1993, and the new name was readily adopted. The end of the second

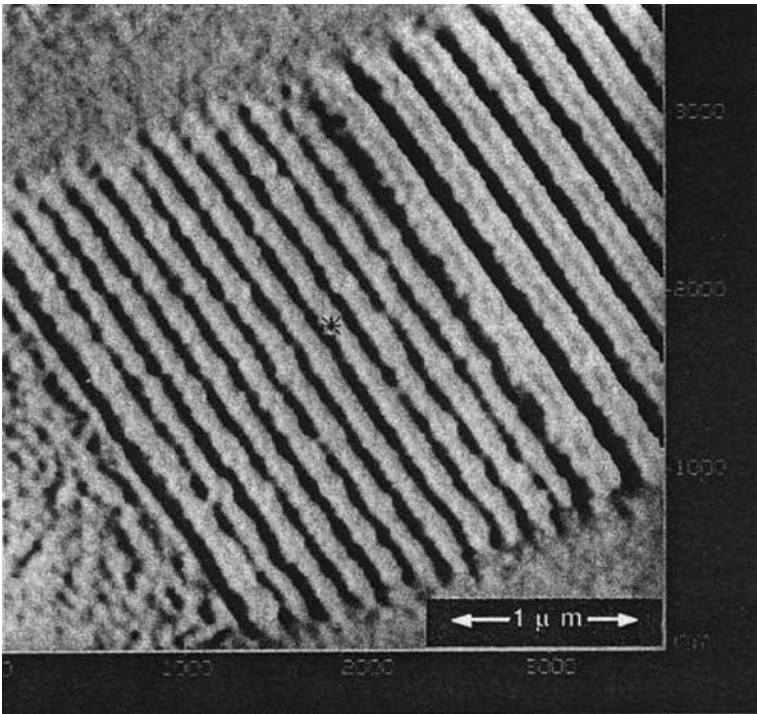


Figure 1.11 AFM of a soft x-ray image in PMMA showing a high-contrast recording of features down to 0.1 μm and a low-contrast recording of 0.05- μm lines and spaces. (Reprinted from G. Kubiak et al., *J. Vac. Sci. & Tech. B* **9**, 3187, 1991, with permission from AVS—The Science & Technology Society.)

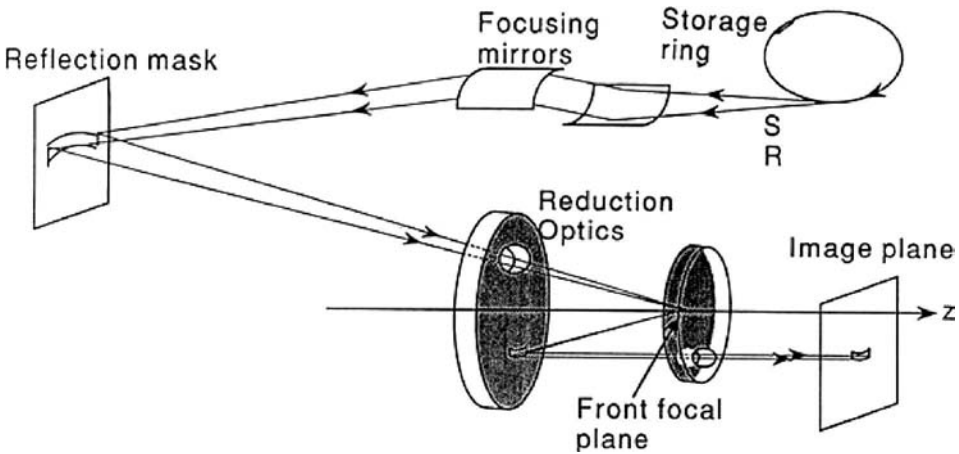


Figure 1.12 Schematic illustration of the two-aspherical-mirror imaging system developed by NTT. (Reprinted from Ref. 19 with permission from the Optical Society of America.)

stage of EUVL development was marked by the fabrication of the first metal-oxide semiconductor (MOS) devices using EUVL in 1996, and the beginning of EUVL commercialization efforts at the EUV LLC in early 1997.

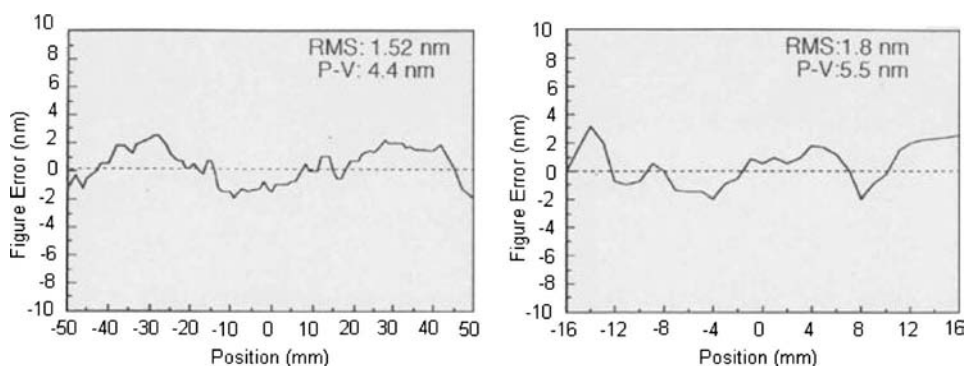


Figure 1.13 Measured figure error of aspherical mirrors fabricated by Tinsley Laboratory in 1993. (Reprinted from Ref. 19 with permission from the Optical Society of America.)

1.3.1 Two-mirror imaging system development

In 1993, H. Kinoshita et al. of NTT fabricated and assembled a $5\times$ reduction, 0.07-NA, two-aspherical-mirror imaging system with a 20×0.4 mm exposure area¹⁹ based on a design described by K. Kurihara et al.¹⁷ Unfortunately, the figure errors of the concave and convex mirrors, 8.8- and 2.0-nm rms, respectively, were out of specification for 0.1- μ m imaging. Nevertheless, when the system was assembled and aligned, imaging of features as small as 0.25 μ m was achieved over a 10×0.6 mm area, and imaging of 0.15- μ m features was achieved over a portion of a 2×0.6 mm ring-shaped field, as shown in Fig. 1.14. In 1996, Haga et al. succeeded in expanding the exposure area of the two-aspherical-mirror imaging system to 20×25 mm by utilizing new critical-illumination optics to illuminate a ring-shaped field area of 20×0.6 mm and by synchronously scanning the mask and wafer stages.²⁰ The exposure time for a 10-mm square area at the NTT superconducting storage ring in Atsugi (Super ALIS) was about 16 minutes when the ring current was 500 mA.

In 1994, a U.S. National EUV Lithography Program, made up of teams of researchers from LLNL, Lawrence Berkeley National Laboratories (LBNL), SNL, and AT&T Bell Labs was launched with financial support from the U.S. Department of Energy. The program was led by Dr. Frits Zernike Jr., formerly of SVG Lithography, and its progress was monitored by a technical advisory group consisting of W. F. Brinkman (AT&T), D. O. Patterson (DARPA), J. R. Carruthers (Intel), J. A. Glaze (JAMAR), K. H. Brown (SEMATECH), G. E. Fuller (Texas Instruments), D. A. Markle (Ultratech Stepper), and C. W. Fowler (U.S. Department of Energy). This program was the first attempt in the U.S. to pursue the development of EUV lithography in an organized way. Prior to this, EUVL projects between U.S. national laboratories and private corporations were carried out via a series of cooperative research and development agreements (CRADAs).

In 1994, G. Sommargren of LLNL developed the $3.4\times$ reduction, 0.06-NA, two-mirror, four-reflection ring-field imaging system shown in Fig. 1.15. This system was used in a testbed facility at LLNL to evaluate “front-end” issues such as

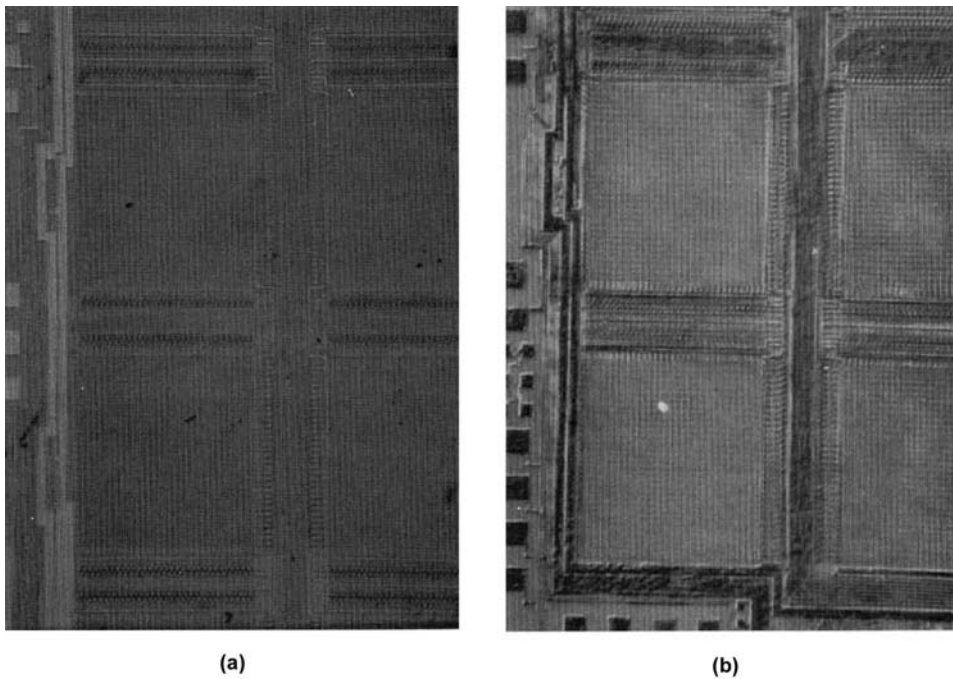


Figure 1.14 Photographs obtained with a two-aspherical-mirror imaging system developed by NTT of (a) reflection mask patterns, and (b) replicated patterns. (Reprinted from Ref. 19 with permission from the Optical Society of America.)

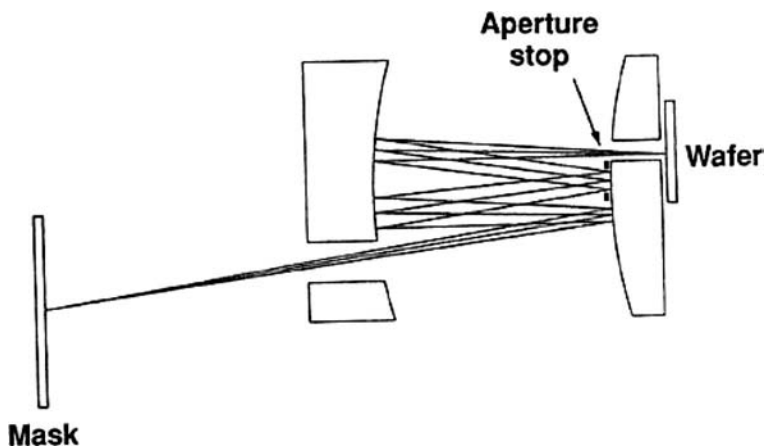


Figure 1.15 Optical layout for an all-spherical, two-mirror, four-reflection, ring-field imaging system developed by LLNL. (Reprinted from Ref. 21 with permission from the Optical Society of America.)

high-repetition-rate laser drivers, CE of laser light to EUV radiation, and condenser systems with specific illumination and coherence requirements.²¹ In 1996, B. La Fontaine et al. used this system to print features as small as $0.137\ \mu\text{m}$.²² The imaging results were not as good as expected given the low, measured imaging system

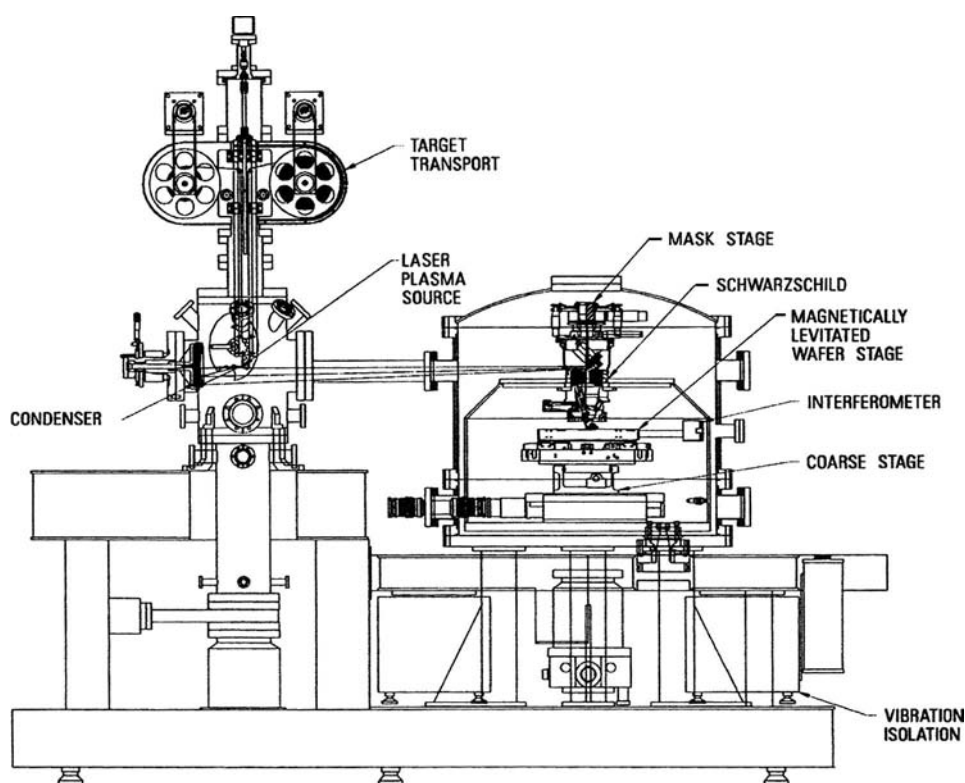


Figure 1.16 Sketch of a laboratory EUVL tool based on a laser plasma source, a $10\times$ -reduction Schwarzschild camera, and a magnetically levitated fine stage developed at SNL. (Reprinted from Ref. 23.)

wavefront error. The lower-than-expected image contrast was attributed to the presence of scattered light in the image plane (flare). Thus, B. La Fontaine et al. were among the first to suggest that, in the future, the surface characteristics of imaging-system optics needed to be specified more fully, i.e., beyond that needed to ensure a low system wavefront error and a high EUV reflectance.²²

In 1995, D. A. Tichenor et al. of SNL began development work on the first EUVL laboratory tool capable of precise overlay.²³ This so-called $10\times$ -II Schwarzschild was the first laboratory EUVL tool that combined a near-diffraction-limited imaging capability, accurate stages, and an integrated through-the-lens alignment system. The major components of the tool, shown in Fig. 1.16, included a $10\times$ reduction, 0.08-NA Schwarzschild imaging system with $0.1\text{-}\mu\text{m}$ resolution (the measured wavefront error was $\sim 1\text{ nm rms}$), a debris-mitigated laser plasma source, a magnetically levitated wafer stage, an electrostatic wafer chuck, and a grazing-incidence optical system to maintain focus. Coarse mask-to-wafer alignment was carried out in a prealignment station equipped with a microscope and a micrometer stage. A manual wafer transfer system was used to transfer wafers to the exposure chamber. Fine mask-to-wafer alignment was performed with a through-the-lens optical Moiré alignment system.²⁴

In 1996, A. A. MacDowell et al. of AT&T Bell Labs described the initial results from AT&T's second 1:1 Offner ring-field imaging system using a new mirror substrate fabricated by SVG Lithography Systems.²⁵ The imaging performance of the previous Offner system, fabricated in 1992, suggested that the imaging would improve significantly if the figure errors of the mirrors were improved. During the mirror fabrication process, emphasis was placed on reducing surface figure errors, but no attempt was made to define errors within the mid-spatial-frequency range. The resolution of the new Offner system was significantly improved, and the new imaging system was able to print 75-nm dense lines/spaces; however, the image modulation was not as high as expected based on the measured system wavefront, which suggested that small-angle scattering of light from mid-spatial-frequency surface roughness (flare) was dominating the imaging results. The disappointing imaging results from the new Offner imaging system provided additional evidence that the substrate surfaces in future EUV imaging systems needed to meet much tighter specifications for figure ($\sim 100\text{--}1\text{ nm}$), mid-spatial-frequency roughness ($\sim 1000\text{--}1\text{ }\mu\text{m}$), and nano-roughness ($\sim 1000\text{--}10\text{ nm}$).

1.3.2 Three-mirror imaging system development

In 1996, D. A. Tichenor et al. of SNL described the fabrication and evaluation of the $5\times$ -reduction, 0.1-NA three-aspheric-mirror ring-field imaging system²⁴ shown in Fig. 1.17. The system was based on a “reflective triplet” design developed in 1994 by J. H. Bruning et al. of Tropel Corporation²⁶ for AT&T Bell Labs. The system utilized low departure aspheric reflectors, its wafer size was telecentric, and it had low-distortion (<0.2 waves at 13-nm wavelengths over a $25 \times 1\text{ mm}$ arc-shaped image field). It had two design limitations: the aperture stop was not accessible, and the three-mirror reflections required the mask and wafer planes to be placed on the same side of the imaging system, which resulted in mechanical interference that limited the scanning. Nevertheless, the design represented a major step

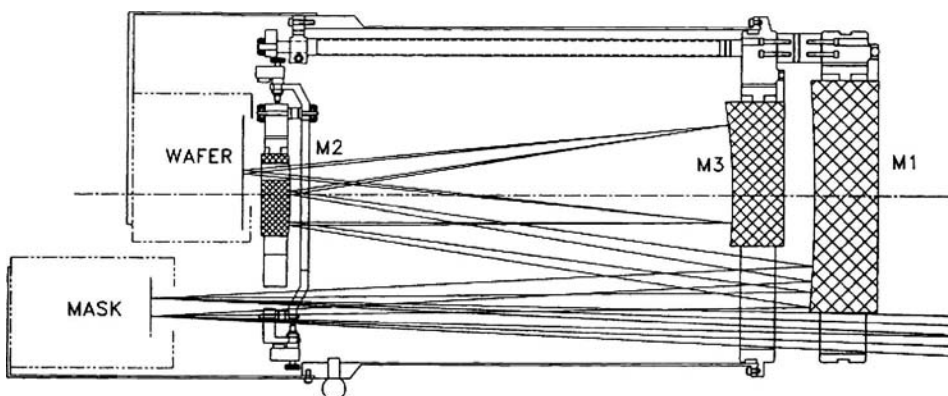


Figure 1.17 Three-aspheric-mirror imaging system developed by SNL, Tropel, and AT&T. (Reprinted from Ref. 23.)

in EUV camera development, beyond that of the spherical systems and two-mirror aspheric systems that had been built previously. The mirrors used in the imaging system were fabricated by Tinsley Laboratory using computer-controlled optical surfacing and computer-generated holographic nulls. All three mirrors were figured to a precision of 0.6 nm rms as measured interferometrically over a spatial scale from about 1 mm to the full clear aperture. At that time, the mirrors for this system were the most precisely figured set of aspheres in existence. Measurements of the mid-spatial-frequency surface errors and the high-spatial-frequency roughness using white-light interferometry and atomic force microscopy, respectively, showed that an additional five-fold reduction in surface errors over most of the spatial frequency spectrum would be necessary before these mirrors could be used in an EUVL manufacturing tool. Finite element analysis was used to design mounts that would assure a stress-free condition and preserve the precise figure of the mirrors. The wavefront error of the assembled and aligned system at various field points ranged from 1.0 to 1.7 nm rms.²⁴ These values were in agreement, to within the accuracy of the measurements, with simulations based on figure data from the individual mirrors. The measured wavefront error was better than that of most spherical EUV systems at that time. The results demonstrated that a small wavefront error could be realized in an advanced aspheric imaging system with a ring-field dimension comparable to that required in a practical EUVL camera design; they also provided the know-how needed to assemble the four-mirror EUV imaging system in the Engineering Test Stand (ETS) developed by the EUV LLC several years later.

1.3.3 MOS device demonstration using EUVL

In 1996, a team from SNL, AT&T, and the University of California at Berkeley fabricated the first demonstration MOS device using the 10×-II EUV Schwarzschild system described above.²⁷ The team fabricated n-type MOS (NMOS) transistors with gate lengths ranging from 0.075 to 2.0 μm using a modified NMOS process in which the active areas were defined by local-oxidation-of-silicon (LOCOS) isolation, as shown in Fig. 1.18. The gate oxide layers were grown by thermal oxidation and had thicknesses of 2.5, 4, and 5.5 nm. The gate was a 150-nm-thick in-situ doped n^+ -polysilicon deposited by low-pressure chemical vapor deposition (LPCVD). It used a blanket boron (B) punch-through stop (80 keV , $3 \times 10^{12}/\text{cm}^2$), and a lightly doped drain structure was formed with low-temperature oxide (LTO) spacers. Shallow junctions were created by low-energy arsenic (As) implantation (10 keV , $3 \times 10^{13}/\text{cm}^2$) and deep junctions by high-energy As implantation (50 keV , $2 \times 10^{15}/\text{cm}^2$). Five lithography steps were used to define the NMOS devices. The active area, EUV alignment marks, contacts, and metal layers were defined using I-line lithography. The EUV alignment marks were patterned directly into the polysilicon layer immediately before trilayer deposition to create marks with the highest possible fidelity. All of the process steps, except for ion implantation and EUV gate-level lithography, were carried out in the Microfabrication Facilities at the University of California-Berkeley. Figure 1.19 shows the

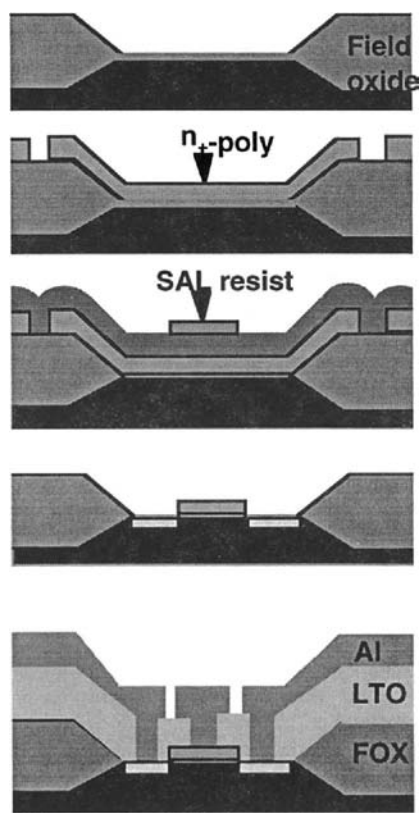


Figure 1.18 Schematic diagram of the NMOS process used to fabricate the first semiconductor devices using EUVL. Legend: Al = aluminum; LTO = low-temperature oxide; FOX = field oxide. (Reprinted from Ref. 27 with permission from the Optical Society of America.)

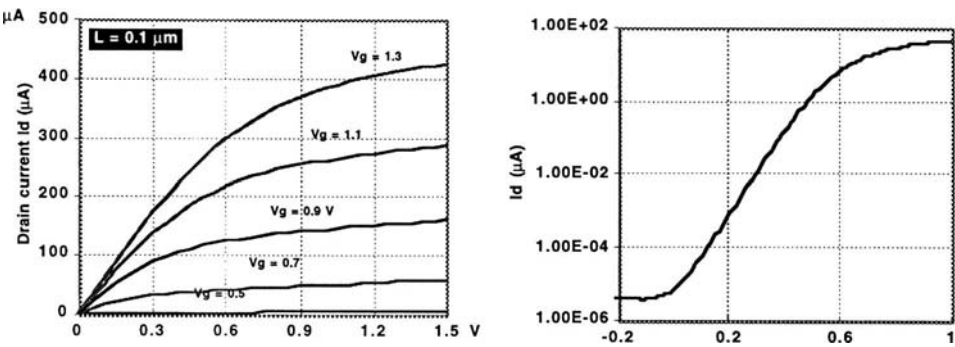


Figure 1.19 Characteristics of a 0.1- μm NMOS transistor with EUVL gate level patterning (3- μm gate width). (Reprinted from Ref. 27 with permission from the Optical Society of America.)

I-V and subthreshold characteristics of one of the NMOS devices with a 0.1- μm long and 3- μm wide gate. The threshold voltage was 0.55 V, the transconductance

was 200 mS/mm, the saturated drain current was 400 μ A, and the subthreshold swing was 90 mV/decade.

The National EUV Lithography Program funded by the U.S. Department of Energy lasted for approximately three years, and when it ended most of the early EUVL research work in the United States also ended. The establishment of the EUV LLC in 1996–1997 marked the beginning of commercialization efforts in the United States. Work at the EUV LLC contributed to all aspects of EUV development until November 2002 and brought EUVL significantly closer to the stage of practical use. Stepper-makers SVG Lithography and ASML participated directly in the program. Many specialists in the fields of optics, polishing, thin films, metrology, and laser plasmas worked together in the EUV LLC in a complicated organizational arrangement, while a consortium of integrated device manufacturers that included AMD, IBM, Infineon, Intel, Micron, and Motorola supplied funding and provided technical guidance to the program. The organization and accomplishments of the EUV LLC are described in detail in Chapter 2 of this book.

1.4 Other Developments in Japan and Europe

From 1984 to 1992, the development of EUVL technology in Japan was pursued mainly by NTT and focused on demonstrating the feasibility of replicating 0.1- μ m patterns using ML-coated Schwarzschild optics. Starting in 1991, Hitachi and Nikon began to make advances in EUVL through experiments at SORTEC and at the High-Energy-Physics Laboratory in Tsukuba, respectively. In 1993, T. Namioka of Tohoku University organized a soft x-ray optics meeting focused on ML coatings and EUV light-source development that intensified EUVL research activities in Japan. The early EUV work at Hitachi confirmed that 70-nm line and space patterns could be printed using 20 $\times$ reduction Schwarzschild optics with either etched ML or absorber-over-layer reflection masks.²⁸ From 1992 to 1995, EUVL work in Japan focused on developing two-aspherical-mirror imaging systems that had an exposure field large enough for practical use.^{20,29,30} By 1996, Hitachi had succeeded in designing, fabricating, and assembling such a system.³⁰ The mirrors for their two-aspherical-mirror imaging system were fabricated using a novel small-tool asphere generator. The figure accuracy for the convex asphere, measured with a Fizeau interferometer, was 18-nm peak to valley, and the surface roughness, measured with an AFM, was 0.16-nm rms. While neither mirror achieved sufficient figure accuracy to support diffraction-limited imaging, when a narrow arc on the mask was illuminated with synchrotron radiation at the Photon Factory in Tsukuba, 0.12- μ m-wide lines and spaces were delineated over portions of the ring field.³⁰ The early EUVL work at Nikon was focused on developing some of the basic technologies needed for EUVL, the fabrication of aspheric surfaces using a small-tool polishing machine, a Kohler-critical illumination system for use with a ring-field reflective imaging system, a debris-mitigated laser-plasma EUV source, and damage-free reflection-mask fabrication technology. In 1996,

K. Murikami et al. of Nikon described the design of a three-aspherical-mirror ring-field imaging system.³¹ After Dr. Kinoshita joined the Himeji Institute of Technology (HIT) in 1995, Nikon and Hitachi launched joint research projects with HIT, eventually resulting in the development of a three-aspherical-mirror EUVL imaging system for demonstration MOS device fabrication.³²

By the autumn of 1998, the need for advanced EUVL equipment development became widely recognized in Japan, and the Association for Super-Advanced Electronics Technologies (ASET) was formed.³³ Soon thereafter, Intel and Samsung began cooperating with ASET on EUVL research, a move that helped accelerate the globalization of EUVL research and development. The ASET EUV program focused on mask fabrication and resist technologies using the EUV imaging system at HIT, and on EUV reflectometry and EUV imaging system wavefront metrology using beamlines at the New SUBARU synchrotron facility. In June 2002, a new government-funded organization—called the Extreme Ultraviolet Lithography System Development Association (EUVA)³⁴—focused on the development of EUV light sources, and projection optics was established.

In Europe, early EUVL research was carried out by various branches of the Fundamenteel Onderzoek der Materie (FOM) Institute and was supported by the government of The Netherlands under the framework of EUREKA. In 1991, this work led to the design for an extended-field EUV imaging system that employed two spherical mirrors and a concave reflection mask,³⁵ as well as a novel coating system for EUV reflective multilayers that employed electron-beam deposition and interface smoothing by ion bombardment.³⁶ By 1993, the work in Europe had expanded to include development of a krypton-fluorine (KrF) laser-induced soft x-ray source³⁷ and a liquid-droplet target system that produced much less debris.³⁸ In January 1994, a collaborative EUVL development program called EX-ULT involving ASM Lithography, the FOM Institute, SOPRA, Carl Zeiss Inc., Technical University Delft, and The Netherlands Center for Laser Research was launched to concentrate on high-power debris-free sources, precision optics fabrication and metrology, and defect-free masks.³⁹ In August 1998, a new European research program, called the Extreme UV Concept Lithography Development System (EUCLIDES), was launched by ASM Lithography, Carl Zeiss Inc., and Oxford Instruments.⁴⁰ By building on results from EUCLIDES and from the French national EUV lithography program called PRogramme Extreme UV (PREUVE), a larger collaborative program called Microelectronics Development for European Applications+ (MEDEA+) was launched in January 2001 and focused on the development of EUV exposure tools, light sources, imaging systems, and mask manufacturing.⁴¹ The MEDEA+ Extreme UV Alpha Tools Integration Consortium (EXTATIC) project recently resulted in the development of two full-field EUV R&D exposure tools.

1.5 The Development of Individual Technologies

The most important advances in EUVL development that were made each year from 1985 to 1996 in Europe, Japan, and the U.S. were detailed in Secs. 1.2, 1.3, and 1.4. A graphical record of these advances is illustrated in the fishbone diagram shown in Fig. 1.20, where one or more highlights from each year's technical progress have been recorded in the lower half of the figure. Four scientific and technological breakthroughs that occurred during this time period, without which EUVL would not have been possible, are also shown in Fig. 1.20 (in the upper half of the figure). These four major advances—the first demonstrations of normal-incidence imaging in the soft x-ray spectral region, the development of MoSi ML coatings, the fabrication of precision aspheres, and the invention of the phase-shifting point-diffraction interferometer (PSPDI)—not only enabled EUVL but also may have accelerated progress in other fields of science and technology that utilize reflective imaging systems, e.g., astronomy, microscopy, satellite surveillance, plasma diagnostics, spectroscopy, and medicine. More information on the first normal-incidence-imaging experiments can be found in Sec. 1.2. More information on the ML coating work of E. Spiller⁴² and T. Barbee¹⁰ can be found in Secs. 1.5.1 and 1.5.4. More information on asphere development at Tinsley Laboratory and on the PSPDI developed by G. Sommargren⁴³ can be found in Sec. 1.5.3. The remainder of Sec. 1.5 focuses on the development of the individual components and subsystems needed for EUVL exposure tools (reflective imaging

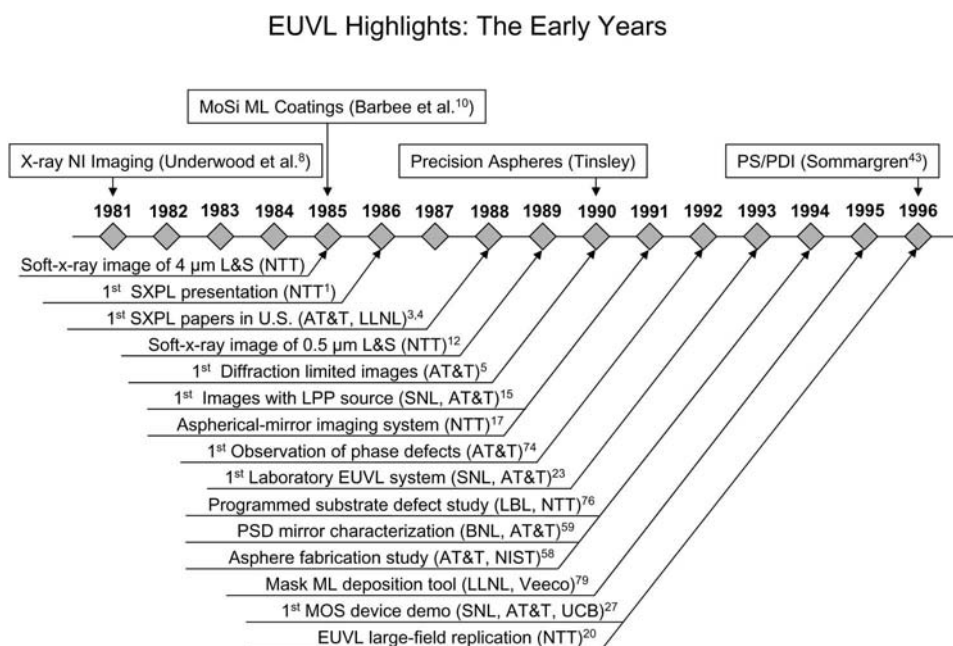


Figure 1.20 Fishbone diagram showing the yearly highlights of early EUVL development from 1981 through 1996.

systems, aspherical mirrors, reflective ML coatings, and short-wavelength radiation sources) and for the supporting infrastructure (reflection masks and resists).

1.5.1 Selection of the exposure wavelength

One of the earliest and most important decisions made in the field of EUVL was the choice of exposure wavelength.¹² That choice influenced the design of the projection optics, set the peak reflectivity and bandwidth of the ML reflective coatings, and had a profound impact on the performance of EUV resist materials. Over the course of the early work, exposure wavelengths as short as 4 nm and as long as 85 nm were considered;⁴⁴ the lower limit for this wavelength range was determined by throughput considerations (the reflectivity of a ML decreases, and its bandwidth becomes smaller as the wavelength becomes shorter), and the upper limit was determined by imaging system requirements (resolution and depth of focus).

The primary motivation for EUVL was to develop an exposure tool capable of a higher resolution and a larger depth of focus than was possible with DUV or 193-nm lithography. The two fundamental relationships describing lithographic imaging system resolution (RES) and depth of focus (DOF) are

$$\text{RES} = k_1 \lambda / \text{NA} \quad (1.1)$$

and

$$\text{DOF} = \pm k_2 \lambda / (\text{NA})^2, \quad (1.2)$$

where λ is the wavelength of the imaging radiation, and NA is the numerical aperture of the imaging system. The parameters k_1 and k_2 are empirically determined and take on values that depend on the critical dimension (CD) tolerance and the size of an acceptable integrated circuit (IC) manufacturing process window. The NA and exposure wavelength required for a given resolution and DOF can be calculated using Eqs. (1.1) and (1.2) and are shown graphically in Fig. 1.21. The resolution and DOF targets in 1989 (resolution better than 0.1 μm and DOF larger than $\pm 1 \mu\text{m}$) could be met by imaging systems with a NA and exposure wavelength in the shaded area shown in Fig. 1.21 ($0.01 < \text{NA} < 0.1$ and $3 \text{ nm} < \lambda < 40 \text{ nm}$).

Multilayer coatings are efficient normal-incidence reflectors at EUV wavelengths from 4.5–30 nm.⁴⁵ A ML consists of alternating layers of high-Z and low-Z materials and functions like a quarter-wave stack, i.e., it provides enhanced reflectivity over a narrow wavelength band peaked at the Bragg wavelength, $\lambda = 2\Lambda \sin(\theta)$, where Λ is the ML period and θ is the angle of incidence. Generally, the highest reflectivity occurs at wavelengths for which the absorption of the low-Z material in the ML is at a minimum and occurs in discrete bands near atomic absorption edges. The best low-Z materials for ML coatings are C (for wavelengths longer than 4.4 nm), B (for wavelengths longer than 6.7 nm), beryllium (Be) (for wavelengths longer than 11.3 nm), Si (for wavelengths longer than 12.5 nm), and lithium (Li) (for wavelengths longer than 23.9 nm).⁴⁴ For practical throughput, the

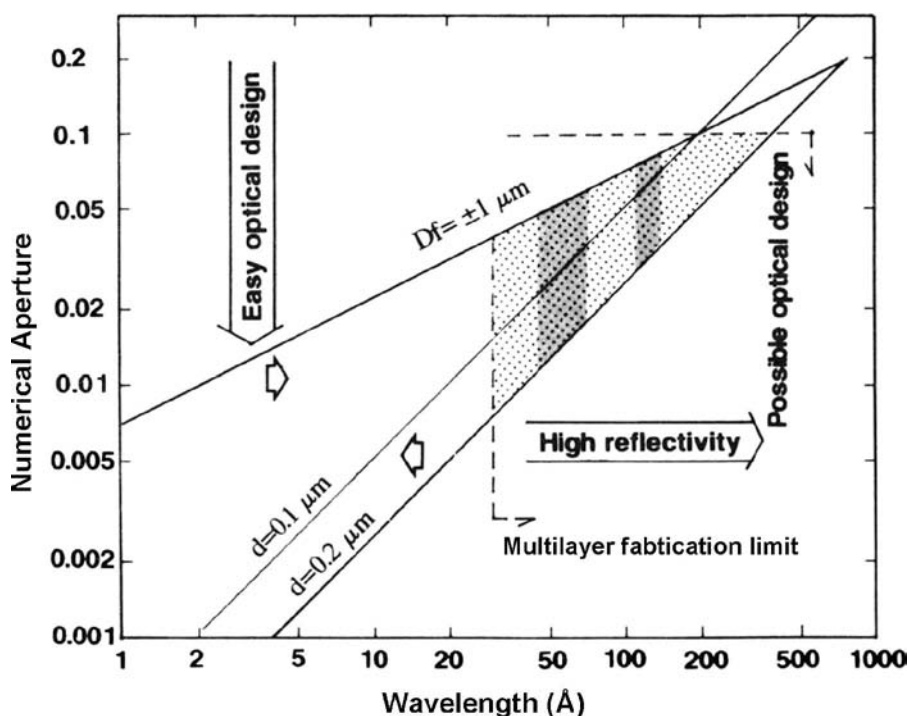


Figure 1.21 Plot of NA versus wavelength used by NTT to select the optimum exposure wavelength for SXPL. (Reprinted from H. Kinoshita, K. Kurihara, Y. Ishii, and Y. Torii, *J. Vac. Sci. & Tech. B* 7, 1648, 1989, with permission from AVS—The Science & Technology Society.)

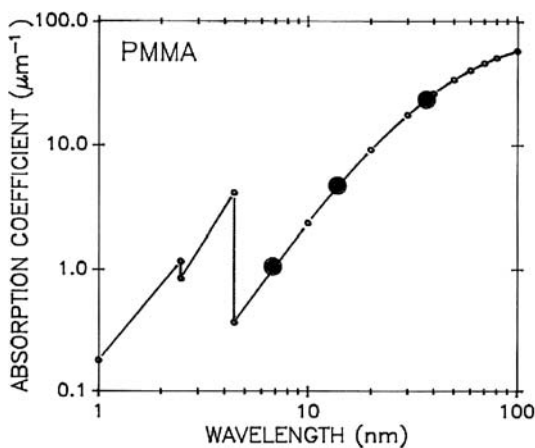


Figure 1.22 Absorption coefficient of PMMA versus wavelength in the EUV spectral region. (Reprinted from Ref. 46 with permission from the Optical Society of America.)

ML must provide $\sim 30\%$ or more peak reflectivity and have a bandwidth of 0.3–0.4 nm so that the different angles of incidence on all of the mirrors in a multimirror projection optic can be matched.¹²

The sensitivity and absorption depth of an EUV resist depends almost entirely on its EUV absorption coefficient. Because PMMA resist is typical of many organic resist materials in the EUV, the absorption coefficient of PMMA versus wavelength is shown in Fig. 1.22. The large discontinuity in absorption near 4.4 nm is due to the K-edge of C. If EUVL could be carried out at 4.4 nm, quite thick resist layers could be used. Unfortunately, C-based MLs, the only materials that give useful normal-incidence reflectance in this wavelength region, are characterized by low reflectance and have an exceedingly narrow reflectance bandwidth. Early experimental work by H. Kinoshita et al.¹² showed that the development depth of PMMA reached a limit at 0.08 μm at an 11.8-nm wavelength but is more than 0.3 μm at a 5-nm wavelength. They concluded that exposure wavelengths longer than ~ 10 nm would require either a bilayer resist process or a new resist material with a development depth of at least 0.3 μm .¹² Later experimental work by O. Wood et al. showed that the large absorption coefficient of carbon-based resist materials at 13.9 nm resulted in unsatisfactory sidewall profiles when the resist was employed in a single-layer process.⁴⁶ The resist sidewall profile is improved somewhat at a 11.3-nm wavelength, which is the reflectance maximum of Be-based MLs⁴⁷ and is improved dramatically at a 6.8-nm wavelength, which is the reflectance maximum of B-based MLs.⁴⁸ However, imaging at a 6.8-nm wavelength is beginning to be degraded by chromatic vignetting.⁴⁹

Taking into account the required resolution and DOF, ML reflectance and bandwidth, and resist performance, the choice of exposure wavelength was narrowed in the earliest work¹² to two wavelength regions: from 4.5 to 7 nm and from 11.5 to 13 nm. In a slightly later work,⁴⁴ the choice was narrowed to discrete wavelength bands in the vicinity of 11.3, 13, 17, and 24 nm. Today, based on more practical considerations such as overall system throughput and worker safety concerns over the use of Be-based MLs in a semiconductor fab, the choice of exposure wavelength has become a narrow band of wavelengths near 13.5 nm. In 1989, the imaging system requirements (resolution better than 100 nm and DOF larger than ± 1 μm) could be met with a 0.1-NA imaging system with three or four ML-coated mirrors. To meet today's targets for resolution and DOF (resolution better than 32 nm and DOF larger than ± 0.15 μm), Mo-Si ML-coated imaging systems with 0.25 NA and six to eight aspheric mirrors are required.

1.5.2 Design of reflective imaging systems

The first EUVL imaging experiment employed Schwarzschild optics,¹² which are notable because they produce an aberration-free image on one axis even though both mirrors have spherical surfaces. However, with that design the blur caused by coma increases linearly with distance from the axis. Thus, the designer of a Schwarzschild system can, in practice, always balance to some extent the aberration and field size on one axis. In 1986, H. Kinoshita et al. proposed an off-axis Schwarzschild system with a scanning stage to enlarge the exposure field. A ray-tracing program was used to design the optics so there would be little aberration at

an off-axis position.^{1,2} In 1988, A. Hawryluk et al. proposed an inverse Cassegrain design with a curved mask to compensate for the aberration of image curvature.⁴ In 1989, O. Wood et al. showed that the 1:1 Offner annular-field system, which provides diffraction-limited imaging in a narrow ring-shaped field at one particular image height (where 3rd- and 5th-order astigmatism are balanced), can be used in the EUV if restricted to NAs around 0.1.⁵⁰ Although these early spherical mirror designs were useful for principle verification, they are not suitable for the projection optics in an EUVL tool. The optical system in a lithographic exposure tool must satisfy the following three minimum requirements:

1. Be telecentric on the image side (to prevent magnification change with image plane defocus);
2. Provide a high resolution and a wide exposure field; and
3. Employ an even number of mirrors (so that object and image are on opposite sides of the projection optics to allow unrestricted wafer travel).

In 1989, a two-aspherical-mirror imaging system satisfying these minimum requirements was developed by H. Kinoshita et al. of NTT.¹⁹ In that design, the primary mirror was convex, the secondary mirror was concave, the radius of curvature of both was about 980 mm, and the separation between the mirrors was about 820 mm. The telecentric design made use of a ring-shaped field and aspherical mirrors to reduce aberrations. The mirrors had conic surfaces (i.e., had no higher-order aspheric terms) to make them easier to fabricate and had about the same radius of curvature so that the image plane would be flat. The reflection mask was planar; a curved reflection mask for aberration correction was not employed to ensure a practical mask fabrication process. The incident angles on the mirrors and mask were set to approximately normal incidence to facilitate wavelength matching of the ML coatings. Since the ML periods were almost equal, the two mirrors and the reflection mask could be coated in a single deposition run. Moreover, the image degradation due to the phase shift that occurs at reflection could be neglected because of the use of near-normal incidence.

In 1990, T. Jewell et al. of AT&T devised a four-aspherical-mirror reflective imaging system with a ring field shown in Fig. 1.23 that satisfied all the requirements for practical 0.1- μm EUV projection lithography.⁵¹ This design was based on a reflective Cooke triplet, with a fourth mirror added between the secondary and tertiary mirrors. It was a $4\times$ reduction system with a NA of 0.1 and provided excellent image quality over a several-millimeter-wide ring. All of the mirrors were rotationally symmetric surfaces with low aspheric departure. The radius at the center of the ring field was 31.5 mm on wafer, which allowed the exposure of large chips by scanning. Adding the fourth mirror enabled several of the requirements of a practical lithography system to be met: (1) it brought the object and image to opposite sides of the projection system, thus allowing unlimited wafer travel; (2) it provided an accessible stop; (3) when power was added to the fourth mirror, it helped to provide a larger back clearance; and (4) it helped to achieve full

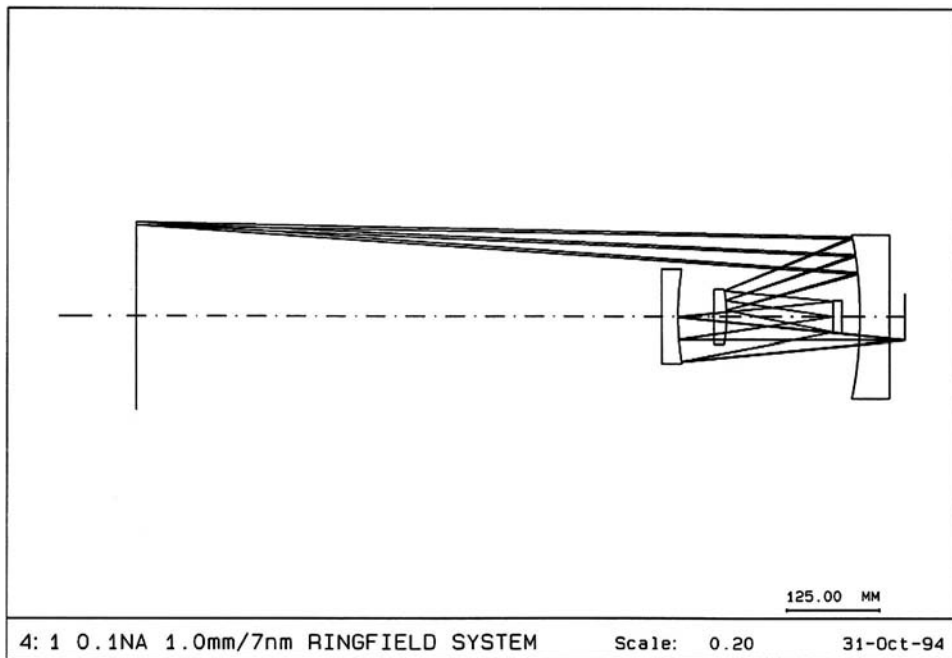


Figure 1.23 Layout of a four-mirror ring-field system designed by Dr. T.E. Jewell of AT&T. (Reprinted from Ref. 104 with permission from the Optical Society of America.)

astigmatic correction over a large field of view, thereby reducing alignment sensitivity. In ring-field systems, the width of the ring is usually limited by astigmatism. However, in the AT&T four-aspherical-mirror design, since the astigmatism was corrected over nearly the entire image field, the width of the ring was limited by distortion. For example, for a 1.0-mm-wide ring, the amount of residual distortion was 7.0 nm in the scan direction and 3.5 nm in the cross-scan direction; for a 2.5-mm-wide ring, the values increase to 40.0 nm and 20 nm, respectively. An additional feature of this design was an optimum chief ray angle in the object space. During system optimization, the chief ray angle with respect to a line normal to the mask was constrained to a minimum of 2.5 deg to allow sufficient room to bring the illumination beam to the mask.

The search for an unobscured reflective imaging system design that would satisfy all of the requirements for the projection optics in an EUV exposure tool started with the two-spherical-mirror systems well known from astronomy and microscopy but quickly progressed to designs involving three or more aspheric reflectors.^{26,52,53} Some of the lessons learned from the early EUV imaging system design work were:

1. The use of aspheres cannot be avoided;
2. Scanning ring-field designs are the simplest systems that can print a large field;

3. To avoid image smear in a scanning system, image distortion must be minimized, not only across the ring width in the radial direction but also all the way to the outer edges of the arc defined by the slit in the cross-scan direction;
4. A practical system must employ an even number of mirrors so that multiple chips on the same wafer can be exposed; and
5. The design must incorporate an accessible stop so that diffraction orders from features at different places on the mask will not be passed or blocked by the limiting apertures in the system and result in a nonuniform image structure.

In 1996, O. Wood et al. began searching for a design for a larger-NA, all-reflective imaging system that would capitalize on recent advances in optical interferometry⁴³ and asphere fabrication.⁵⁴ The optical layout for one such design, a $5\times$ reduction, 0.5-NA six-aspherical-mirror imaging system, is shown in Fig. 1.24.⁵⁵ Its image field was a 30-mm-wide by 1-mm-wide ring. It had an accessible aperture stop. All of its beam clearances were acceptable, and the magnitude of the largest aspheric departure was $\sim 150\text{ }\mu\text{m}$. Some of the lessons learned during the 1996 reflective imaging system design work were:

1. To minimize scan distortion and mirror substrate size, the design should be of the ring-field type;
2. Good designs will likely have a minimum of six aspheric mirrors;

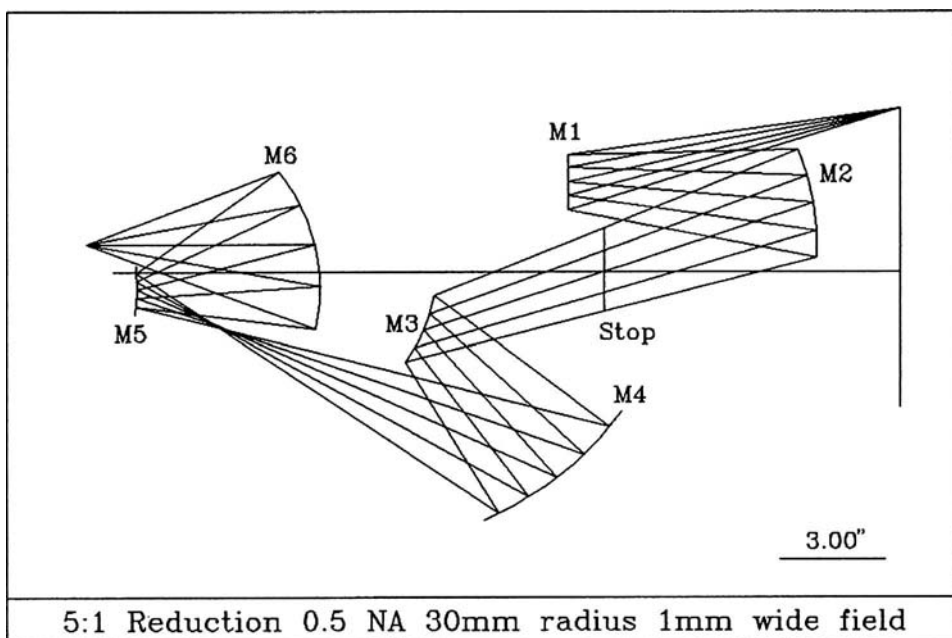


Figure 1.24 Layout for a six-mirror 0.50-NA ring-field imaging system. (Reprinted from Ref. 55 with permission from the Optical Society of America.)

3. The two mirrors closest to the image should probably utilize the Schwarzschild design form; and
4. The complexity of reflective imaging system design is reduced considerably when the NA is kept at or below 0.5.

1.5.3 Fabrication and evaluation of aspherical mirrors

In the late 1980s, the surface figure and surface finish tolerances of the mirrors needed for EUV imaging systems were well beyond the capabilities of the optics industry. Since that time, a number of new and more accurate optical polishing and metrology techniques have been developed to support EUVL applications, many of which have found application in other areas of optics as well (astronomy, aerial reconnaissance, satellite communications, etc.).

Before 1990, commercial phase-measuring interferometers (PMIs) offered $\lambda/1000$ resolution and $\lambda/300$ repeatability. Absolute figure uncertainty was about $\lambda/20$ for flats up to 150 nm in diameter and no better than $\lambda/10$ or so for spheres, largely because of the quality of the reference surfaces that were available at that time. For aspheres, the absolute figure uncertainty was only about $\lambda/5$ or so, provided that the asphere could be compared to a reference sphere that had no more than a few waves of figure departure.⁵⁶ Around 1990, the highest precision obtainable for an aspherical surface was about 8-nm rms. At about that time, Tinsley Laboratories helped Ball Aerospace develop the COSTAR correction optics for the Hubble Space Telescope. This spectacular achievement increased confidence in the computer-controlled surfacing (CCOS) technique that Tinsley had employed.⁵⁷ The first step in Tinsley's asphere fabrication process, illustrated in Fig. 1.25, involved precision machining with a diamond grinding wheel to produce an initial

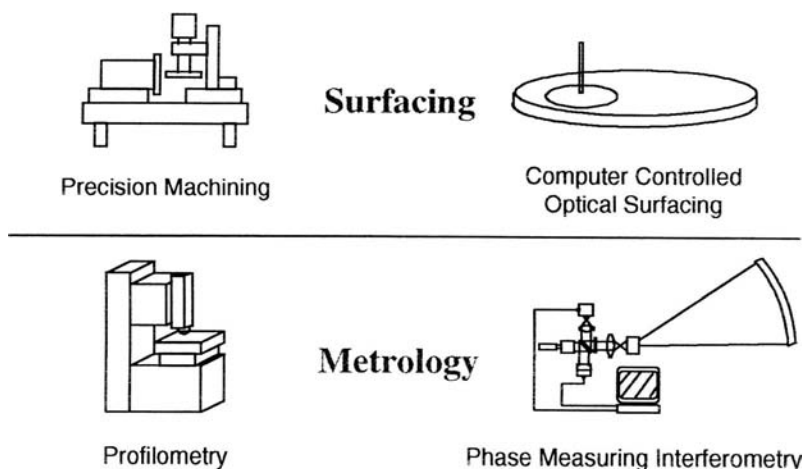


Figure 1.25 Aspheric fabrication process at Tinsley Laboratory using four core technologies. (Reprinted from a presentation by D. Bajuk and R. Kestner at the Second U.S.-Japan Workshop on Soft X-Ray Optics: Technical Challenges, Lake Yamanaka, Japan, Nov. 12–14, 1996, with permission from D. Bajuk.)

spherical surface accuracy of 1 to 2 μm , as measured with a contact-type profilometer. In the second process step, an aspherical surface meeting the required specifications was fabricated by an iterative process that employed subaperture polishing tools and a PMI to measure the shape. In 1993, Tinsley Laboratories fabricated two aspherical mirrors for a two-mirror, 0.07-NA EUV imaging system, but the accuracy was only 1.5 nm for the concave mirror and 1.8 nm for the convex mirror.¹⁹ In 1995, NTT used these mirrors to replicate patterns less than 100 nm in size in an area over 10-mm square by employing a scanning mechanism for the mask and wafer.²⁰

From 1991 to 1994, a precision optics fabrication study⁵⁸ was carried out by AT&T Bell Labs (with partial financial support from NIST's ATP program) to determine the current state of the art in aspheric fabrication and to identify promising approaches to further reduce surface figure errors. Four leading optics manufacturers were asked to fabricate an aspheric reflector substrate for an existing three-mirror EUV imaging system design. This element, called M2, was an on-axis asphere having an outside diameter of 92 mm, a clear aperture of 64 mm, and a maximum aspheric departure from the best-fit sphere of less than 2 μm . Various fabrication methods were used, including conventional artisan figuring, ion milling, and computer-controlled polishing. The metrology methods used in the fabrication and evaluation of the final part included the use of PMI with a refractive null, PMI with a computer-generated holographic (CGH) null, and a custom non-null Fizeau interferometer. The best reported measurement obtained from this study indicated that one manufacturer had achieved a figure error of ~ 0.6 -nm rms after removal of tilt, power, and coma.²³ Subsequent advances in the fabrication and metrology of aspheres were made, and an accuracy of 0.3 nm was achieved in 2000. A record of the progress in the manufacture of aspherical mirrors at Tinsley Laboratories is shown in Fig. 1.26.

Visible-light PMI is the metrology most commonly used to provide the feedback needed for substrate figuring. Since PMI is a comparative technique, its accuracy is limited by the quality of the reference, whether it be an optical surface, a null lens, or a CGH. In the past, many methods were developed to increase the accuracy of PMI, including making a series of measurements with the reference in transposed positions, but no technique had demonstrated the accuracy needed for EUV optics development. In 1996, G. Sommargren of LLNL developed a new type of PMI that utilized a diffraction-based reference, the principle of which is illustrated in Fig. 1.27.⁴³ Light leaving the end of a single-mode optical fiber diffracted to form a spherical wavefront. Part of this wavefront was incident on the optic under test and was reflected back toward the fiber. This aberrated wavefront reflected from a semitransparent metal film on the face of the fiber and interfered with part of the original spherical wavefront to produce an interference pattern on a CCD camera. Initial measurements of surface figure with such an interferometer showed that its measurement accuracy was better than 0.50-nm rms. Additional developments since that time have resulted in measurement accuracies approaching 0.10-nm rms.

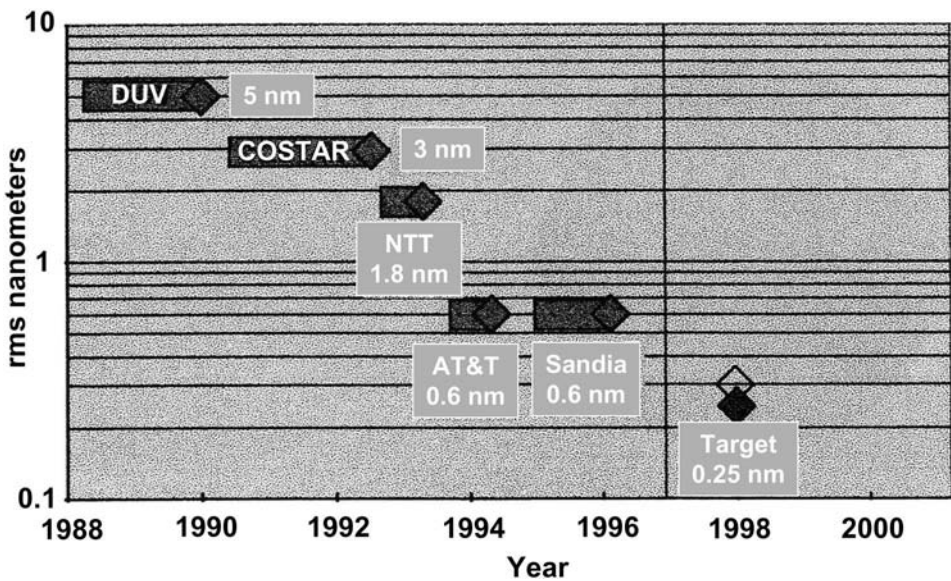


Figure 1.26 Advances in aspherical mirror fabrication at Tinsley Laboratory. (Reprinted from Ref. 57 with permission from D. Bajuk.)

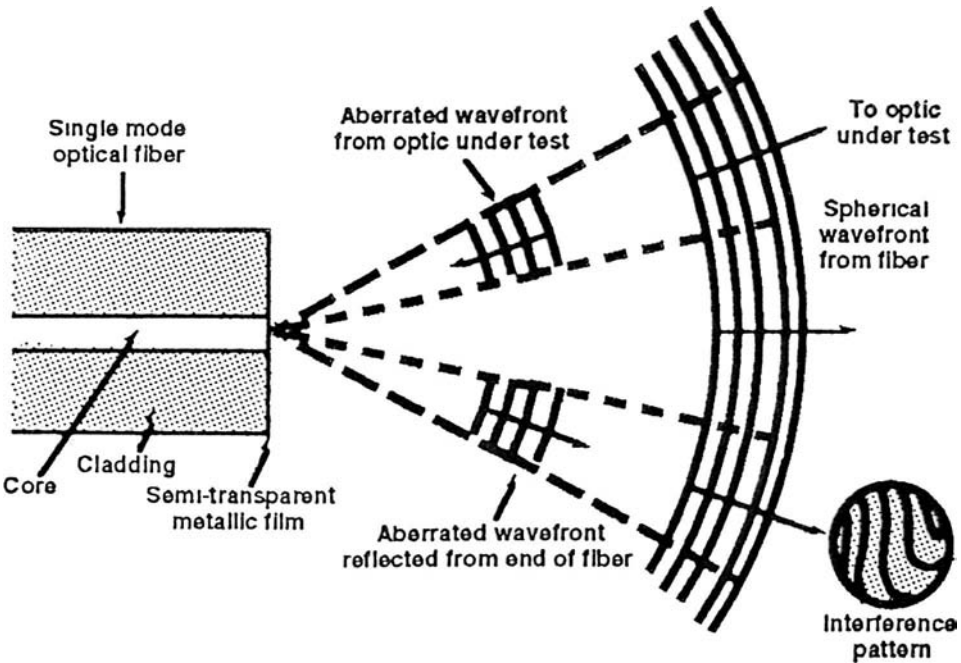


Figure 1.27 Principle of operation of the PSPDI developed by Gary Sommargren. (Reprinted from Ref. 43 with permission from the Optical Society of America.)

The surface topography of mirrors for EUVL must be precisely controlled from spatial scales extending from the clear aperture of the part to the wavelength of the illumination. Surface figure data at low spatial frequencies obtained from

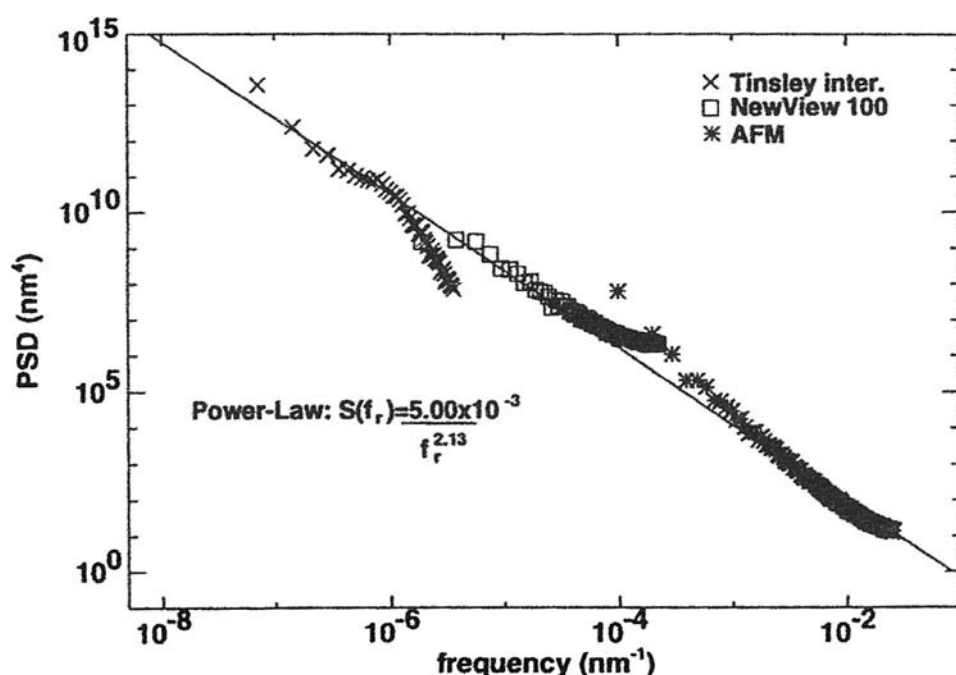


Figure 1.28 Plot of the 2D power spectral density description of the surface of a convex aspheric substrate. (Reprinted from Ref. 61 with permission from the Optical Society of America.)

visible light interferometry are needed to ensure diffraction-limited imaging. Surface finish data at mid and high spatial frequencies obtained with a white-light interferometric microscope and an AFM are needed to predict the distribution of scattered radiation in the imaging system. These fine-scale fluctuations in the effective surface height are best described in statistical terms.⁵⁹ Eugene Church of the U.S. Army Armament Research, Development and Engineering Center was one of the first to point out that highly polished optical surfaces (such as x-ray mirror substrates) are frequently fractal-like,⁶⁰ with power spectra given by an inverse power law. Power spectral density (PSD) surface height data for an aspheric optic fabricated for an EUVL imaging system are shown in Fig. 1.28.⁶¹ This aspheric substrate exhibits both a precise figure and minimal surface roughness at higher spatial frequencies. Power-law fits to the PSDs are also shown in Fig. 1.28. If most of the roughness power is concentrated at high-spatial-frequency roughness (HSFR), which is the case for highly polished optics, the scattered light will not reach the image plane; hence, it will not contribute to contrast loss in the image plane, but instead will merely result in EUV reflectivity loss. On the other hand, mid-spatial-frequency roughness (MSFR) can scatter light into the image plane and will result in a corresponding loss in contrast. For this reason, MSFR and its concomitant “image flare” is a serious concern for EUVL, even today.

Progress in the fabrication and metrology of aspheres since the early 1990s is nothing short of miraculous. In the beginning, only low-departure aspheres could be fabricated, and these were found to be only marginally useful for two-mirror

EUV imaging systems. Today, aspheres that meet the stringent requirements of a large-NA six-mirror EUVL imaging system (<0.2 -nm rms for figure, MSFR, and HSFR) are available commercially. As evidence for this, at the 5th International EUVL Symposium in Barcelona in October 2006, one aspheric mirror substrate with 0.05-nm rms figure, 0.15-nm rms MSFR, and 0.09-nm rms HSFR was reported by Carl Zeiss Inc.; another substrate with a 0.18-nm rms figure, 0.135-nm rms MSFR, and 0.09-nm rms HSFR was reported by Nikon Corporation.

For high resolution, an imaging system must meet or exceed the classical diffraction limit, i.e., the total wavefront error must be less than 0.25 waves peak to valley (Rayleigh criterion) or 0.07 waves rms (Marechal criterion). The total wavefront error in a lithographic imaging system must be smaller still (0.02 waves rms) to ensure that the residual aberrations will not result in a significant loss in DOF and CD control.⁶² The total system wavefront error at each point in the image field of an EUV imaging system will depend on the surface profile and alignment of each mirror, and on the spatially varying properties of its ML reflective coating because EUV coatings behave differently at their design wavelength than they do in visible light. It was recognized very early on that undulator radiation would be an ideal source for EUV interferometry,⁶³ and several different EUV interferometers were developed.^{64,65} The most accurate one was the PSPDI.^{66,67} Foucault and Ronchi's testing of the alignment of EUV optics was also demonstrated using both synchrotron and laser-plasma light sources.^{68,69} The early experimental work showed that functional testing at the operational wavelength, i.e., EUV interferometry, was particularly important when aligning and qualifying a new EUV imaging system.

1.5.4 Multilayer coatings and reflection masks

At normal incidence, no naturally occurring material provides more than about 1% reflectance in the EUV spectral region at wavelengths below 30 nm, because the index of refraction of all materials in this region is approaching unity. This fact is illustrated in the plots of the normal-incidence reflectance of aluminum (Al) and Ir versus wavelength⁷⁰ shown in Fig. 1.29(a). In 1972, E. Spiller of IBM showed that ML structures composed of thin layers of materials that have widely different EUV absorption values can lead to constructive interference and therefore enhanced reflection.⁴² In 1981, J. Underwood and T. Barbee⁸ demonstrated normal-incidence soft x-ray imaging at a wavelength of 4.46 nm, and in 1988, A. Walker et al. obtained soft x-ray images of the solar corona with a normal incidence Cassegrain multilayer telescope.⁷¹ This was the turning point for EUV optics—the point where it became clear that normal-incidence ML-coated optics offered clear advantages over the severe aberrations, small field of view, and difficulty of manufacture of grazing-incidence optics. A further key development occurred in 1985, when T. Barbee et al.¹⁰ demonstrated that the ML combination of Mo and Si had an exceptionally high normal-incidence reflectivity at wavelengths just longer than the Si L_1 absorption edge at 12.4 nm. The normal-incidence reflectance of the best modern Mo-Si MLs now approaches 70% in a narrow band of wavelengths near 13 nm,⁷² as shown in Fig. 1.29(b).

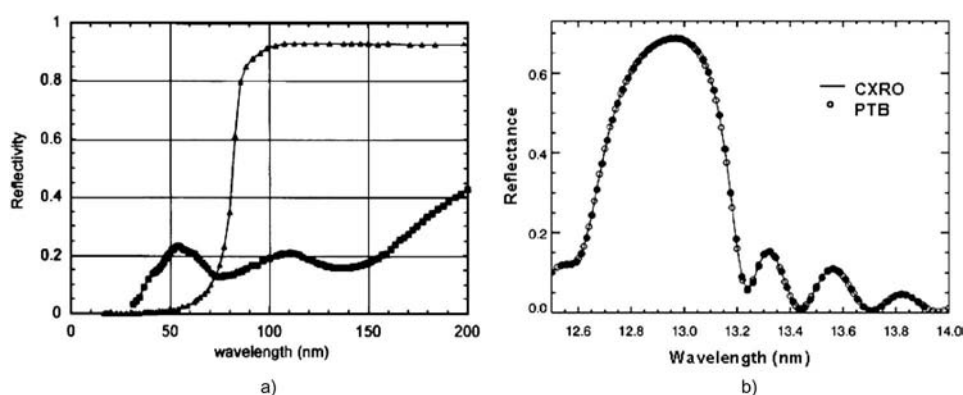


Figure 1.29 (a) Normal incidence reflectances of clean Al (triangles) and Ir (squares) surfaces. (Reprinted from Ref. 70.) (b) Normal-incidence reflectance of a Mo/Si ML with 40 bilayers measured at the Center for X-Ray Optics (CXRO) and at Physikalisch-Technische Bundesanstalt (PTB). (Reprinted from Ref. 72.)

Depositing a ML film on a curved optical surface produced several practical problems. One was peeling due to the large stress in a ML film deposited on a spherical substrate with a small radius of curvature. Also, the ML was strongly affected by humidity; when it was left in air, exfoliation occurred. Moreover, the instant it was taken out of the sputtering equipment, the stress balance collapsed and pinholes formed. In addition, since the bottom layer initially was Si and the top layer was Mo, scattering occurred due to the roughening of the Mo surface due to oxidation, which reduced the contrast of replicated patterns. H. Takenaka and his colleagues at NTT solved these problems one by one; for example, they used C or Si as a capping layer to reduce scattering, and they finally managed to make a stable ML on a spherical surface. Each of the mirrors in an EUVL exposure tool must have the highest possible reflectivity at 13 nm (to maximize tool throughput), and more importantly, the central wavelength of the reflectivity must be controlled to better than 0.01 nm (to maximize imaging performance). To provide diffraction-limited printing resolution, the mirror surfaces must have surface figure errors of the order of ~ 0.1 -nm rms, and the ML coating deposition must not contribute more than 0.25 of this total error, a requirement that leads to strict requirements on the coating thickness over the entire optical surface.

Today, EUV mask blanks are similar to mask blanks for conventional optical lithography except they are coated with 40 layer pairs of Mo (2.8-nm thick) and Si (4.1-nm thick) instead of a single layer of chrome. The 6-inch-square $\times$ 0.25-inch-thick mask substrate is a low thermal expansion material (LTEM) instead of quartz. A variety of technologies for patterning ML-coated reflective masks were evaluated early on, including patterned gold (Au)¹¹ and other absorbing overlayers,⁷³ reactive-ion-etched MLs,^{12,73} and ion-damaged ML regions by ion implantation.⁷³ Among the three patterning techniques, the formation of buffer and absorber layers atop a Mo-Si ML-coated blank, like that shown in Fig. 1.30, is now preferred because it offers the most straightforward repair options. The buffer layer be-

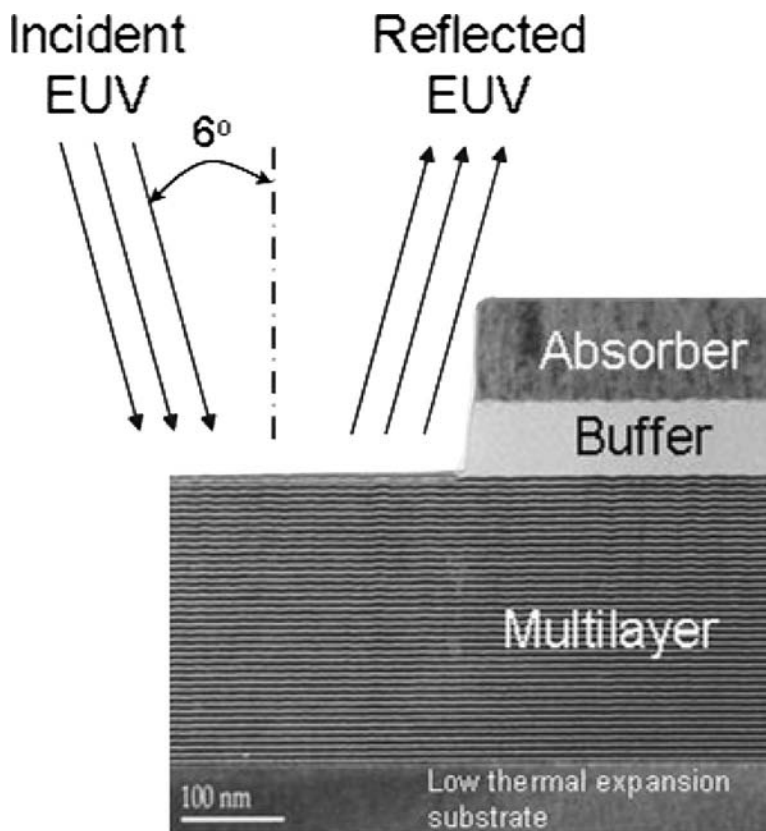


Figure 1.30 Cross-sectional transmission electron microscope (TEM) image showing EUV reflective mask architecture. (Reprinted from H. J. Levinson, *Principles of Lithography, 2nd Edition*, SPIE Press, Bellingham, WA, 2005.)

tween the absorber and the ML reflector protects the ML from damage during absorber patterning and repair. Just as is done with chrome-on-quartz masks for optical lithography, the patterned absorber on an EUV mask can be inspected using a commercially available DUV mask inspection tool and repaired as needed using focused-ion or electron-beam techniques.⁷⁴ EUV masks are unlike masks for conventional optical lithography because a few hours of exposure to an EUV beam in vacuum can leave behind a carbon footprint on an EUV reflective mask, which is caused by cracking of residual hydrocarbons in the vacuum system (as shown in Fig. 1.31).⁷⁵ This suggests that an EUV mask must be able to withstand repeated cleanings.

While the repair of defects that occur during the absorber patterning process is relatively straightforward, repair of defects in the ML coating or on the substrate below the reflective coating is more problematic. Examples of these “phase defects” were found during EUV printing experiments as early as 1992, in which a long diagonal feature was printed on the wafer using a mask that had no obvious corresponding absorber feature.⁷⁴ Subsequent examination of the mask revealed a 2.7-nm-deep, 8- μm -wide depression on the substrate beneath the ML coating.

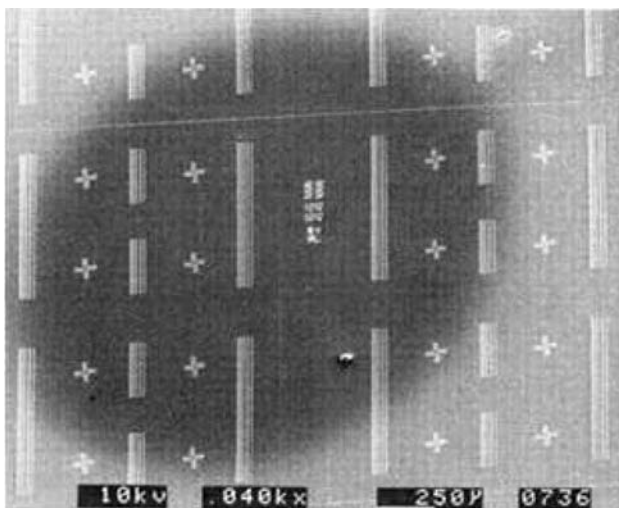


Figure 1.31 SEM micrograph of a Mo/Si ML reflection mask after several hours of soft x-ray irradiation. The rather poor vacuum (10^{-6} Torr) resulted in the cracking of residual hydrocarbons so that C is plated out on the mask (dark area). (Reprinted from Ref. 75 with permission from the Optical Society of America.)

Since the depth of this depression was nearly the 0.25 wavelength depth needed for perfect cancellation of the reflected waves, its presence resulted in an unexpected, high-contrast feature in the aerial image. The fact that this feature was not noticed prior to resist printing pointed to the need for at-wavelength inspection to qualify EUV blanks. The first systematic observation of the effect of substrate defects in EUVL masks on resist images was carried out by K. Nguyen et al.^{76–78} in 1993. That study employed a 5:1 reduction reflection mask with programmed substrate defects of various shapes and sizes. The defects, patterned using e-beam lithography and lift-off, were 20-nm high, and their widths on the mask ranged from 2 to 0.2 μm . The reflective ML coating consisted of 30 Mo/Si bilayers with a d spacing of 7.25 nm; the reflection peak was at a 14.0-nm wavelength. The absorber patterns consisted of a repeating series of 10-, 5-, 2-, and 1- μm lines and spaces in evaporated Au that was 150-nm thick. An optical phase contrast microscope image of the mask, showing the 150-nm thick absorber lines in the foreground and the 20-nm thick programmed defects in the background, is shown in Fig. 1.32(a). A scanning electron microscopy (SEM) image of the programmed defect mask in PMMA resist exposed using the two-mirror EUV imaging system (resolution: 0.15 μm) at the Photon Factory in Tsukuba, Japan, is shown in Fig. 1.32(b). The circled areas show the effects of two gross defects, one in the absorber layer and the other on the substrate, that were used as markers for the location and observation of the smaller programmed defects. Because defects in and under the ML reflective coating were found to be such a serious issue, a project was launched in 1995 to design and build a deposition system specifically to produce low-defect EUV blanks. The system utilized an ion-beam sputter-deposition technique to deposit complete,

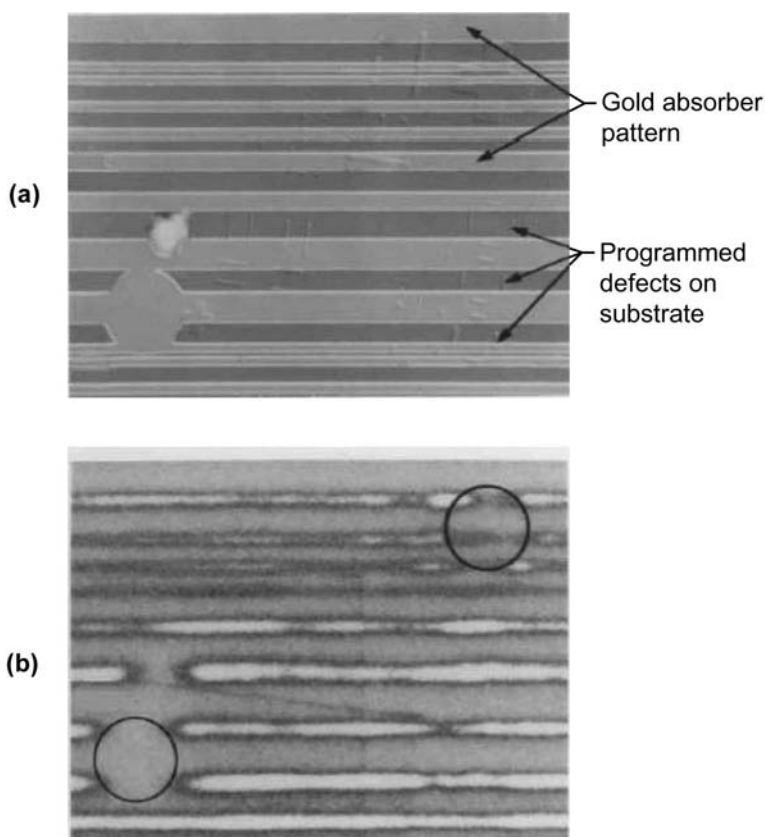


Figure 1.32 (a) Optical phase contrast microscope image of a programmed defect mask. (b) PMMA resist SEM image of the programmed defect mask exposed using the two-mirror EUV aspheric system at the Photon Factory in Tsukuba, Japan. (Reprinted from Ref. 76 with permission of the Optical Society of America.)

81-layer-high Mo-Si MLs on 150-mm diameter (100) oriented Si substrates.⁷⁹ This deposition system was subsequently shown to produce MLs with five orders of magnitude fewer particle defects than typical ML coatings, with the best samples achieving defect densities of $2 \times 10^{-2}/\text{cm}^2$.

The early work on EUV ML coatings resulted in the selection of Mo/Si as the reflective coating of choice as well as the development of several different deposition techniques to control the ML coating thickness on curved mirror substrates. The early work on EUV reflection masks identified the mask architecture that has become standard today, recognized the importance of carbon contamination on an EUV mask, observed and systematically studied blank substrate phase defects, suggested that at-wavelength inspection of EUV mask blanks might be needed, and developed an ion beam sputter deposition system to deposit low-defect-density Mo-Si MLs on Si wafers—the forerunner to the Veeco LDD ML deposition tool in use today at International SEMATECH’s Mask Blank Development Center in Albany, New York, and at other mask shops in Japan and Europe.

1.5.5 EUV resist development

In 1989, in some of the earliest work on candidate soft x-ray resist materials, G. Kubiak et al. of SNL characterized the near-edge x-ray absorption fine-structure spectra, exposure sensitivity, contrast, and post-exposure processing of selected polysilane resists exposed at photon energies close to the Si L_{2,3} absorption edge (100 eV).⁸⁰ They found sensitivities in the range of 600 to 3000 mJ/cm² and contrasts in the range from 0.5 to 1.4 depending on the polysilane side chain. In 1990, D. Berreman et al. of AT&T reported on the soft x-ray sensitivity and contrast of three e-beam resists: polybutene-1 sulfone (PBS), 2,2,2-trifluoroethyl α -chloroacrylate (EBR-9), and PMMA.⁸¹ By incorporating thin imaging layers of these materials into a trilayer resist scheme, D. Berreman et al. succeeded in exposing, developing, and transferring features as small as 0.2 μ m into Si using undulator radiation at a $\sim$ 36-nm wavelength. In 1990, G. Taylor et al. of AT&T pointed out that the absorption of resist materials is substantially higher (10 to 100 times higher) in the soft x-ray region than in the visible and DUV regions because soft x-ray absorption results from the atomic nature of the excitation rather than from the making or breaking of molecular bonds.⁸² G. Taylor et al. published the absorption parameters for 10 polymers, representative of well-known resist materials, derived from the atomic scattering factors given in the Henke Tables.⁸³ In 1991, W. Mansfield et al. of AT&T studied the performance of PMMA at 37.5- and 14-nm exposure wavelengths, and presented measurements of thickness removed versus exposure dose, lithographic sensitivity, and the exposure independent absorption coefficient; they found with both simulation and experiment that the smaller absorption coefficient in PMMA at 14 nm caused the profile of the minimum features to be of significantly higher quality.⁸⁴ W. Mansfield et al. also concluded that the absorption coefficient of PMMA is the primary determinant of sensitivity and contrast in the soft x-ray region. In 1993, A. MacDowell et al. of AT&T attempted to circumvent the resist absorption problem by using a surface-imaging resist process with an organosilane monolayer film that was first exposed to soft x-ray radiation, then selectively metalized using lithium salt of ethylenediamine (LiEDA) grafting chemistry, and finally nickel (Ni) plated.⁸⁵ Using this process, A. MacDowell et al. managed to demonstrate resolution $\leq$ 0.25 μ m at an exposure dose of 50-mJ/cm² but found that the printed features were exceedingly grainy, probably because of a nonoptimal Ni-plating process. In 1994, O. Wood et al. showed, via resist printing experiments in positive-tone PMMA and in negative-tone AZ PN114 at three different exposure wavelengths, that high resist absorption leads to unsatisfactory sidewall profiles except at the shortest wavelength (19 deg at 37.5 nm, 65 deg at 13.9 nm, and 83 deg at 6.8 nm).⁴⁶ O. Wood et al. were concerned that sloping sidewalls would result in poor CD control and pointed out that using an illumination wavelength between 6.8 and 13.9 nm would be advantageous.

In 1996, D. Wheeler et al. of SNL reviewed the sensitivity, resolution, optical density, and etch selectivity of the four most promising EUV resist schemes that had been studied up to that time: trilayer resists (a thin imaging layer on top of a

pattern transfer layer on top of planarizing and processing layers), bilayer resists (solution-developed resists containing inorganic materials to enhance their etch resistance), plasma-deposited organo-metallic resists, and silylated resists.⁸⁶ They concluded that none of the candidate resist schemes would be able to meet the requirements of the first pilot production exposure tools: resolution better than 40 nm, sidewall angle >88 deg, linearity between $\pm 5\%$ to 10%, line edge roughness (LER) and CD control no greater than 5 nm, and sensitivity better than 5 mJ/cm². Given the cost and complexity of developing a new resist and using history as a guide, it is not surprising that, even after 10 additional years of development, the availability of an EUV resist that can simultaneously meet the resolution, LER, and sensitivity requirements of an EUVL pilot production tool continues to remain near the top of the EUV critical issue list.

1.5.6 EUV light source development

Although the development of EUVL light sources has been covered in depth in a recently published technical volume,⁸⁷ the light sources employed in the early years of EUVL development—synchrotron radiation from electron storage rings and laser-produced plasmas (LPP)—are briefly described in this section. The key issues with EUV sources, during the early years and today, were their low conversion efficiency and requirement for extensive debris mitigation.

In 1993, J. Murphy et al. of Brookhaven National Laboratory (BNL) discussed the design requirements for a compact 600-MeV electron storage ring that could be used as a source for EUVL and deliver in excess of 1 W of 13-nm light in a 2% bandwidth.⁸⁸ Based on the assumptions (unrealistic given today's reality) that an EUVL exposure tool would employ a three-mirror imaging system and would only be required to print fifteen 6-in.-diameter wafers per hour using a resist with a sensitivity of ~ 5 mJ/cm², it was shown that a compact synchrotron source would be able to supply the flux needed for six EUVL exposure tools. The floor plan of a small 600-MeV storage ring that can supply flux to six EUV exposure tools is shown in Fig. 1.33; the figure does not show the 100-MeV electron linear accelerator that serves as the electron source because it is assumed to be located in a subfab. While it is now generally agreed that a synchrotron light source cannot provide the average power needed for a modern commercial EUVL exposure tool, synchrotron light sources continue to play an important role in actinic defect inspection of EUV reticle blanks, actinic wavefront metrology of EUV imaging systems, advanced EUV resist screening, and accelerated life testing of oxidation-resistant coatings for EUV optics.

In the early 1990s, a number of experimental and theoretical studies showed that LPP sources could achieve CEs from laser energy to EUV energy in a $\sim 2\%$ bandwidth near a 13-nm wavelength of $\sim 1\%$ to 2% depending on target material, laser intensity, laser pulse width, and laser wavelength.^{89–91} For example, Fig. 1.34 shows the EUV CE for an LPP source that employed a frequency-doubled Nd:YAG (532 nm) laser as a function of the atomic number of the target material, from

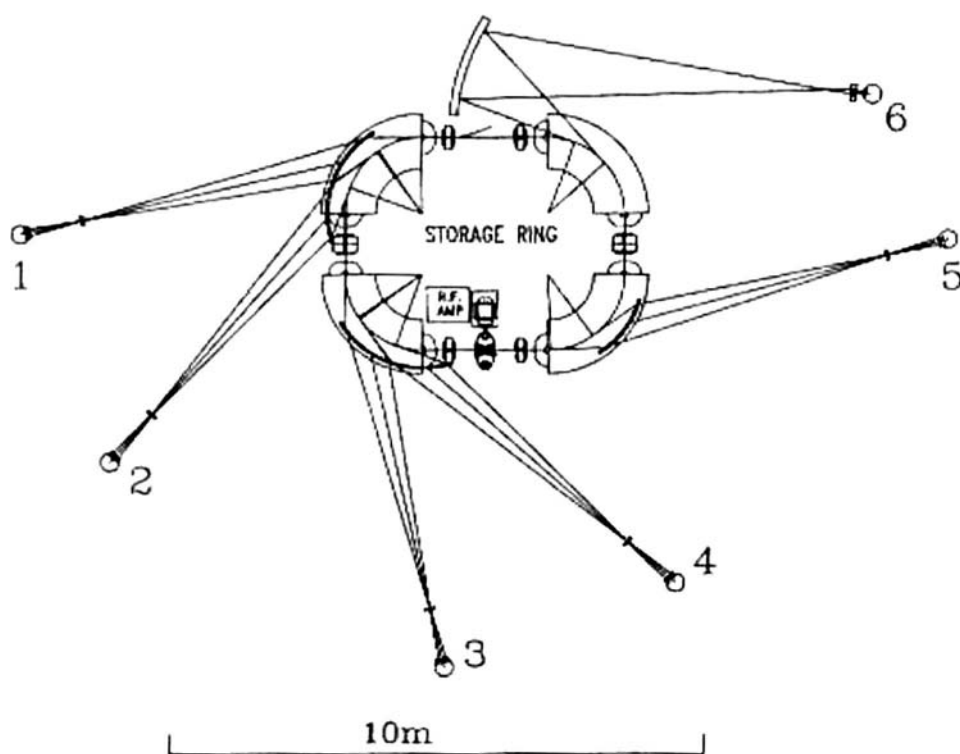


Figure 1.33 Schematic plan view of a 600-MeV storage ring designed at BNL together with six EUVL cameras. (Reprinted from Ref. 88 with permission of the Optical Society of America.)

a paper by R. Kauffman et al. of LLNL.⁹¹ The CE is highest for tin (Sn) and antimony (Sb) targets and is also high for high-Z targets such as Au and lead (Pb). With a Sn target, a CE using 0.53- μm laser light was found to increase rapidly with laser intensity until it peaked at $\sim 2 \times 10^{11} \text{ W/cm}^2$ and then fell off slowly at higher intensities.

In 1991, the first EUV imaging system at SNL utilized an LPP source that employed a KrF (248-nm) laser and a Au-drum target.¹⁵ It was immediately apparent that debris ejected from the source posed a major threat to the lifetime of nearby condenser mirrors due to (1) deposition of debris (particulates) from the source hardware, (2) deposition of atomic vapor from the source plasma, and (3) erosion by high-energy ions. Since that time, a great deal of effort has been put into designing and testing a variety of debris-mitigation schemes, including placing a low-pressure inert gas in the source vacuum chamber to decelerate particles from the source,⁹² positioning a gas jet in front of the components to be protected,⁹³ using a fast mechanical shutter or rotating mechanical chopper to block debris that arrives long after the EUV radiation,⁹⁴ and utilizing an electrostatic repeller field.⁹⁵ The deceleration of source particles using a gas jet, typically of argon (Ar) and helium (He), and a repeller field is such that the average fast-particle energy can be

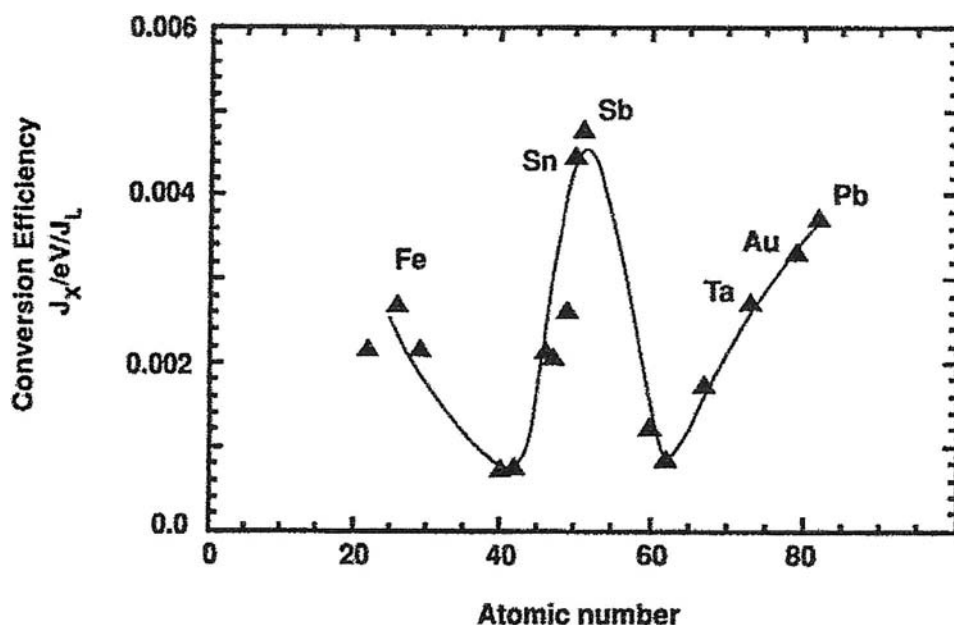


Figure 1.34 Dependence of the LPP CE at 13 nm on the atomic number of the target material. (Reprinted from Ref. 91 with permission of the Optical Society of America.)

decreased from keV levels to near 100 eV. Unfortunately, even this lower-energy debris must be eliminated, especially if it is an atomic vapor such as Sn, since a ~ 1 -nm-thick coating of Sn on the collector optics results in a 1% drop in EUV reflectance, so it must be removed periodically using an in-situ cleaning process. The use of a gas flow and a rotating mechanical chopper was found to reduce the rate of debris deposition from a metal target by a factor of about 1000; however, no known combination of debris-mitigation techniques was identified that could provide the degree of cleanliness needed for a commercial system, and today the effectiveness of the debris-mitigation system still places an upper limit on the collector life.

The only alternative to debris mitigation is to minimize debris production using a so-called mass-limited target.⁹⁶ The basic idea behind a mass-limited target is to supply only the amount of target material that is needed for efficient production of EUV radiation. When a mass-limited target is exposed to the high-intensity central part of a beam from a pulsed laser, a very large fraction of the target atoms are highly ionized and emit EUV radiation, the net effect being a significant reduction in the number of ejected atoms, ions, and particles. The most promising method of producing a mass-limited target is to introduce a stream of tiny droplets into the laser focus.⁹⁷ A number of mass-limited target ideas have been tested experimentally, including thin metal films on Mylar tape,⁹⁸ gas puff targets,⁹⁹ liquid droplet targets,¹⁰⁰ cryogenic pellet targets,¹⁰¹ and supersonic gas cluster targets.¹⁰² In 1996, G. Kubiak et al. of SNL developed a system that employed a target consisting of high-density gas clusters.¹⁰² A schematic diagram of a supersonic xenon (Xe) cluster source is shown in Fig. 1.35. Early CE measurements showed that

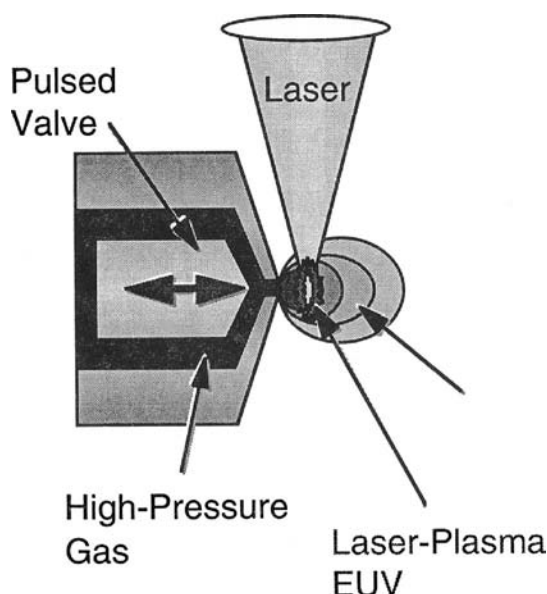


Figure 1.35 Configuration of laser plasma EUV source at SNL based on a supersonic Xe cluster jet target. (Reprinted from Ref. 102 with permission from the Optical Society of America.)

an LPP source based on the Xe cluster jet was approximately 58% as efficient at 13.5 nm as sources based on a solid Au target; they were also very close to the values for solid copper (Cu), Mo, and W targets. Furthermore, when a Xe jet is irradiated, it produces no solid debris—and because Xe has a high vapor pressure at room temperature, it does not condense on nearby mirrors. The reflectance of ML-coated condenser mirrors placed near the Xe jet EUV source was found to be reduced by only 14% after 1.4×10^8 plasma pulses, an improvement of more than 100,000 fold over the first solid Au target EUV source. A progress record of the condenser mirror lifetimes for LPP EUV sources between 1991 and 1999 is shown in Fig. 1.36.¹⁰³ The lifetime of EUV source collector optics is rated today as one of the most worrisome EUV critical issues.

1.6 EUVL Conferences

As noted in Sec. 1.2, the first conference on Soft-X-ray Projection Lithography was held in Monterey, California, on April 10–12, 1991. Jeff Bokor of AT&T Bell Labs and John Bruning of GCA Tropel helped organize the meeting, which was sponsored by the OSA and supported by the U.S. Air Force Office of Scientific Research. Two additional OSA topical meetings with the same name were held in the same city in 1992 and 1993. Two OSA Topical Meetings on Extreme Ultraviolet Lithography were held again in Monterey in 1994, and in Boston, Massachusetts, in 1996. A Workshop on At-Wavelength Testing of Soft X-ray Projection Optics was held in Gaithersburg, Massachusetts, on June 22, 1992. John Bjorkholm and

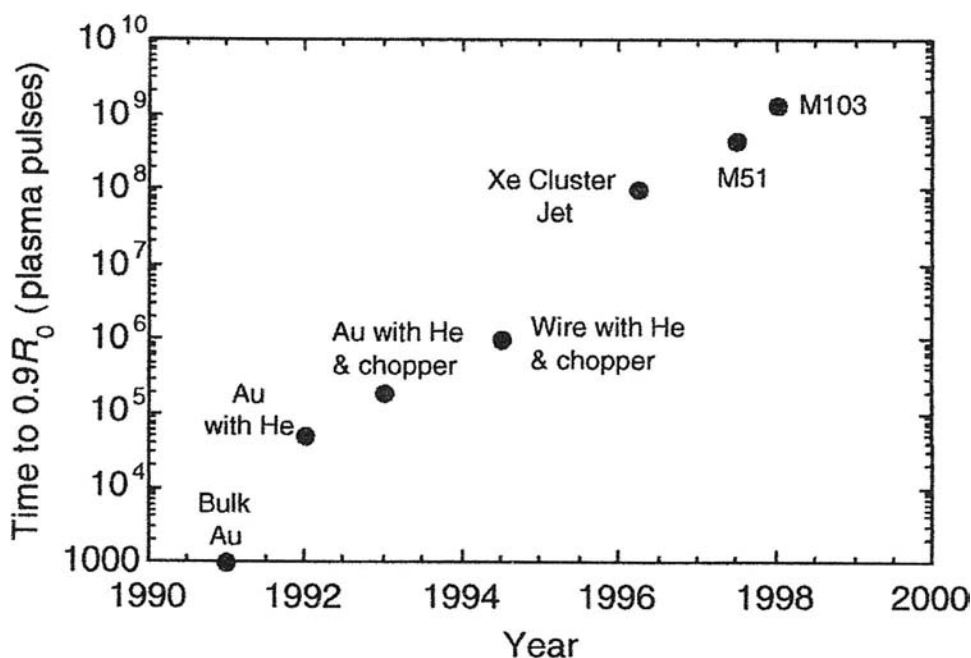


Figure 1.36 Progress on EUVL condenser mirror lifetime, expressed as the number of plasma pulses required to reduce the original mirror reflectivity by 10%. (Reprinted from Ref. 103.)

Mark Himel of AT&T and Tom Lucatorto of the National Institute of Standards and Technology (NIST) organized the workshop, which was sponsored by NIST and AT&T Bell Labs and supported by the U.S. Department of Commerce Advanced Technology Program and the U.S. Defense Advanced Research Projects Agency Microelectronics Technology Office. A joint U.S.-Japan Workshop on Soft X-ray Projection Lithography, organized by Professor Takeshi Namioka of Tohoku University, was held at the Hotel Mt. Fuji in Lake Yamanaka, Japan, on October 27–29, 1993. An International Workshop on EUV Lithography was held in Oberkochen, Germany, on November 14–15, 1995, where the presentations were collected and distributed to the participants but not published. A second U.S.-Japan Workshop on Soft X-ray Optics: Technical Challenges was held in Lake Yamanaka, Japan, on November 12–14, 1996. This meeting was chaired by M. Ginter of the University of Maryland, M. Peckerar of the U.S. Naval Research Laboratory, H. Kinoshita of Himeji Institute of Technology, and M. Yamamoto of Tohoku University, and it was sponsored by the ONR Asian Office and the Japan Society for Precision Engineering (JSPE). Tables 1.1 and 1.2 feature a selection of technical journals and conference proceedings that contain the majority of papers describing the developments in EUV (SXPL) lithography from the beginning through 1996.

Table 1.1 List of technical journals containing papers on early EUVL development.

Journal/Publisher	Volume (Issue)	Date/Year
<i>Applied Optics</i> /Optical Society of America	32(34)	Dec 1993
<i>Journal of Vacuum Science and Technology B</i> /AVS	6(6)	Nov/Dec 1989
<i>Journal of Vacuum Science and Technology B</i> /AVS	7(6)	Nov/Dec 1990
<i>Journal of Vacuum Science and Technology B</i> /AVS	8(6)	Nov/Dec 1991
<i>Journal of Vacuum Science and Technology B</i> /AVS	9(6)	Nov/Dec 1992
<i>Journal of Vacuum Science and Technology B</i> /AVS	10(6)	Nov/Dec 1993
<i>Journal of Vacuum Science and Technology B</i> /AVS	11(6)	Nov/Dec 1994
<i>Journal of Vacuum Science and Technology B</i> /AVS	12(6)	Nov/Dec 1995
<i>Journal of Vacuum Science and Technology B</i> /AVS	13(6)	Nov/Dec 1996
<i>Journal of X-ray Science and Technology</i> /IOS Press	3	1993
<i>Microelectronic Engineering</i> /Elsevier	9(1–4)	May 1989
<i>Microelectronic Engineering</i> /Elsevier	13(1–4)	March 1991
<i>Microelectronic Engineering</i> /Elsevier	17(1–4)	March 1992
<i>Microelectronic Engineering</i> /Elsevier	23(1–4)	Jan 1994
<i>Microelectronic Engineering</i> (MNE'94)/Elsevier	27(1–4)	Feb 1995
<i>Microelectronic Engineering</i> (MNE'95)/Elsevier	30(1–4)	Jan 1996

1.7 Summary

According to the latest *International Technology Roadmap for Semiconductors* (ITRS), EUVL will be used to fabricate large-scale integrations (LSIs) at the 32-nm half-pitch device node starting in 2011. To achieve that goal, the trial production of 32-nm LSIs using an EUVL beta-level exposure tool must be accomplished by 2009. Several EUVL exposure tools with 0.3-NA imaging systems and exposure areas less than 1 mm in diameter are currently available. These tools provide a resolution of 30 nm or better in resist materials, although a better than 20-nm resolution should be possible based on the performance of the optics. The most-important critical issue at the present time is the development of an EUV light source that can support a 100 wafer/hour throughput. Since the specification of the EUV imaging system has already been decided, the problem is determining how to boost the intensity of an EUV light source from ~ 6 W (the maximum power today) to 115 W (the power required for 100 wafer/hour throughput, assuming 5 mJ/cm² resist sensitivity) without a concomitant increase in debris production. Another critical issue is the development of a resist with an LER of 2 m or less because LER influences the width of an exposed pattern. For resists, there appears to be a trade-off between LER and sensitivity, and it is important to find a material with a small LER that requires a small exposure dose. Unlike a conventional optical imaging system, an EUVL imaging system operates in reflection, so increasing the number of mirrors in the system rapidly decreases its throughput. All possibilities for improving the exposure tool, light source, and resist must be investigated with the goal of mitigating the severity of the specifications so that a practical EUVL exposure tool can be realized as quickly as possible.

In conclusion, EUVL research and development over the past 20 years has led to a number of significant breakthroughs. The drive to develop a practical EUVL

Table 1.2 List of conference proceedings containing papers on early EUVL development.

Conference Proceedings	Editor(s)	Vol.	Year
OSA Proc. on Soft-X-Ray Projection Lithography	J. Bokor	12	1991
OSA Proc. on Soft-X-Ray Projection Lithography Topical Meeting, Monterey, CA, May 10–12, 1993	A. M. Hawryluk R. H. Stulen	18	1993
OSA Proc. on Extreme Ultraviolet Lithography Topical Meeting, Monterey, CA, Sept. 19–21, 1994	F. Zernike D. T. Attwood	23	1994
OSA TOPS on Extreme Ultraviolet Lithography Topical Meeting, Boston, MA, May 1–3, 1996	G. D. Kubiak D. Kania	4	1996
Proc. SPIE— <i>Electron-Beam, X-Ray, and Ion-Beam Technology Submicrometer Lithographies IX</i>	D. J. Resnick	1263	May 1990
Proc. SPIE— <i>Electron-Beam, X-Ray, and Ion-Beam Technology Submicrometer Lithographies for Manufacturing</i>	M. C. Peckerar	1465	Aug. 1991
Proc. SPIE— <i>Electron-Beam, X-Ray, and Ion-Beam Technology Submicrometer Lithographies for Manufacturing II</i>	M. C. Peckerar	1671	July 1992
Proc. SPIE— <i>Electron-Beam, X-Ray, and Ion-Beam Technology Submicrometer Lithographies III</i>	D. O. Patterson	1924	June 1993
Proc. SPIE— <i>Applications of Laser Plasma Radiation</i>	M. C. Richardson	2015	1994
Proc. SPIE— <i>Electron-Beam, X-Ray, and Ion-Beam Technology Submicrometer Lithographies IV</i>	D. O. Patterson	2194	May 1994
Proc. SPIE— <i>Electron-Beam, X-Ray, and Ion-Beam Technology Submicrometer Lithographies V</i>	J. M. Warlaumont	2437	May 1995
Proc. SPIE— <i>X-Ray and Extreme Ultraviolet Optics</i>	R. B. Hoover A. B. C. Walker Jr.	2515	June 1995
Proc. SPIE— <i>Electron-Beam, X-Ray, and Ion-Beam Technology Submicrometer Lithographies VI</i>	D. E. Seeger	2723	May 1996
<i>X-ray Microscopy II: Proceedings of the Second International Symposium on X-ray Microscopy</i> (Springer-Verlag, Berlin, 1988)	A. G. Michette G. R. Morrison C. J. Buckley		1988
<i>X-ray Microscopy III: Proceedings on the Third International Symposium on X-ray Microscopy</i> (London, September 3–7, 1990)	D. Sayre, J. Kurz M. Howells H. Rarback		1992
<i>X-ray Microscopy IV: Proceedings on the Fourth International Symposium on X-ray Microscopy</i> (Chernogolovka, Russia, Sept 20–24, 1993)	V. V. Aristov A. I. Erko		1994

technology spread to both hemispheres in the latter half of the 1980s; we can now look back at the history of the early development work with a wonderful feeling of accomplishment. Many lithographic technologies have been developed and screened during the last 20 years. Several critical problems still remain, including light source power and reliability; mask defectivity and flatness; and resist resolution, sensitivity, and LER. However, it now appears that solutions can be found because the two biggest obstacles—the fabrication of aspherical mirrors and of reflective MLs—have been overcome.

The first international conference with “EUVL” in the title was held near Mt. Fuji in 1993. In his opening address at that conference, Dr. Kinoshita said, “As long as we do not lose the desire that has sprung from within us, technology will steadily advance from the micro to the nano to the pico.” The many improvements

that have been made during the course of EUVL development, particularly in the fabrication of aspherical mirrors and reflective MLs, have already validated Dr. Kinoshita's 1993 prediction.

Acknowledgments

So many scientists and engineers were involved in early EUVL development that an all-inclusive listing of their names and institutions is probably not possible. Even so, the authors gratefully acknowledge Eberhard Spiller (IBM) and Troy Barbee (Stanford University) for the development of reflective ML coatings, Dan Bajuk and Bob Kestner (Tinsley Laboratories) for the development of precision aspheric surfaces, and Gary Sommargren (LLNL) for the development of the PSPDI. Without these seminal contributions, EUVL would not be possible. The authors would also like to acknowledge the contributions of the more than 300 individuals listed below.

In Japan, important contributions were made by the following:

ETL: Kouichi Hoh, N. Tanino.

Hitachi: Masaaki Ito, Souichi Katagiri, Shigeo Moriyama, Taro Ogawa, Hiroaki Oizumi, Eiichi Seya, Tsuneo Terasawa, Hiromasa Yamanashi.

Nikon: Noriaki Kandaka, Hiroyuki Kondo, Kiyoto Mashima, Katsuhiko Murakami, Hiroshi Nagata, Masayuki Ohtani, Tetsuya Oshino, Sumito Shimizu, K. Ilzuka, Shoichiro Yishida.

NTT: Tsuneyuki Haga, Yoshikazu Ishii, Kenji Kurihara, Tomoaki Kawamura, Hiroo Kinoshita, Tsutomu Mizota, Hisataka Takenaka.

Osaka University: Hiroaki Aritome, Hiroyuki Diado, M. Kado, K. A. Tanaka, K. Yamashita.

SORTEC: Nobufumi Atoda, Yukihiro Maejima, Tushihiko Tanaka, Takeo Watanabe, Yoshio Yamashita.

Tohoku University: Takeshi Namioka, Masaki Yamamoto, Mihiro Yanagihara.

Others: Yasuaki Fukuda (Canon), Shigetaro Ogura (Kobe Design University), Kiyoshi Fujii (NEC), Izumi Kaytaoka (JAE), Souichi Inoue (Toshiba).

In the U.S., important contributions were made by the following:

AT&T: Dwight Berreman, John Bjorkholm, Jeff Bokor, Craig Boyce, Bill Brinkman, Kevin Dreyer, Raissa D'Souza, Kathy Early, Lou Eichner, Linus Fetter, Rick Freeman, Joe Griffith, Lloyd Harriott, Marc Himel, R. Hull, Rich Hutton, D. Y. Jeon, Tanya Jewell, Bruno La Fontaine, Alex Liddle, Alastair MacDowell, Bill Mansfield, Peter Mulgrew, Megan O'Malley, John Pastalan, Eric Raab, Joe Russo, Chuck Shank, Z. Shen, Bill Silfvast, Steve Spector, Susan Stein, Leo Szeto, Zhengquan Tan, Don Taylor, Garry Taylor, Greg Timp, Don Tennant, Sheila Vaidya, Warren Waskiewicz, Don White, David Windt, Obert Wood.

Grumman: Vincent Calia, A. Grillo, Robert Gutowski, Jayaram Krishnaswamy, Ira Lehrman, Alan Todd.

IBM: Norman Bobroff, Doug Goodman, Alan Rosenbluth, Eberhard Spiller.

Los Alamos National Laboratory (LANL): J. Abdallah, B. Carlsten, R. D. Fulton, J. C. Goldstein, M. E. Jones, D. P. Kilcrease, J. M. Kinross-Wright, S. H. Kong, Brian Newnam, D. C. Nguyen, D. M. Oro, D. S. Prono, J. K. Studebaker, R. Sturgess, Vriddhachalam Viswanathan.

LBNL: Erik Anderson, Dave Attwood, Raul Beguiristain, Daniel Chen, Paul Denham, Ken Goldberg, Ronald Gronsky, Eric Gullikson, Malcolm Howells, Keith Jackson, Chantal Khan-Malek, Masato Koike, Jeff Kortright, Hector Medeck, Tai Nguyen, Regina Soufli, Jim Underwood, Max Wei.

LLNL: Craig Alford, Sherry Baker, Troy Barbee, Ray Beach, Rich Bionta, M. J. Carey, Nat Ceglio, D. Celliers, Charles Cerjan, Henry Chapman, Dino Ciarlo, Simon Cohen, T. P. Daly, Brent Dane, Louis DaSilva, K.W. DeLong, B. L. Fix, Dave Gaines, Jim Glaze, Lloyd Hackel, H.W. Hauschildt, Andy Hawryluk, Mark Hermann, John Honig, Ralph Hostetler, Don Kania, Robert Kauffman, Pat Kearney, Rick Levesque, Dan Makowiecki, Claud Montcalm, T. Orzechowski, Don Phillion, Robert Rosen, Lynn Seppala, Ken Skulina, Gary Sommargren, James Spallas, Ronnie Spitzer, Dan Stearns, A. Stith, Don Sweeney, John Taylor, Pat Troccoli, Steve Vernon, F.W. Weber, Luis Zapata.

NIST: Charles Clark, Dave Ederer, Tyler Estler, Chris Evans, J. Fu, Tom Lucatorto, T. McWaid, Bob Parks, Charlie Tarrio, Ted Vorburger, Rich Watts.

Ovonics: Georgy Gutman, John Keem, Kevin Parker, Jim Wood.

SNL: Richard Arling, Kurt Berger, Luis Bernardez, S. R. Birtola, L. A. Brown, Greg Cardinale, Weng Chow, Bruce Draper, Archie Farnsworth, Denis Grady, Robert Gutowski, R. S. Goeke, Steve Haney, Craig Henderson, Tom Hunter, Robert Hwang, Paul Jin, A. A. Jojola, P. N. Keifer, Ron Kensek, Eric Kneidler, Stewart Kohler, Kevin Krenz, Glenn Kubiak, Paul Mahl, Mike Malinowski, C. C. Neumann, Rod Nissen, Rick Olson, Duane Outka, Phillip Paul, Yon Perras, Avi Ray-Chaudhuri, Paul Resnick, Paul Rockett, Randal Schmitt, Michelle Schulberg, Rich Shagam, Tony Smith, Rick Stulen, Bill Sweatt, Dan Tichenor, Tim Trucano, Ruben Urenda, Mial Warren, R. D. Watson, J. W. Weed, L. I. Weingarten, J. R. Wendt, Dave Wheeler, G. A. Wilkerson, John Wronosky.

University of California-Berkeley: Charlie Fields, H. Fujioka, Ken Gustafson, Chenming Hu, Derek Lee, Bernice Lum, Andy Neureuther, David Newmark, Khanh Nguyen, Bill Oldham, Edita Tejnli, Alfred Wong.

University of Central Florida/CREOL: Kenneth Beck, Howard Bender, C. DePriest, Ann Marie Eligon, Kai Gabel, Art Hanzo, Jim Harvey, Fing Jin, M. A. Klossner, Donna O'Connell, Martin Richardson, G. Shimkaveg, Bill Silfvast, Jerry Thorpe, D. Torres, Victor Yanovsky.

Veeco Instruments: B. Druz, A.V. Hayes, H. Hedge, E. Osten, aR. Rajan.

Contributions were also made by the following:

Bill Arnold (**AMD**), George Lawrence (**Applied Optics Research**), Yuanda Cheng (**Arizona State University**), Jim Murphy and Peter Takacs (**BNL**), M. Isaacson (**Cornell University**), John Bruning and Chunsheng Huang (**GCA Tropol**),

John Carruthers and Patrick Troccoli (**Intel**), Michael Powers and Harry Shields (**Jamar**), Nick Economou and Diane Stewart (**Micrion**), Jeff Calvert and Tim Koloski (**NRL**), Paul Fisher and Michael Gouge (**Oak Ridge National Laboratory**), Mike Rodgers and Kevin Thompson (**Optical Research Associates**), Michael Kassner and Michael Viliardos (**Oregon State University**), Stan Mrowka (**Oxford Research Group**), Malcolm McGeoch (**PLEX**), Mitch Ruda (**Ruda Associates**), Karen Brown and Gil Shelden (**SEMATECH**), Dave Shafer (**Shafer Optical Design**), R. Browning and Fabian Pease (**Stanford University**), Dave Williamson and Frits Zernike (**SVG Lithography**), Dan Bajuk and Bob Kestner (**Tinsley Laboratories**), David Shealy and Cheng Wang (**University of Alabama**), Rajiv Singh (**University of Florida**), Dave Markle (**Ultratech**), Gene Church (**U.S. ARDEC**), Franco Cerrina and Waiman Ng (**University of Wisconsin-Madison**).

In Europe, important contributions were made by the following:

DIMES, Delft: Nigel Duddles, J. Romijn, B. A. C. Rousseeuw, E. W. J. van der Drift.

FOM: Fred Bijkerk, Eric Louis, Alexander Mitrofanov, Eric Puik, R. Schlattmann, Leonid Shmaenok, Marnix van der Wiel, A. van Honk, Gert van Dorsen, Y. Y. Platonova, A. P. Shevelko, Jan Verhoeven, Harm-Jan Voorma, H. Zeijelmaker.

Lambda Physik: R. Desor, Helmut Frowein, Bernard Nikolaus, Frank Voss.

Lund Institute of Technology: Hans Hertz, Lars Malmqvist, Lars Rymell.

Philips: Joseph Braat.

PTB-Berlin: Detlef Fuchs, Michael Krumrey, Frank Scholze, Gerhard Ulm.

References

1. H. Kinoshita, T. Kaneko, H. Takei, N. Takeuchi, and S. Ishihara, "Study on x-ray reduction projection lithography," presented at the 47th Autumn Meeting of the Japan Society of Applied Physics, Paper No. 28-ZF-15 (1986).
2. T. Namioka, "Current research activities in the field of multilayers for soft x-rays in Japan," *Revue Phys. Appl.* **23**, 1711–1726 (1988).
3. W. T. Silfvast and O. R. Wood II, "Tenth micron lithography with a 10 Hz 37.2 nm sodium laser," *Microelectron. Eng.* **8**, 3–11 (1988).
4. A. M. Hawryluk and L. G. Seppala, "Soft x-ray projection lithography using an x-ray reduction camera," *J. Vac. Sci. Technol. B* **6**, 2162–2166 (1988).
5. J. Bjorkholm, J. Bokor, L. Eichner, R. R. Freeman, J. Gregus, T. E. Jewell, W. M. Mansfield, A. A. MacDowell, E. L. Raab, W. T. Silfvast, L. H. Szeto, D. M. Tennant, W. K. Waskiewicz, D. L. White, D. L. Windt, O. R. Wood II, and J. H. Bruning, "Reduction imaging using multilayer coated optics: printing of features smaller than 0.1 microns," *J. Vac. Sci. Technol. B* **8**, 1509–1513 (1990).
6. J. Henry, E. Spiller, and M. Weisskopf, "Imaging performance of a normal incidence x-ray telescope measured at 0.18 KeV," *Proc. SPIE* **316**, 166–168 (1981).

7. I. Lovas, W. Stanty, E. Spiller, R. Tibbetts, and J. Wilczynski, "Design and assembly of a high resolution Schwarzschild microscope for soft-x-rays," *Proc. SPIE* **316**, 90–97 (1981).
8. J. H. Underwood and T. W. Barbee, Jr., "Soft x-ray imaging with a normal incidence mirror," *Nature* **294**, 429–431 (1981).
9. K. Takei and Y. Maeda, "Preparation of multi-layered tungsten-carbon films by ion beam sputtering," *Jpn. J. Appl. Phys.* **24**, 1366–1367 (1985).
10. T. W. Barbee, Jr., S. Mrowka, and M. Hettrick, "Molybdenum-silicon multilayer mirrors for the extreme ultraviolet," *Appl. Opt.* **24**, 883–886 (1985).
11. A. Hawryluk, N. Ceglio, and D. Gaines, "Reflection mask technologies for x-ray projection lithography," *J. Vac. Sci. Technol. B* **7**, 1702–1704 (1989).
12. H. Kinoshita, K. Kurihara, Y. Ishii, and Y. Torii, "Soft-x-ray reduction lithography using multilayer mirrors," *J. Vac. Sci. Technol. B* **7**, 1648–1651 (1989).
13. D. W. Berreman, J. E. Bjorkholm, L. Eichner, R. R. Freeman, T. E. Jewell, W. M. Mansfield, A. A. MacDowell, M. L. O'Malley, E. L. Raab, W. T. Silfvast, L. H. Szeto, D. M. Tennant, W. K. Waskiewicz, D. L. White, D. L. Windt, O. R. Wood II, and J. H. Bruning, "Soft-x-ray projection lithography printing of 0.20- μm features using 20:1 reduction," *Opt. Lett.* **15**, 529–531 (1990).
14. A. MacDowell, J. E. Bjorkholm, J. Bokor, L. Eichner, R. R. Freeman, W. M. Mansfield, J. Pastalan, L. H. Szeto, D. M. Tennant, O. R. Wood II, T. E. Jewell, W. K. Waskiewicz, D. L. White, D. L. Windt, W. T. Silfvast, and F. Zernike, "Soft x-ray projection lithography using a 1:1 ring field optical system," *J. Vac. Sci. Technol. B* **9**, 3193–3197 (1991).
15. G. D. Kubiak, D. A. Tichenor, M. E. Malinowski, R. H. Stulen, S. J. Haney, K. W. Berger, L. A. Brown, J. E. Bjorkholm, R. R. Freeman, W. M. Mansfield, D. M. Tennant, O. R. Wood II, J. Bokor, T. E. Jewell, D. L. White, D. L. Windt, and W. K. Waskiewicz, "Diffraction-limited soft-x-ray projection lithography with a laser plasma source," *J. Vac. Sci. Technol. B* **9**, 3184–3188 (1991).
16. H. Kinoshita, K. Kurihara, T. Mizota, T. Haga, H. Takenaka, and Y. Ishii, "Soft-x-ray reduction lithography using a reflection mask," in *OSA Proceedings on Soft-X-Ray Projection Lithography, 1991*, Vol. 12, pp. 11–15 (1991).
17. K. Kurihara, H. Kinoshita, T. Mizota, T. Haga, and Y. Torii, "Two-mirror telecentric optics for soft x-ray reduction lithography," *J. Vac. Sci. Technol. B* **9**, 3189–3192 (1991).
18. H. Kinoshita, "SXPL in Japan," in *OSA Proc. on Soft X-ray Projection Lithography, 1993*, Vol. 18, pp. 74–78 (1993).
19. H. Kinoshita, K. Kurihara, T. Mizota, T. Haga, H. Takenaka, and Y. Torii, "Large-area, high-resolution pattern replication by the use of a two-aspherical-mirror system," *Appl. Opt.* **32**, 7079–7083 (1993).
20. T. Haga, M. Tinone, H. Takenaka, and H. Kinoshita, "Large-field ($>20 \times 25 \text{ mm}^2$) replication by EUV lithography," *Microelectron. Eng.* **30**, 179–182 (1996).

21. G. E. Sommargren, "Performance of a two mirror, four reflection, ring field imaging system," *OSA Proc. on Extreme Ultraviolet Lithography, 1994*, Vol. 23, pp. 103–108 (1995).
22. B. La Fontaine, D. P. Gaines, D. R. Kania, G. E. Sommargren, S. L. Baker, and D. Ciarlo, "Performance of a two-mirror, four-reflection ring-field optical system operating at $\lambda = 13$ nm," *OSA Trends Opt. Photon.* **4**, 186–191 (1996).
23. D. A. Tichenor, G. D. Kubiak, S. J. Haney, R. P. Nissen, K. W. Berger, R. W. Arling, A. K. Ray-Chaudhuri, K. B. Nguyen, R. H. Stulen, J. B. Wronosky, J. D. Jordan, T. G. Smith, J. R. Darnold, P. M. Kahle, A. A. Jojola, S. M. Kohler, R. S. Urenda, D. R. Wheeler, J. E. Bjorkholm, O. R. Wood II, G. N. Taylor, and R. S. Hutton, "Recent results in the development of an integrated EUVL laboratory tool," *Proc. SPIE* **2437**, 292–307 (1995).
24. D. A. Tichenor, A. K. Ray-Chaudhuri, G. D. Kubiak, K. B. Nguyen, S. J. Haney, K. W. Berger, R. P. Nissen, Y. E. Perras, P. S. Jin, L. I. Weingarten, P. N. Keifer, R. H. Stulen, R. N. Shagam, W. C. Sweatt, T. G. Smith, O. R. Wood II, A. A. MacDowell, J. E. Bjorkholm, T. E. Jewell, F. Zernike, B. L. Fix, and H. W. Hauschildt, "Progress in the development of EUV imaging systems," *OSA Trends Opt. Photon.* **4**, 2–8 (1996).
25. A. A. MacDowell, Z. Shen, K. Fujii, J. E. Bjorkholm, R. R. Freeman, L. Fetter, D. W. Taylor, D. M. Tennant, L. Eichner, W. K. Waskiewicz, D. L. White, D. L. Windt, O. R. Wood II, S. Haney, and T. Jewell, "Extreme ultraviolet 1:1 ring-field lithography machine," *OSA Trends Opt. Photon.* **4**, 192–198 (1996).
26. J. H. Bruning, A. R. Phillips, Jr., D. R. Shafer, and A. D. White, "Lens system for x-ray projection lithography camera," U.S. Patent No. 5,353,322 (October 4, 1994).
27. K. B. Nguyen, G. F. Cardinale, D. A. Tichenor, G. D. Kubiak, K. Berger, A. K. Ray-Chaudhuri, Y. Perras, S. J. Haney, R. Nissen, K. Krenz, R. H. Stulen, H. Fujioka, C. Hu, J. Bokor, D. M. Tennant, and L. A. Fetter, "Fabrication of MOS devices with extreme ultraviolet lithography," *OSA Trends Opt. Photon.* **4**, 208–211 (1996).
28. M. Ito, H. Oizumi, T. Soga, H. Yamanashi, T. Ogawa, S. Katagiri, E. Sega, and E. Takeda, "Soft x-ray projection imaging with multilayer reflection masks," *Microelectron.Eng.* **27**, 285–290 (1995).
29. M. Ito, S. Katagiri, H. Yamanashi, E. Seya, T. Ozawa, H. Oizumi, and T. Terasawa, "Optical technology for EUV lithography," *OSA Trends Opt. Photon.* **4**, 9–12 (1996).
30. S. Katagiri, M. Ito, H. Yamanashi, E. Seya, and T. Terasawa, "Optical system for high-throughput EUV lithography," *Proc. SPIE* **2723**, 34–45 (1996).
31. K. Murakami, T. Oshino, S. Shimizu, W. Wasa, H. Kondo, M. Ohtani, N. Kandaka, K. Mashima, and K. Nomura, "Basic technologies for extreme ultraviolet lithography," *OSA Trends Opt. Photon.* **4**, 16–20 (1996).

32. H. Kinoshita, T. Watanabe, M. Niibe, M. Ito, H. Oizumi, H. Yamanashi, K. Murakami, T. Oshino, Y. Platonov and N. Grupido, "Three-aspherical mirror system for EUV lithography," *Proc. SPIE* **3331**, 20–31 (1998).
33. S. Okazaki, "EUV lithography research program at ASET," *Proc. SPIE* **3676**, 238–245 (1999), <http://www.aset.or.jp>.
34. Extreme UltraViolet Lithography System Development Association (EUVA), Japan, <http://www.euva.or.jp>.
35. F. Bijkerk, H.-J. Voorma, E. J. Puik, E. Louis, G. E. van Dorssen, M. J. van der Wiel, J. Verhoeven, E. W. J. M. van der Drift, J. Romijn, and B. A. C. Rousseeuw, "Design of an extended image field soft-x-ray projection system," in *OSA Proc. on Soft-X-Ray Projection Lithography, 1991*, Vol. 12, pp. 51–53 (1991).
36. E. Puik, M. J. van der Wiel, H. Zeijlemaker, and J. Verhoeven, "Ion bombardment of x-ray multilayer coatings: comparison of ion etching and ion assisted deposition," *Appl. Surf. Sci.* **47**, 251–260 (1991).
37. F. Bijkerk, E. Louis, L. Shmaenok, H.-J. Voorma, M. J. van der Wiel, R. Schlattmann, J. Verhoeven, F. Voss, R. Desor, and B. Nikolaus, "Enhanced performance of KrF laser-induced x-ray sources and multilayer mirrors for SXPL," in *OSA Proc. on Soft X-Ray Projection Lithography, 1993*, Vol. 18, pp. 114–116 (1993).
38. L. Rymell and H. M. Hertz, "Droplet target for low-debris laser-plasma soft x-ray generation," *Opt. Commun.* **103**, 105–110 (1993).
39. F. Bijkerk, "Development of extreme ultraviolet lithography along the European route," *OSA Trends Opt. Photon.* **4**, 13–15 (1996).
40. J. P. H. Benschop, W. M. Kaiser, and D. C. Ockwell, "ECLIDES, the European EUVL program," *Proc. SPIE* **3676**, 246–252 (1999).
41. Microelectronics Development for European Applications+ (MEDEA+), France, <http://www.medeaplus.org>.
42. E. Spiller, "Multilayer optics for x-rays," in *Physics, Fabrication and Applications of Multilayer Structures*, P. Dhez and C. Weisbuch, Eds., pp. 271–309, Plenum, New York (1987).
43. G. Sommargren, "Phase shifting diffraction interferometry for measuring extreme ultraviolet optics," *OSA Trends Opt. Photon.* **4**, 108–112 (1996).
44. A. M. Hawryluk and N. M. Ceglio, "Wavelength considerations in soft-x-ray projection lithography," *Appl. Opt.* **32**, 7062–7067 (1993).
45. D. G. Stearns, R. S. Rosen, and S. P. Vernon, "Multilayer mirror technology for soft-x-ray projection lithography," *Appl. Opt.* **32**, 6952–6960 (1993).
46. O. R. Wood II, J. E. Bjorkholm, K. F. Dreyer, L. Fetter, M. D. Himmel, R. R. Freeman, D. M. Tennant, J. E. Griffith, G. N. Taylor, W. K. Waskiewicz, D. L. White, D. L. Windt, A. A. MacDowell, B. LaFontaine, B. M. Lum, A. R. Neureuther, J. B. Kortright, E. M. Gullikson, and K. B. Nguyen, "Experiments and simulations of EUV lithographic resist patterning at wavelengths from 7 to 40 nm," in *OSA Proc. on Extreme Ultraviolet Lithography 1994*, Vol. 23, pp. 83–88 (1995).

47. K. Skulina, C. Alford, R. Bionta, D. Makowiecki, E. M. Gullikson, R. Soufli, J. B. Kortright, and J. H. Underwood, "Beryllium based multilayers for normal incidence EUV reflectance," in *OSA Proc. on Extreme Ultraviolet Lithography 1994*, Vol. 23, pp. 52–55 (1995).
48. J. B. Kortright, E. M. Gullikson, and P. E. Denham, "Masked deposition techniques for achieving multilayer period variations required for short-wavelength (68-A) soft-x-ray imaging optics," *Appl. Opt.* **32**, 6961–6968 (1993).
49. D. W. Berreman, "Multilayer reflecting x-ray optical systems: chromatic vignetting by narrow reflection bands," *Appl. Opt.* **30**, 1741–1745 (1991).
50. O. R. Wood II, T. E. Jewell, and W. T. Silfvast, "Short-wavelength annular-field optical system for imaging tenth-micron features," *J. Vac. Sci. Technol. B* **6**, 1613–1615 (1989).
51. T. Jewell, J. Rodgers, and K. Thompson, "Reflective systems design study for soft x-ray projection lithography," *J. Vac. Sci. Technol. B* **8**, 1519–1523 (1990).
52. K. Murakami, T. Oshino, S. Shimizu, W. Wasa, H. Knodo, M. Ohtani, N. Kandaka, K. Mashima, and K. Nomura, "Basic technologies for extreme ultraviolet lithography," *OSA Trends Opt. Photon.* **4**, 16–20 (1996).
53. W. C. Sweatt, "Ring-field EUVL camera with large etendu," *OSA Trends Opt. Photon.* **4**, 178–180 (1996).
54. R. Kestner, "Precision asphere fabrication and metrology to tolerances <1 nm rms," *Extreme Ultraviolet Lithography OSA Technical Digest 77*, Optical Society of America, Washington, D.C. (1996).
55. O. R. Wood II, J. E. Bjorkholm, A. A. MacDowell, S. Vaidaya, and D. R. Shafer, "Projection lithography with all-reflecting optics," *OSA Trends Opt. Photon.* **4**, 181–184 (1996).
56. W. T. Estler and C. J. Evans, "Surface figure metrology for x-ray optics," in *OSA Proc. on Soft-X-Ray Projection Lithography, 1991*, Vol. 12, pp. 145–146 (1991).
57. D. Bajuk and R. Kestner, The Japan Society for Precision Engineering (JSPE) Proceedings of the Second U.S.-Japan Workshop on Soft X-ray Optics: Technical Challenges, Mt. Fuji, Japan, Nov. 12–14, 1996.
58. J. E. Bjorkholm, "Fabrication and testing of precision optics for soft x-ray projection lithography," NIST ATP Program (1991), <http://www.atp.nist.gov>. Search the ATP Funded Project Database for AT&T.
59. D. L. Windt, W. K. Waskiewicz, and J. E. Griffith, "Surface finish requirements for soft x-ray mirrors," *Appl. Opt.* **33**, 2025–2031 (1994).
60. E. L. Church, "Fractal surface finish," *Appl. Opt.* **27**, 1518–1526 (1988).
61. D. P. Gaines, D. W. Sweeney, K. W. DeLong, S. P. Vernon, S. L. Baker, D. A. Tichenor, and R. Kestner, "Surface characterization of optics for EUV lithography," *OSA Trends Opt. Photon.* **4**, 103–106 (1996).
62. D. M. Williamson, "The elusive diffraction limit," in *OSA Proc. on Extreme Ultraviolet Lithography, 1994*, Vol. 23, pp. 94–97 (1994).

63. D. T. Attwood, G. Sommargren, R. Beguiristain, K. Nguyen, J. Bokor, N. Ceglio, K. Jackson, M. Koike, and J. Underwood, "Undulator radiation for at-wavelength interferometry of optics for extreme-ultraviolet lithography," *Appl. Opt.* **32**, 7022–7031 (1993).
64. K. A. Goldberg, R. Beguiristain, J. Bokor, H. Medeck, K. Jackson, D. T. Attwood, G. E. Sommargren, J. P. Spallas, and R. Hostetler, "Point diffraction interferometry at EUV wavelengths," in *OSA Proc. on Extreme Ultraviolet Lithography, 1994*, Vol. 32, pp. 134–141 (1995).
65. J. E. Bjorkholm, A. A. MacDowell, O. R. Wood II, Z. Tan, B. LaFontaine, and D. M. Tennant, "Phase-measuring interferometry using extreme ultraviolet radiation," *J. Vac. Sci. Technol. B* **13**, 2919–2922 (1995).
66. E. Tejnil, K. A. Goldberg, H. Medeck, R. Beguiristain, J. Bokor, and D. T. Attwood, "Phase-shifting point diffraction interferometry for at wavelength testing of lithographic optics," *OSA Trends Opt. Photon.* **4**, 118–122 (1996).
67. H. Medeck, E. Tejnil, K. A. Goldberg, and J. Bokor, "Phase-shifting point diffraction interferometer," *Opt. Lett.* **21**, 1526–1528 (1996).
68. Z. Tan, A. A. MacDowell, B. LaFontaine, J. Russo, J. E. Bjorkholm, D. Tennant, D. Taylor, M. Himel, O. R. Wood II, R. R. Freeman, W. K. Waskiewicz, D. L. Windt, D. L. White, S. Spector, A. K. Ray-Chaudhuri, and R. H. Stulen, "At wavelength metrology of EUV cameras using lateral-shearing interferometry," in *OSA Proc. on Extreme Ultraviolet Lithography, 1994*, Vol. 32, pp. 151–160 (1995).
69. A. K. Ray-Chaudhuri, R. H. Stulen, W. Ng, F. Cerrian, S. Spector, Z. Tan, J. Bjorkholm, and D. Tennant, "EUV metrology of multilayer optics," in *OSA Proc. on Extreme Ultraviolet Lithography, 1994*, Vol. 32, pp. 161–165 (1995).
70. C. Tarrio, R. E. Vest, and S. Grantham, "Absolute extreme-ultraviolet metrology," *Proc. SPIE* **4450**, 94–107 (2001).
71. A. B. C. Walker, T. W. Barbee, R. B. Hoover, and J. F. Lundblom, "Soft x-ray images of the solar corona with a normal incidence Cassegrain multilayer telescope," *Science* **241**, 1781 (1988).
72. F. Scholze, J. Tummeler, E. Gullikson, and A. Aquilla, "Comparison of extreme ultraviolet reflectance measurements," *J. Microlithography, Microfabrication & Microsystems* **2**, 233–235 (2003).
73. D. M. Tennant, J. E. Bjorkholm, R. M. D'Souza, L. Eichner, R. R. Freeman, J. Z. Pastalan, L. H. Szeto, O. R. Wood II, T. E. Jewell, W. M. Mansfield, W. K. Waskiewicz, D. L. White, D. L. Windt, and A. A. MacDowell, "Reflective mask technologies and imaging results in soft x-ray projection lithography" *J. Vac. Sci. Technol. B* **9**, 3176–3183 (1991).
74. D. M. Tennant, L. A. Fetter, L. R. Harriott, A. A. MacDowell, P. P. Mulgrew, W. K. Waskiewicz, D. L. Windt, and O. R. Wood II, "Defect repair for soft x-ray projection lithography masks," *J. Vac. Sci. Technol. B* **10**, 3134–3140 (1992).

75. A. A. MacDowell, J. E. Bjorkholm, K. Early, R. R. Freeman, M. D. Himel, P. P. Mulgrew, L. H. Szeto, D. W. Taylor, D. M. Tennant, O. R. Wood II, J. Bokor, L. Eichner, T. E. Jewell, W. K. Waskiewicz, D. L. White, D. L. Windt, R. M. D'Souza, W. T. Silfvast, and F. Zernike, "Soft-ray projection imaging with a 1:1 ring-field optic," *Appl. Opt.* **32**, 7072–7078 (1993).
76. K. Nguyen, D. Attwood, T. Mizota, T. Haga, and H. Kinoshita, "Imaging of EUV lithographic masks with programmed substrate defects," in *OSA Proc. on Extreme Ultraviolet Lithography, 1994*, Vol. 23, pp. 193–203 (1994).
77. K. B. Nguyen, T. Mizota, T. Haga, H. Kinoshita, and D. T. Attwood, "Imaging of extreme ultraviolet lithographic masks with programmed substrate defects," *J. Vac. Sci. Technol. B* **12**, 3833–3840 (1994).
78. K. B. Nguyen, A. K. Ray-Chaudhuri, R. H. Stulen, K. Krenz, L. A. Fetter, D. M. Tennant, and D. L. Windt, "Printability of substrate and absorber defects on extreme ultraviolet lithographic masks," *J. Vac. Sci. Technol. B* **13**, 3082–3088 (1995).
79. S. P. Vernon, D. R. Kania, P. A. Kearney, R. A. Levesque, A. V. Hayes, B. Druz, E. Osten, R. Rajan, and H. Hedge, "Reticle blanks for extreme ultraviolet lithography: ion beam sputter deposition of low defect density Mo/Si multilayers," *OSA Trends Opt. Photon.* **4**, 44–48 (1996).
80. G. D. Kubiak, D. A. Outka, and J. M. Zeigler, "Soft x-ray resist characterization: Studies with a laser plasma x-ray source," *Proc. SPIE* **1263**, 272–281 (1990).
81. D. W. Berreman, J. E. Bjorkholm, M. Becker, L. Eichner, R. R. Freeman, T. E. Jewell, W. M. Mansfield, A. A. MacDowell, M. L. O'Malley, E. L. Raab, W. T. Silfvast, L. H. Szeto, D. M. Tennant, W. K. Waskiewicz, D. L. White, D. L. Windt, and O. R. Wood II, "Use of trilevel resists for high-resolution soft-x-ray projection lithography," *Appl. Phys. Lett.* **56**, 2180–2182 (1990).
82. G. N. Taylor, R. S. Hutton, D. L. Windt, and W. M. Mansfield, "Resist schemes for soft x-ray lithography," *Proc. SPIE* **1343**, 258–273 (1990).
83. B. L. Henke, P. Lee, T. J. Tanaka, R. L. Shirnabukuro, and B. K. Fujikawa, *Atomic Data and Nuclear Data Tables* **27**, 1 (1982).
84. W. M. Mansfield, J. E. Bjorkholm, A. A. MacDowell, R. R. Freeman, L. H. Szeto, G. N. Taylor, D. M. Tennant, W. K. Waskiewicz, D. L. Windt, D. L. White, O. R. Wood II, R. M. D'Souza, and A. R. Neureuther, "Effects of absorption on resist performance in soft-x-ray projection lithography," in *OSA Proc. on Soft-X-Ray Projection Lithography, 1991*, Vol. 12, pp. 129–131 (1991).
85. A. A. MacDowell, J. M. Calvert, T. S. Koloski, and O. R. Wood II, "New surface imaging resist technology for SXPL," in *OSA Proc. on Soft-X-Ray Projection Lithography, 1993*, Vol. 18, pp. 87–93 (1993).
86. D. R. Wheeler, G. Kubiak, A. Ray-Chaudhuri, and C. Henderson, "Basic issues associated with four potential EUV resist schemes," *OSA Trends Opt. Photon.* **4**, 33–38 (1996).

87. V. Bakshi, Ed., *EUV Sources for Lithography*, SPIE Press, Bellingham, Washington (2005).
88. J. B. Murphy, D. L. White, A. A. MacDowell, and O. R. Wood II, "Synchrotron radiation sources and condensers for projection x-ray lithography," *Appl. Opt.* **32**, 6920–6929 (1993).
89. P. D. Rockett, J. A. Hunter, R. Kensek, R. E. Olson, G. D. Kubiak, and K. W. Berger, "XUV conversion efficiency in a low-intensity KrF laser plasma for projection lithography," in *OSA Proc. on Soft X-Ray Projection Lithography*, Vol. 12, pp. 76–79 (1991).
90. R. C. Spitzer, R. L. Kauffman, T. Orzechowski, D. W. Phillion, and C. Cerjan, "Soft x-ray production from laser produced plasmas for lithography applications," *J. Vac. Sci. Technol B* **11**, 2986–6900 (1993).
91. R. L. Kauffman, D. W. Phillion, and R. C. Spitzer, "X-ray production ~ 13 nm from leaser-produced plasmas for projection x-ray lithography applications," *Appl. Opt.* **32**, 6897–6900 (1993).
92. M. L. Ginter and T. J. McIlrath, "Debris and VUV emission from a laser-produced plasma operating at 150 Hz using a krypton fluoride laser," *Appl. Opt.* **27**, 885–889 (1988).
93. L. Rymell and H. M. Hertz, "Debris elimination in a droplet-target laser-plasma soft x-ray source," *Rev. Sci. Instru.* **66**, 4916–4920 (1995).
94. M. Richardson, W. T. Silfvast, H. A. Bender, A. Hanzo, V. P. Yanovsky, F. Jin, and J. Thorpe, "Characterization and control of laser plasma flux parameters for soft-x-ray projection lithography," *Appl. Opt.* **32**, 6901–6910 (1993).
95. F. Jin and M. Richardson, "New laser plasma source for extreme ultraviolet lithography," *Appl. Opt.* **34**, 5750–5760 (1995).
96. M. Richardson, K. Gabel, F. Jin, and W. Silfvast, "Cryogenic targets for laser-plasma x-ray lithography sources," in *OSA Proc. on Soft X-Ray Projection Lithography, 1993*, Vol. 18, pp. 156–162 (1993).
97. E. Noda, S. Suzuki, and O. Morimiya, "Droplet target delivery method for high pulse-rate laser-plasma extreme ultraviolet light source," U.S. Patent No. 4,723,262 (1988).
98. S. J. Haney, K. W. Berger, G. D. Kubiak, P. D. Rockett, and J. Hunter, "Prototype high-speed tape target transport for a laser plasma soft-x-ray projection lithography source," *Appl. Opt.* **32**, 6934–6937 (1993).
99. H. Fiedorowicz, A. Bartnik, Z. Patron, and P. Parys, "X-ray emission from laser-irradiated gas puff targets," *Appl. Phys. Lett.* **62**, 2778–2780 (1993).
100. L. Rymell and H. M. Hertz, "Droplet target for low-debris laser-plasma soft x-ray generation," *Opt. Commun.* **103**, 105–110 (1993).
101. G. D. Kubiak, K. Krenz, P. D. Rocket, J. A. Hunter, M. J. Gouge, and P. Fisher, "Cryogenic pellet laser plasma source targets," in *OSA Proc. on Extreme Ultraviolet Lithography, 1994*, Vol. 23, pp. 248–254 (1995).
102. G. D. Kubiak, L. J. Bernardez, K. D. Krenz, D. J. O'Connell, R. Gutowski, and A. M. M. Todd, "Debris-free EUVL sources based on gas jets," *OSA Trends Opt. Photon.* **4**, 66–71 (1996).

103. J. E. M. Goldsmith, G. D. Kubiak, and W. P. Ballard, "LPP source development and operation in the Engineering Test Stand," *EUV sources for Lithography*, V. Bakshi, Ed., pp. 649–667, SPIE Press, Bellingham, Washington (2005).
104. T. E. Jewell, "Four-mirror ring-field system for EUV projection lithography," in *OSA Proc. on Extreme Ultraviolet Lithography, 1994*, Vol. 23, pp. 98–102 (1994).



Hiroo Kinoshita is an expert with over 30 years' experience in lithography. He worked for NTT, where he developed the step and repeat x-ray lithography system and an EUVL experimental system. He moved to Himeji Institute of Technology (now the University of Hyogo) in 1995, and since then he has been responsible for the industrial application of synchrotron radiation. He has authored over 100 technical papers on EUVL.



Obert Wood is a principal member of technical staff in the Strategic Lithography Technology Department at Advanced Micro Devices. He was a member of technical staff at Bell Labs for 34 years and has extensive experience in EUVL, ultra-high-intensity lasers, and laser surgery. He received his BS, MS, and PhD degrees in electrical engineering from the University of California-Berkeley in 1964, 1965, and 1969. He is the author or co-author of 215 technical papers, and the inventor or co-inventor of 20 patents. He is a Fellow of the Optical Society of America, a senior member of IEEE, and a member of the AAAS, the American Physical Society, the American Vacuum Society, and SPIE.

Chapter 3

EUV Source Technology

Vivek Bakshi

Contents

3.1	Introduction	104
3.2	EUV Source Requirements	106
3.2.1	Definition of EUV source	106
3.2.2	Joint requirements	107
3.2.3	Throughput model	109
3.3	DPP and LPP Source Technologies	109
3.3.1	Discharge-produced plasma (DPP)	109
3.3.2	Laser-produced plasma (LPP)	111
3.4	EUV Source Performance	112
3.4.1	Conversion efficiency of EUV sources	112
3.4.1.1	DPP versus LPP	112
3.4.1.2	CE for Xe, Li, and Sn	112
3.4.1.3	Utility requirements	114
3.4.2	EUV source performance results	115
3.4.2.1	EUV source power measurements	115
3.4.2.2	Factors influencing effective EUV light collection	116
3.4.2.2.1	Geometrical collector efficiency	117
3.4.2.2.2	Collector reflectivity	117
3.4.2.2.3	Gas transmission	117
3.4.2.2.4	SPF transmission	117
3.4.2.2.5	Étendue mismatch	118
3.4.2.2.6	Other factors affecting source power requirements	119
3.4.2.3	EUV source power results	120
3.4.2.3.1	DPP	121
3.4.2.3.2	LPP	123
3.4.3	Source components and their lifetimes	125
3.5	Summary and Future Outlook	126
	References	127

3.1 Introduction

EUV lithography (EUVL) is the leading technology, beyond 193-nm-based optical lithography, for printing circuits at the 32-nm node¹ and below in a high volume manufacturing (HVM) environment fab. In EUVL, a 13.5-nm radiation wavelength generated by an EUV source is used to print circuits. Because light is strongly absorbed at this wavelength, the entire EUVL scanner system must be in a vacuum environment, and all optics must be reflective instead of refractive. Based on the HVM requirements of 100 wafers per hour (WPH) throughput and other system requirements for optics, resist sensitivity, and overhead (see Sec. 3.2.3), a power requirement of 115 to 180 W, based on resist sensitivity, has been specified for HVM EUVL scanners. Besides power, EUV sources must meet additional specifications (Sec. 3.2.2). The production-level requirements for EUV sources (Table 3.1) have been jointly agreed upon by major EUVL scanner manufacturers.^{2,3} Table 3.2 shows the change in EUV source requirements over time.

Discharge-produced plasma (DPP) and laser-produced plasma (LPP) are the leading technologies for generating high-power EUV radiation at 13.5 nm. In both technologies, hot plasma of ~ 30 eV of the chosen fuel material is generated, which produces EUV radiation. In DPP, magnetic pinching of low-temperature plasma generates the high-temperature plasma. In LPP, the target material is heated by a laser pulse to generate the high-temperature plasma. Today, tin (Sn) is the leading fuel for HVM-level EUV sources, with xenon (Xe) still being used to meet the lower power requirements of metrology sources, microexposure tools (METs), and alpha-level scanners.

The cost-effective implementation of EUVL in HVM has many technical challenges, with EUV source power remaining the number one challenge (Table 3.3).

Table 3.1 Joint requirements for EUV sources (November 2007).

Source characteristics	Requirements
Wavelength (nm)	13.5
EUV power (inband) (W)	115 W* @ 5 mJ/cm ² 115 W* @ 5 mJ/cm ² –180 W* @ 10 mJ/cm ²
Repetition frequency (kHz)	>7–10 kHz*** There is no upper limit.
Integrated energy stability (%)	± 0.3 , 3σ over 50 pulses
Source cleanliness (hours)	Reflectivity degradation $\leq 10\%$ (in relative) after 30,000 light-on hours**
Étendue of source output (mm ² sr)	max 3.3 mm ² sr***
Max. solid angle input to illuminator (sr)	0.03–0.2 [sr]***
Spectral purity:	
130–400 nm (DUV/UV) (%)	<1% at wafer, values at IF-design dependent
>400 nm (IR/visible) at wafer (%)	<10–100% at wafer, values at IF-design dependent

* At intermediate focus (IF).

** After IF.

*** Design dependent.

Table 3.2 Changes in joint requirements for EUV sources.

Source characteristics	Feb. 2002	Oct. 2002	Feb. 2003	Sept. 2003	Feb. 2004	Nov. 2004	Feb. 2005	Nov. 2005	May. 2006	Nov. 2006
Wavelength (nm)	13–14	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5
EUV power (inband) (W)	47–120	80–120	115	115	115	115	115	115 > 115 @ > 5 mJ	115–180	115–180
Repetition frequency (kHz)	5	6	7–10	7–10	7–10	7–10	> 7–10	> 7–10	> 7–10	> 7–10
Étendue of source output (mm ² sr)	1	1–3.3	1–3.3	1–3.3	1–3.3	3.3	3.3	3.3	3.3	3.3
Max. solid angle	0.2	0.03–0.2	0.03–0.2	0.03–0.2	0.03–0.2	0.03–0.2	0.03–0.2	0.03–0.2	0.03–0.2	0.03–0.2

Table 3.3 EUV critical issues as ranked by the International EUVL Symposium Steering Committees from 2003–2007.

	2003	2004	2005	2006	2007
Source power and lifetime including condenser optics lifetime		Availability of defect-free mask	Resist resolution, sensitivity, and LER met simultaneously	Reliable high power source and collector module	Reliable high power source and collector module
Availability of defect-free mask		Lifetime of source components and collector optics	Collector lifetime	Resist resolution, sensitivity, and LER met simultaneously	Resist resolution, sensitivity, and LER met simultaneously
Reticle protection during storage, handling, and use		Resist resolution, sensitivity, and LER met simultaneously	Availability of defect-free mask	Availability of defect-free mask	Availability of defect-free mask
Projection and illuminator optics lifetime		Reticle protection during storage, handling, and use	Source power	Reticle protection during storage, handling, and use	Reticle protection during storage, handling, and use
Resist resolution, sensitivity, and LER		Source power	Reticle protection during storage, handling, and use	Projection and illuminator optics quality and lifetime	Projection and illuminator optics quality and lifetime
Optics quality for 32-nm half-pitch node		Projection and illuminator optics lifetime	Projection and illuminator optics quality and lifetime		

Today, more than four suppliers and consortia worldwide are working to develop high-power EUV sources for HVM applications. In addition, some suppliers that are working to develop low-power EUV sources are finding applications in metrology to support EUVL development. This chapter reviews EUV source technology and presents the current status and technical challenges that must be overcome to meet the specifications for high-power EUV sources in HVM. For detailed information on EUV source technology, readers are encouraged to consult the monograph *EUV Sources for Lithography*.⁴

3.2 EUV Source Requirements

3.2.1 Definition of EUV source

A high-power EUV source consists of plasma that generates EUV light. This high-temperature plasma (~ 30 eV) can be generated through two approaches, DPP or LPP, which are described in Sec. 3.3. Currently either Xe or Sn is used as the fuel to generate this plasma. The light generated by plasma is collected using collector optics. There are two types of collectors: grazing-incidence (GI) or normal-incidence (NI) angle. Collectors collect light from the source and focus it at a point called the intermediate focus (IF). Source specification is defined at IF. The IF is also the entrance point to the illuminator of the EUVL scanner. The EUV light characteristics, called joint requirements (presented in Sec. 3.2.2), specified at the IF are independent of the type of EUV source or fuel that is used to generate the EUV light. A schematic of an EUV source is shown in Fig. 3.1.

Plasma sources generate not only EUV light, but also ionic and neutral debris and light in the EUV-IR region. Because this debris must not reach the collector mirror, a mitigation device is used to remove the debris. The spectral purity of light reaching the wafer is defined in the joint specifications; a spectral purity filter (SPF) is needed to allow sources to meet these specifications.

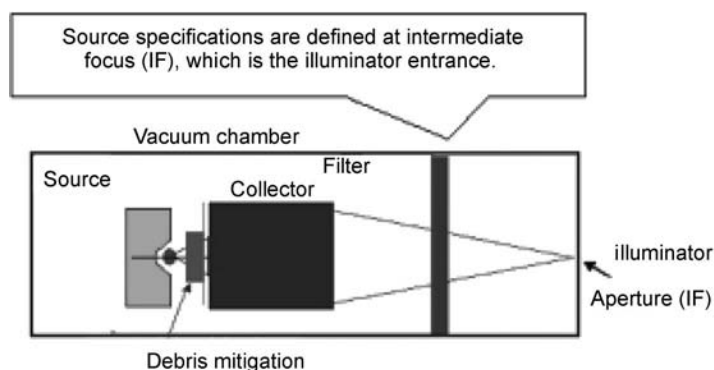


Figure 3.1 Schematics of EUV source. (Reprinted from Ref. 2.)

3.2.2 Joint requirements

Table 3.1 lists the joint requirements of EUV sources; Table 3.2 shows the historical trend of changing EUV source requirements. This section briefly explains these specifications.

EUVL scanners are based on multilayer mirrors (MLMs) with a peak reflectivity at 13.5 nm. The choice of multilayer (ML) determines the wavelength of 13.5 nm. The historical background for choosing this wavelength for EUV scanners can be found in Ref. 2.

EUV source power requirements are based on 100 WPH throughput, which is what is expected from a HVM scanner (see Sec. 3.2.3 for a description of the throughput model). Source power requirements have been constant at 115 W for several years; however, researchers have recently realized that an EUV resist that meets resolution and line edge roughness (LER) requirements may have a sensitivity of 10 mJ/cm² or higher. This number is much higher than the required 5 mJ/cm², which is used in the throughput model² (and also see Sec. 3.2.3) to estimate the 115 W of power at IF.

The repetition frequency requirements are derived from the dose uniformity specification of 0.35 (3 σ)², and HVM requirements are <7 to 10 kHz. Currently, DPP sources operate at 5 kHz. Since typical high-power pulse lasers operate at a much higher frequency, it should be easier for LPP sources to meet this requirement.

The source cleanliness requirements of 30,000 light-on hours is estimated to correspond to a 10-year lifetime for the illuminator. Illuminator mirrors cannot be easily replaced, but adherence to strict source cleanliness requirements can extend their lifetime. It is expected that collector mirrors will be replaced frequently, with an estimated lifetime of 80 billion pulses or 1 year. Even for source collectors, the cost of ownership (CoO) requirements will determine the acceptable lifetime. In addition to source debris, hydrocarbons and water vapor from sources may degrade the reflectivity of EUVL scanner mirrors. Hence, contamination monitoring and mitigation are needed. Damage from debris and contamination, and degradation of components, also may result from normal operation. System end-of-life transmission is estimated as 65%. Table 3.4 lists the end-of-life transmission requirements for various source components and scanner. The collector, electrode (for DPP), and filters are parts of the source. In the end, total system transmission determines the system life.

Étendue is the “light collection power” of the optical system. Light from the source that is emitted into a larger étendue than specified by the system cannot be coupled into the illuminator. For a reticle area of 50 mm², a numerical aperture (NA) of 0.25, and coherence (σ) of 0.5, the illuminator étendue is 3.5 mm² sr². For some illuminator designs, étendue can be as low as 1 mm² sr.

Because plasma sources emit in EUV-IR regions and MLs have finite reflectivity in all regions, photons from all wavelength regions can reach the wafer

Table 3.4 Conditions of component degradation calculations.²

Collector end-of-life transmission	90%
Electrode end-of-life efficiency	90%
ML end-of-life transmission	85%
Filter end-of-life transmission	95%
System end-of-life transmission	65%
<i>Remarks</i>	
End-of-life means replace or clean component	
Anticipated required margin	90%

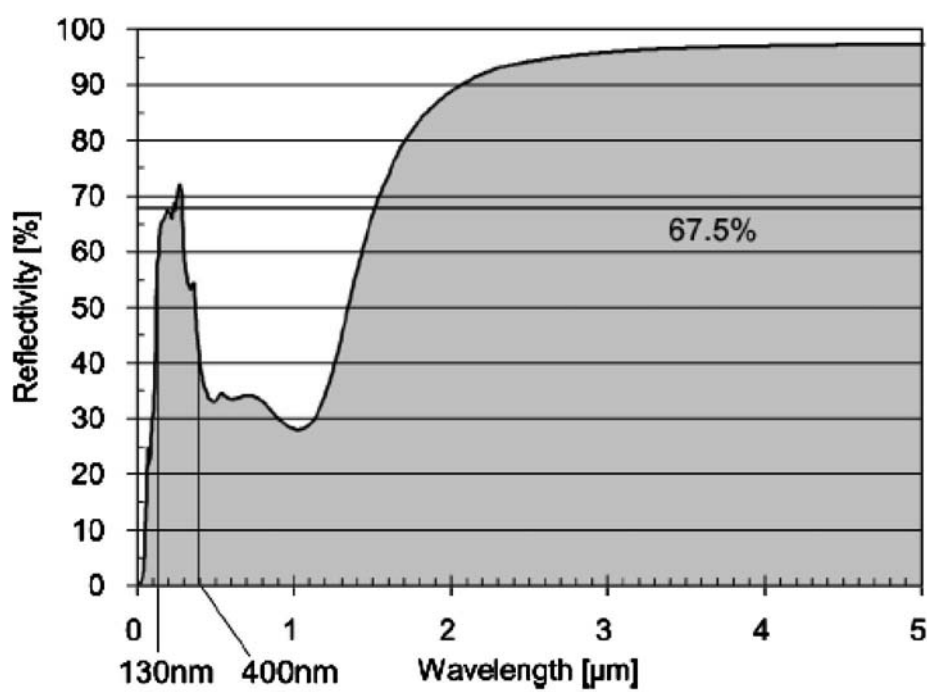


Figure 3.2 Spectral reflectivity of a ML-coated mirror. (Reprinted from Ref. 2.)

from the plasma source (Fig. 3.2). Light from the deep ultraviolet (DUV)/visible region causes flare and issues with critical dimension (CD) control. EUV MLM reflectivity in the IR region is >90%, and therefore IR light is transmitted efficiently to the wafer where the heating it causes can lead to overlay issues.

Although it is not addressed in the joint specifications, CoO is a major factor in deciding whether to adopt a technology. Chapter 12 addresses the CoO of EUVL. Initial calculations⁵ indicate that the collector lifetime must be >20B pulses to ensure that the replacement collector’s contribution to CoO is no more than 15%. A highly reliable source with a mean time between failure (MTBF) of 400 hours

Table 3.5 Typical wafer throughput model to estimate source power.²

Throughput	wafers/h	100
<i>Time per item</i>		
Total time per wafer	sec	36.0
Stage overhead	sec	27.0
Exposure time	sec	9.0
<i>Field and wafer parameters</i>		
Wafer diameter	mm	300
Fraction of wafer exposed	%	78.7
Penalty for not using full field height	%	96.2
Resist sensitivity	mJ/cm ²	5.0
<i>Intermediate derivatives at wafer</i>		
Total energy per wafer	J	2.9
Power at wafer	W	0.321
<i>PO Box</i>		
Reflectivity, mirror	%	67.5
Number of near-normal mirrors		6
Bandwidth mismatch loss	%	5.0
Polarization loss	%	5.0
Gas absorption PO	%	5.0
Total transmission PO	%	8.1
<i>Reticle</i>		
Reflectivity reticle	%	65.0
Power at reticle	W	6.1
<i>Illuminator</i>		
Total transmission	%	8.4
<i>General</i>		
Overall component degradation	%	37.0
Power: captured clean photons	W	115.2

and a capital cost of \$5 million (U.S.) supports an \$8.57 good wafer level exposure (GWLE) CoO contribution.

3.2.3 Throughput model

As stated in Sec. 3.2.2, the 115 to 180 W power requirements are based on a 100-WPH scanner and certain inputs. Table 3.5² gives typical inputs used in this throughput model. The relationships of various parameters in this table can be used to derive an approximate throughput value as a function of source power and resist sensitivity.^{6,7} Figure 3.3 shows the EUVL scanner throughput as a function of source power for various values of resist sensitivities.

3.3 DPP and LPP Source Technologies

3.3.1 Discharge-produced plasma (DPP)

In DPP, hot plasma is created through the magnetic compression of low-temperature plasma, called the “pinch effect.”³ Plasma is compressed with the magnetic field generated by the current used to heat the plasma. Figure 3.4 shows two typical

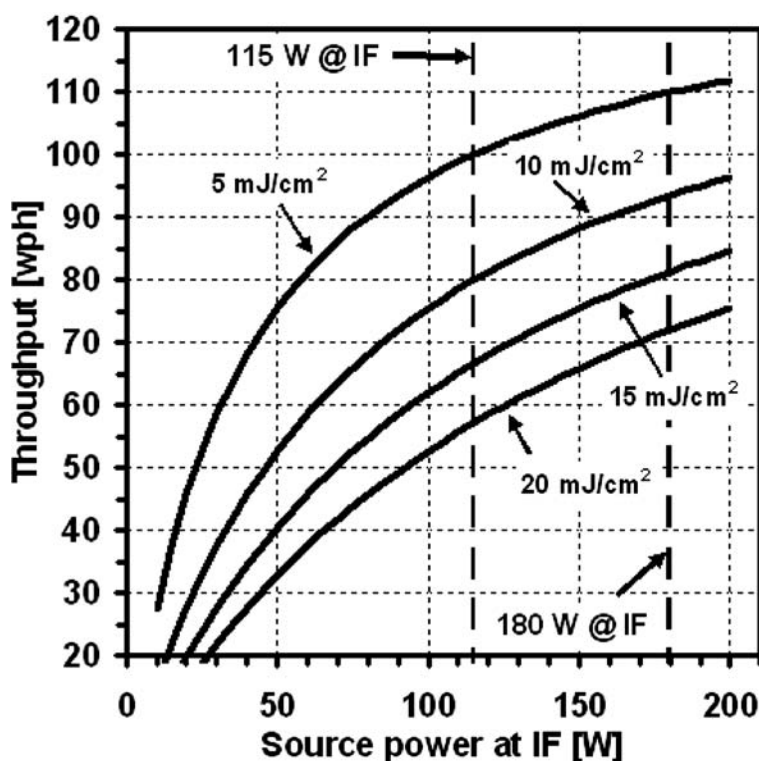


Figure 3.3 Relationship of Source power and throughput for various values of resist sensitivity. (Reprinted from Ref. 7 with permission from the Pennwell Corporation.)

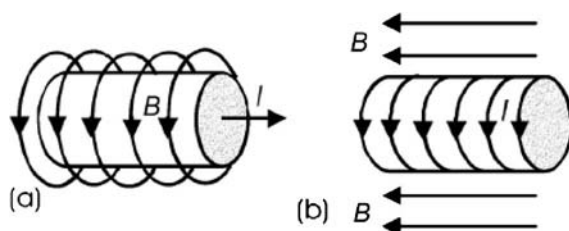


Figure 3.4 Geometries for a DPP (a) liner or Z-pinch, or (b) θ pinch. (Reprinted from Ref. 8.)

geometries for generating DPP. The first is called the liner or Z pinch, and the second is called the theta pinch. Variations of these geometries are described in Ref. 3. Because plasma is compressed by magnetic field B of current I , which generates the plasma, plasma is self-heating. Two forces are present: the magnetic field pressure $B^2/2\mu_0$ and the plasma pressure. When these two forces are equal, the plasma achieves an equilibrium, and the pinching stops. This is called the Bennett relation:

$$\mu_0 I^2 / 4\pi = (Z_{eff} + 1) N_i k T_e, \quad (3.1)$$

where I = total current, T_e = electron temperature, $N_i = \pi r^2 n_i$, n_i = ion density, and Z_{eff} = the mean charge of the ions. Capacitor banks supply this discharge current in a pulsed mode.

Although a qualitative description of pinch formation can be made using the “snow plow” model, magnetohydrodynamics (MHD) equations combined with radiation transport and detailed atomic physics are needed to describe these plasmas completely. For a typical industrial EUV source, the stored energy is in the range of 2 to 20 J, with a maximum current from 10 to 30 kA and a first current half-cycle lasting from about 100 ns to 0.5 ms.⁸ The most common DPP values in the field today are closer to the lower range of these parameters. The plasma radius is determined by the balance between Joule heating and radiation loss [Eq. (6.10) in Ref. 6]. At a current of 20 kA, the effective charge is 10, the electron temperature is 40 eV, and the equilibrium radius of the pinch in Sn DPP is 100 μm , which is in good agreement with experiments.

The main concern in DPP is related to power scaling, because a large amount of heat must be dissipated close to the electrode surfaces and in the source system. As an example, to generate 200 W of 2% bandwidth (BW) EUV radiation with 2% conversion efficiency (CE) and 10% collection ability, 100 kW of power is needed in a very small volume on the order of 1 cm^3 .

3.3.2 Laser-produced plasma (LPP)

LPP is generated by focusing a laser beam on a target material. The initial ionization of the target occurs through photoionization, and the electric field of the laser accelerates these electrons. Nonelastic collisions further ionize the plasma while elastic collision with the ions transfers the electron’s kinetic energy into ionic kinetic energy. This process of heating plasma by free-free absorption is called inverse bremsstrahlung absorption (IBA). The absorption coefficient for IBA is written as follows⁹:

$$\alpha_{IB} = \frac{1.08 \times 10^{-5}}{\lambda^2} Z^* \left(\frac{n_e}{n_c} \right) \frac{\ln \Lambda}{\sqrt{1 - (n_e/n_c)}} \frac{1}{T_e^{3/2}}. \quad (3.2)$$

This equation is written in the SI system of units with the absorption coefficient expressed in m^{-1} units, where λ is the wavelength of the incident laser beam in m units, Z^* is the average ion charge, T_e is the electron temperature in eV units, n_e is the electron density, and n_c is the critical density at which the electron plasma frequency is equal to the laser light frequency. When $n_e = n_c$, the laser light is reflected from the target. The critical density is 10^{25} m^{-3} $\times$ 10^{28} m^{-3} for a CO_2 laser wavelength (10 μm) and excimer laser wavelength (248 nm wavelength), respectively. The electron density is well below this value for droplet-based LPP sources and approximately proportional to the square of the electron density, for a given electron temperature.

As plasma expands, thermal energy is converted into kinetic energy and density decreases. The expansion velocity of Sn plasma at ~ 30 eV is about $2 \times 10^6 \text{ cm/s}$.⁹

This decreases both the IBA and CE. Therefore, the laser pulse length should not be very long; 10 ns is considered a good time scale for a laser pulse. The corresponding optimum laser intensity, for maximum CE, is 1×10^{11} W/cm² for a Nd:YAG laser and 1×10^{10} W/cm² for CO₂ lasers.¹⁰ Modeling has shown that CE depends on the laser wavelength. A 10.6- μ m laser gives approximately 1.9 higher CE than a 1.06 μ m laser, while a 0.26- μ m laser gives a CE 0.55 times lower.¹⁰

3.4 EUV Source Performance

3.4.1 Conversion efficiency of EUV sources

The CE is the ratio of the energy radiated by the EUV source in a 2% BW window around 13.5 nm to the energy input to the EUV source. The CE is used to estimate the utility requirements and fuel choice, and to understand the power scaling limits. The fundamental CE for a fuel represents the upper limit of CE for that particular fuel.

3.4.1.1 DPP versus LPP

For DPP, the input energy is the electrical energy consumed by the entire system (energy dissipated in the plasma plus energy lost in the electrical system). However, sometimes the CE values presented in the literature take into account only the energy deposited into the plasma. This is called intrinsic CE. In DPP, some energy is lost in the electrical components. Therefore, the reported CE will depend on system-specific details, and without those details, it will be difficult to separate the CE from the fundamental CE limits for a given fuel. Ref. 11 gives an example of the CE for the entire system as well as the fundamental CE.

For a given fuel, it is possible to optimize the system operation to maximize its CE.¹² Many times the highest CE reported for a fuel and source design combination does not correspond to that of the optimal operating conditions. In this situation, it is best to use the CE for the optimal operating conditions to realistically estimate utility consumption and understand the power scaling limits. For a LPP system, the laser power and the EUV output in the 2% BW around 13.5 nm are used to estimate the CE. However, for LPP systems, the overall system CE is much lower than that of a DPP system because of the low wall plug-to-laser light CE (*wall-plug efficiency*) of a laser system, which is typically less than 10%.

3.4.1.2 CE for Xe, Li, and Sn

Three materials—Xe, lithium (Li), and Sn—have been investigated as EUV fuel sources. Figure 3.5 shows a relative variation of CE as a function of atomic number.¹³ This figure demonstrates why Sn is the fuel material of choice for EUV sources.

Although Xe has been favored as a fuel because it is a noble gas, its low CE requires a high energy input to meet HVM EUV source power requirements. For

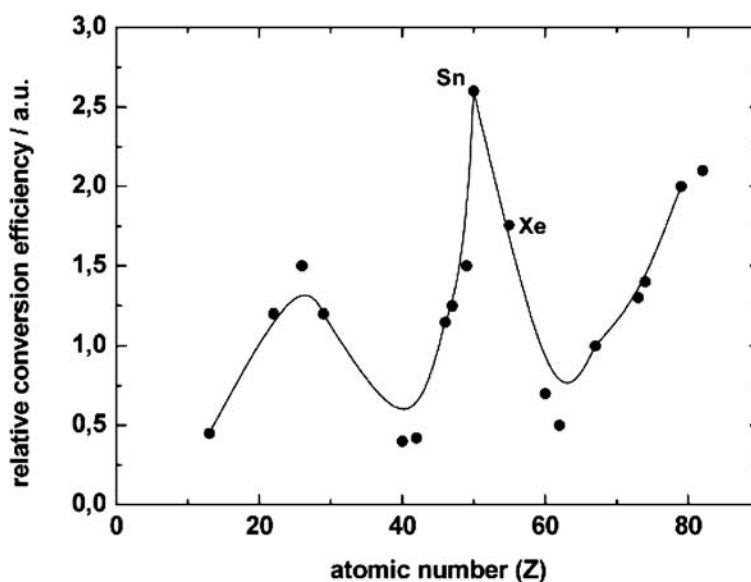


Figure 3.5 Relative CE into 13.5-nm radiation as a function of the atomic number of the emitter. The highly efficient Sn ($Z = 50$) and the frequently used Xe ($Z = 54$) are marked. (Reprinted from Ref. 14.)

Xe plasma, only the Xe^{10+} ionic stage is responsible for emission in the 13.5-nm radiation BW,¹⁴ which results in a 1% or less CE. The energy inputs necessary to offset this low CE are prohibitive due to DPP thermal management limits and the lack of high-power lasers for LPP, thus precluding Xe as the fuel of choice for high-power EUV sources. As suppliers learn to optimize their source systems, measured CEs have continued to increase. Historical data for such an increase are not given in this section but can be reviewed in the technology descriptions of various source designs.¹⁵ Although modeling has predicted a wide range of fundamental CE limits for Xe (2 to 4%),¹⁶ only a 1% CE has been observed experimentally for Xe plasmas. CEs for a Xe DPP system have been reported of around 0.45%, 0.5%, and 1%.^{17–19} However, one must be cautious about accepting high CE numbers, since (for example) a given DPP design may require a source size larger than allowed by the system's étendue requirements. Therefore, the maximum CE may correspond to the available power at the source and not to the acceptable power at the EUVL scanner. In the case of LPP, the source size is smaller (on the order of 100×100 nm), than for DPP so the étendue mismatch is not a concern (see Sec. 3.4.2.2.5 for details on this topic). For Xe LPP, CEs of 0.7%, 0.8%, and 0.8 to 1% have been reported.^{19–21} It has been shown that for Xe LPP, the transient nature of the Xe^{+10} population may be limiting the CE, and pulse shaping and pulse trains may help increase it.²² The above CE values are for LPPs produced using Nd:YAG lasers. For LPP systems using pulsed CO_2 lasers, CEs of 0.7% and 0.8% have been reported.^{20,23} For any given LPP system, the CE depends on the laser wavelength.¹⁰ For Sn, multiple ionic stages, Sn^{+8} to Sn^{+12} , contribute to emissions

around 13.5 nm, resulting in a higher CE;²⁴ much higher theoretical CE estimates for Sn (4 to 7.5%) have been reported.¹⁶ Recent work also predicts CEs of 3.5 to 6% for Sn-based EUV sources.²⁵ A factor of 3 to 4 for Sn over Xe is usually quoted in the literature for experimental CE measurements.^{26,27} For Sn DPP EUV sources, 2% CE has been reported.^{18,28} The supplier roadmap goal is 3% CE,¹⁹ and this goal may be achieved by reducing the étendue mismatch and optimizing the system design. Higher CE values have been reported for Sn LPP: 4.5% using Sn-doped droplet targets²⁹ and 4% using a rotating Sn plate target.³⁰ However, solid Sn targets are probably not practical as a fuel in an EUV source, because they may generate large amounts of debris. The third material of choice, Li, was recently revisited by EUV source suppliers for both LPP¹⁷ and DPP systems.³¹ In the past, very low CEs of 0.1% for capillary discharges³² and 0.23% for dense plasma focus (DPF) systems³³ were reported. Recently, much higher CE measurements of 2.5 to 3% have been reported for Li-based LPP EUV sources;¹¹ a 2.5% CE is expected for Li-based DPP EUV sources.³¹

3.4.1.3 Utility requirements

Utility requirements for EUV sources and for a wafer manufacturing fab in general should be considered, because these requirements reveal why some potential EUV source technologies may not be cost effective. Although firm numbers are not available for laser utility requirements and full-scale scanners, utility consumption estimates can still point out potential issues. EUVL is expected to be implemented in a 300-mm HVM fab. Based on current data, the utility requirements in 300-mm fabs have been estimated.^{34,35} In an HVM 300-mm fab (defined as 30,000 to 40,000 wafer starts per month), the average power requirement for the entire fab is 50 MW. For a typical fab, 40% of the energy consumed is used by tools. In today's fabs, 193-nm scanners are the leading-edge scanners. On average, in an HVM fab, 10 scanners of leading-edge technology are needed to pattern critical layers. The utilities for a 193-nm scanner are rated for 75 kW, which means the consumption by 10 scanners is 750 kW, or 4% of the total tool power consumption. For this discussion, the equipment power rating has been used for the tool's actual power consumption. In reality, the actual power consumption is less, as this is rated power; however, such data is not readily available. We should also note that the estimates for power consumption by EUVL scanners given below in this section are for actual power consumption and the rated values for power consumption will be higher. A 40 W, 193-nm laser used in a 193-nm scanner has utilities rated for 50 kW.³⁶ A HVM Sn DPP EUV source is expected to consume 30 kW of power; therefore, for DPP EUV sources, no increase in utilities (power consumption or cooling requirements) is expected. Today's EUVL microscanners are rated for 100 kW of power usage. Their Xe DPP EUV sources generate 1 W of power using ≈ 2 kW of power input (based on a 0.5% CE for Xe), or 2% of the energy. For an alpha-level EUVL scanner with 25 W of a Sn DPP source, utilities are rated for 150 kW. A good estimate assumes that for a production-level EUVL scanner, ≈ 150 kW of energy will be required, meaning only a modest increase in power

consumption is expected in the HVM environment for one EUVL scanner, and ≈ 750 kW for 10 EUV scanners. The utility estimate for EUVL scanners will be different if LPP-based EUV sources are used. The power scaling for DPP sources is limited due to thermal management limits on electrode cooling. If future EUVL applications demand higher power, LPP can provide the needed power scaling. However, the utility requirements for LPP raise concerns, depending on the type of laser employed by the EUV source. For a Nd:YAG laser, the wall plug-to-laser light CE (*wall-plug efficiency*) is estimated to be 10%, which means 120 kW of power is needed to generate 12 kW of laser light. This is the amount necessary to produce the required 115 W of power; hence, the power requirement for EUV sources is increased by 70 kW over that of a 193-nm scanner light source. For 10 scanners, this will mean an additional 700 kW of power, which, although a substantial increase, may be acceptable. However, single-module, high-power Nd:YAG lasers do not seem to be technically feasible or cost effective.²⁰ Suppliers are looking at a pulsed CO₂ laser, which is expected to demonstrate $\approx 8\%$ wall-plug efficiency. The main concern for utility requirements, however, comes with excimer lasers. Current wall-plug efficiency estimates range from 0.5% to 2%, or a power input from 600 kW to 2.4 MW to generate 12 kW of laser power.^{36,37} This would mean additional power requirements of 550 kW to 2.35 MW per EUV source, or 5.5 to 23.5 MW for 10 such EUV sources, as compared to the requirements of 193-nm light sources. Such estimates of additional utility requirements could render excimer-laser-driven LPP EUV sources as not cost effective.

3.4.2 EUV source performance results

3.4.2.1 EUV source power measurements

The EUV source requirements are specified at the IF in the 2% BW around 13.5 nm. However, most measurements are still performed by directly observing the EUV source. Consequently, the power estimated at the IF requires the user to estimate losses between the source and IF. Metrology for measurements at IF has been developed.^{38–41} Since measurements at IF are more cumbersome and IF metrology equipment is more expensive, power measurements will likely continue to be taken directly at the source. Absolute EUV power is measured using one or more MLMs and EUV diodes, although absolutely calibrated charge-coupled devices (CCDs) combined with spectrometers can also perform these measurements. Mirrors and diodes are both calibrated at the beamline. SEMATECH has sponsored the Flying Circus (FC) project to independently assess source performance,¹¹ cross-calibrate suppliers' EUV sensors, and cross-calibrate other commercial EUV energy sensors.^{11,42,43} Such measurement campaigns have produced confidence in the source power measurements and source performance data. For the FC, an accuracy of better than 3% is estimated for absolute EUV power measurements on a beamline.⁴⁴ These absolute accuracies are only good for the Xe-based systems. For Sn-based EUV sources, because of varying spectral correction factors, an FC-type device with special 2% BW mirrors has been used. The special MLMs, designed to

simulate the performance of the 11-mirror system, allow one to estimate the EUV radiation in the 2% BW around 13.5 nm without spectral feature information for the Sn source in a wide spectral-range calibration.⁴⁵

3.4.2.2 Factors influencing effective EUV light collection

All of the EUV radiation emitted by sources cannot be collected and transmitted to the IF. The following sections review various factors that affect the collection of EUV light at the IF. Table 3.6 summarizes these discussions of EUV source technology limits. This table reveals why Xe-based sources are not a practical solution for HVM and why LPP sources are more effective due to the larger collection efficiency of their collector design. This table does not differentiate between burst mode and continuous operation. Additionally, the reliability aspect of a particular source technology is not reflected.

Table 3.6 EUV source technology limits.

	DPP Xe today	Ultimate	Sn today	Ultimate
Input power (W)	30000	30000	10000	30000
Conversion efficiency	0.83%	1.00%	2.00%	3.00%
Power at the source (W)	249	300	200	900
Collection in sr (out of 2π sr)	1.8	3.14	1.8	3.14
Collection ability (% of 2π)	29%	50%	29%	50%
Collector transmission	65%	70%	65%	70%
Debris mitigation transmission	80%	80%	80%	80%
Gas transmission	85%	85%	85%	85%
SPF transmission	40%	70%	40%	70%
Étendue match	65%	100%	75%	100%
Effective collection capability	3%	17%	4%	17%
Power at IF (W)	8	50	8	150
	LPP Xe today	Ultimate	Sn today	Ultimate
Input power (W)	1000	15000	1000	15000
Conversion efficiency	0.80%	1.20%	2.50%	3.00%
Power at the source (W)	7	180	25	450
Collection in sr (out of 2π sr)	3.14	5	3.14	5
Collection ability (% of 2π)	50%	80%	50%	80%
Collector transmission	65%	70%	65%	70%
Debris mitigation transmission	100%	100%	100%	100%
Gas transmission	85%	85%	85%	85%
SPF transmission	40%	70%	40%	70%
Étendue match	100%	100%	100%	100%
Effective collection capability	11%	33%	11%	33%
Power at IF (W)	1	60	3	150

3.4.2.2.1 Geometrical collector efficiency Due to geometrical constraints, in today's system designs a DPP EUV source collector collects less light than a LPP source collector. Currently, a 1.8-sr collector consisting of concentric hyperbolic-elliptical mirror shells (Wolter type 1 GI optics) is being used for DPP EUV sources.^{46–48} For these collectors, EUV light undergoes two reflections before it is collected at the IF. These collectors are produced by coating a nickel (Ni) shell with palladium (Pd) or other materials such as gold (Au), rhodium (Rh), or ruthenium (Ru); some new proprietary alloys also have been proposed. For DPP EUV sources, suppliers have been proposing a collector of 3.14 sr, which will collect 50% of the light. However, no such design has yet been realized, and doing so will be challenging. Separate studies are underway⁴² to investigate the collection limit of collectors. For LPP, collectors are made from molybdenum-silicon (Mo-Si) MLs, which are protected by a thin coating layer (e.g., Ru). Today, suppliers have demonstrated 3.14-sr collectors for LPP, and work is underway to design and manufacture a 5-sr collector that will have 80% collection efficiency.¹⁹

3.4.2.2.2 Collector reflectivity Collector materials have limited reflectivity, contributing to a loss of EUV light in the system. For Pd-coated shells used as collectors for DPP, the reflectivity at 13.5 nm decreases linearly from 85% to 65% for a GI angle of 5 to 15 deg.⁴⁰ Due to the finite size of the plasma and the multi-shell collector design, the modeled effective reflectivity must be verified using reflectometer setups,⁴⁸ although generally an upper limit of 70% reflectivity is used. Ultimately, the transmission of the entire source collector module must be considered and therefore entire systems need to be modeled using ray tracing.⁴⁹ For LPP collectors based on MLs, an upper limit of 70% is likewise projected. However, to withstand the thermal load, ML collectors are engineered with special coatings and interlayer diffusion barriers that reduce the overall reflectivity of the ML. Recently 47% reflectivity has been reported for such ML-based collectors.²⁹

3.4.2.2.3 Gas transmission Absorption of EUV light by a background gas such as Xe is expected in DPP and LPP systems. Although absorption-versus-pressure data are readily available,⁵⁰ suppliers do not provide pressure data because of pressure gradients and the proprietary nature of such data. From the FC2 experiment,⁴² for 2.1 mTorr of Xe, a loss of 15% for a 900-mm distance in an EUV source can be expected. Suppliers usually expect a 15% loss, or 85% transmission, for Xe, which indicates the path length and gas pressure of EUV radiation to the IF. For Sn-based DPP systems, the choice of carrier gas is not publicly known. Experiments with various Sn halides have shown that absorption by carrier gases can be a problem.⁵¹ An 85% value is used in Table 3.6, but measurements must be performed to assess the practical transmission for Sn-based DPP EUV sources.

3.4.2.2.4 SPF transmission EUV sources radiate over a range from the EUV to the IR. The ML optics in the EUVL scanner (Fig. 3.6) and grazing-angle collector also reflect in most wavelength regions. This combination of source emission

and optics reflectivity will result in the transmission of a wide spectrum of radiation through the system to the wafer. Radiation out of a 2% BW around 13.5 nm is called out-of-band (OOB) radiation. The main radiation bands of concern are 130 to 400 nm and >400 nm. In the 130- to 400-nm band, MLs have significant reflectivity, transmitted radiation will cause flare at the wafer, and the longer-wavelength radiation will heat the optics, reticle, and wafers, causing overlay problems⁵² and the need to cool the optics. In addition, there is some concern about the ionization of environmental contamination by vacuum ultraviolet (VUV) light.⁵³

The specifications for OOB radiation are given in Table 3.1. For 130 to 400 nm, spectral purity requirements are $<1\%$ (of in-band EUV radiation) at the wafers while the values at the IF are not agreed upon. The spectral purity for the region >400 nm is 10 to 100% (of in-band EUV radiation). The spectral requirements outside the 2% BW in 18 to 130 nm have not been addressed by scanner manufacturers, because the ML reflectivity in that range is very small. Note that these OOB specifications are at the wafer level, and values at the IF are not given in joint specifications because they are design-dependent.

In the most recent OOB data for Xe DPP, it has been shown that for 160- to 300-nm values at the IF are 3.9%, while from 300 to 400 nm, 4.2% of OOB radiation is present.⁵⁴

For Sn LPP, data are available for a mass-limited droplet-based LPP system. OOB radiation in the 130- to 325-nm region was found to be negligible. However, in the 325- to 850-nm region, it is 13%, compared to 9% measured for Xe DPP in the same region.¹¹ Absolute spectral measurements are needed of OOB radiation for various fuels. The source operation parameters (temperature and density) affect the OOB radiation, so systematic measurements of OOB radiation are needed as a function of those parameters. In today's EUVL microscanners, a thin film is used as the SPF, which also doubles as a debris filter and vacuum barrier. Although such filters work well at lower EUV powers, they will not be able to tolerate the thermal load at high EUV power. Any SPF designed for high-power manufacturing will need to address the thermal load. Recently, one supplier demonstrated a high-throughput (77%) SPF that can sustain temperatures up to 700°C from a >1 W/cm² thermal load. This SPF consists of an ultrathin (60 nm) Zr film.⁵⁵

3.4.2.2.5 Étendue mismatch EUV sources have étendue limitations; there is an upper limit to the size of the source that can be accepted by the scanner. The current maximum acceptable étendue is 3.3 mm² sr, with a maximum solid angle of input to the illuminator of 0.03 to 1.2 sr. Because the acceptable source size specifications may vary among scanner manufacturers, the collectable source power for a given source will vary for different EUVL scanners.

Today a typical DPP source supplier expects a 50 to 100% étendue match for its source.^{19,23,56} The main problem for DPP is that the source size increases as the output power increases, limiting the maximum power that the DPP source can deliver to IF. It has been reported that the Sn pinch is smaller than the Xe

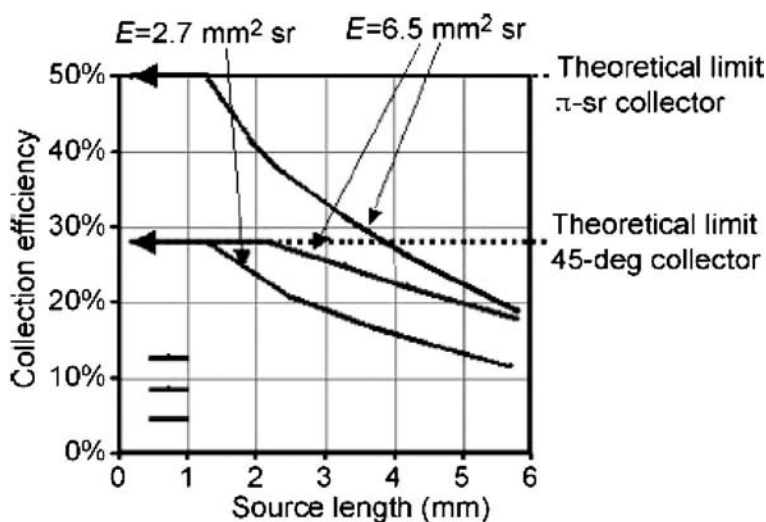


Figure 3.6 Collection efficiency over 2 m² sr as a function of pinch length for a 0.5-mm pinch radius and two different collector designs, according to Ref. 49.

pinch;²⁶ however, Sn DPP sources also have the problem of larger sources corresponding to greater source power, when further power scaling is realized. Figure 3.6 shows the collection efficiency of a 3.14-sr and a 1.57-sr collector for a given source length and scanner étendue values.⁵⁷ In contrast, the LPP source is small ($\approx 300 \times 150$ nm)²⁹ so source size should not be an issue. The full-spectrum and in-band source sizes also raise some questions, and measurements are not conclusive. Measurements have found an 18% larger in-band size than full-spectrum size for a Xe DPP source,⁵⁸ although for a Xe LPP source, the in-band source size could be smaller than the full-spectrum source size.⁵⁹ To decrease the loss of EUV photons due to an étendue mismatch, higher étendue scanner designs have been proposed.⁶⁰

3.4.2.2.6 Other factors affecting source power requirements Because the requirement for source power arises from the throughput model, the EUV source power requirements can increase depending on how some of the requirements change. Currently source requirements are in the 115 to 180 W range, depending upon resist specifications of 5 mJ/cm² or 10 mJ/cm². It is important to consider some of the major factors that may increase or decrease source power requirements.

3.4.2.2.6.1 Resist sensitivity The EUVL scanner throughput model assumes an EUV resist sensitivity of 5 mJ/cm². Although this is the only characteristic mentioned in the throughput model, an EUV resist must meet many additional specifications (e.g., LER and resolution). There is a tradeoff among sensitivity, LER, and resolution.⁶¹ For example, increasing absorption will improve the resist sensitivity but will worsen the profile and resolution. Because resist sensitivity depends on how many times a resist molecule causes a reaction, more reactions mean

increased sensitivity as well as higher LER. Today, the best resist performance is for 10 mJ/cm² resist with an LER of 5.9 nm (3 σ for 50-nm structures). This resist can resolve features up to 25 nm but with worse LER.⁶² In additional resist performance benchmarking, the best performance has been shown to be at 26-nm resolution, with 5.9-nm LER at 17 mJ/cm² resist sensitivity.⁶³ Resist performance must improve or higher source power may be necessary to achieve the required throughput.

3.4.2.2.6.2 Mirror reflectivity The current throughput model assumes 67.5% reflectivity for MLs. It has been shown that a higher reflectivity of 70% is possible⁵⁵ and that a sustained reflectivity >67% can reduce power requirements. At the same time, the reflectivity of collectors and mirrors decreases as they erode. Currently, a 10% reflectivity loss is accepted as the end of lifetime for optics. Carbon deposition is expected to be the leading cause of optics contamination in the scanner.⁶⁴ One EUVL scanner has demonstrated an in-situ cleaning technique that can help to recover the reflectivity.⁶⁴ Long-term damage from in-situ cleaning has not been identified, and if reflectivity degradation occurs over 30,000 h, more source power may compensate for the reflectivity loss in the mirrors and collector optics in an EUVL scanner.

3.4.2.2.6.3 Additional factors Additional factors that can potentially affect power requirements are the overhead time and the number of mirrors. According to the EUVL scanner throughput model, out of a total of 36 s spent per wafer in the EUV scanner, 27 s are devoted to overhead time, and only 9 s are spent on exposing the photoresist on the wafer. Ota et al. discuss the basis of the overhead time chosen in the throughput model.² A small decrease in overhead time can mean a decrease in the required source power. Also, if the number of mirrors for certain scanner designs increases as EUVL is implemented at smaller nodes, more power will be needed. Studies⁶ have shown the tradeoff between exposure time and overhead time for a range of values for source power and resist sensitivities (Fig. 3.7). Additionally, new scanner designs have been proposed that require fewer mirrors in the scanner and reduce the power requirements.⁶⁰

3.4.2.3 EUV source power results

Table 3.6 shows the technology limits for various EUV source technologies and estimates the average value for sources of power loss between the source and IF. The actual power values for a given design will depend on the source design details and must be measured. The technology limit values estimate the upper limit of obtainable power from a given technology under a given set of assumptions. The purpose of the table is to show how changing certain parameters can affect the collected power at the IF. This table represents the current best estimates; if a better value than that shown in the table can be achieved, then even higher power is possible. For current performance values, one must depend upon the values presented by suppliers; however, many times it is not clear whether the values are for continuous operation or for burst mode. When continuous performance data are

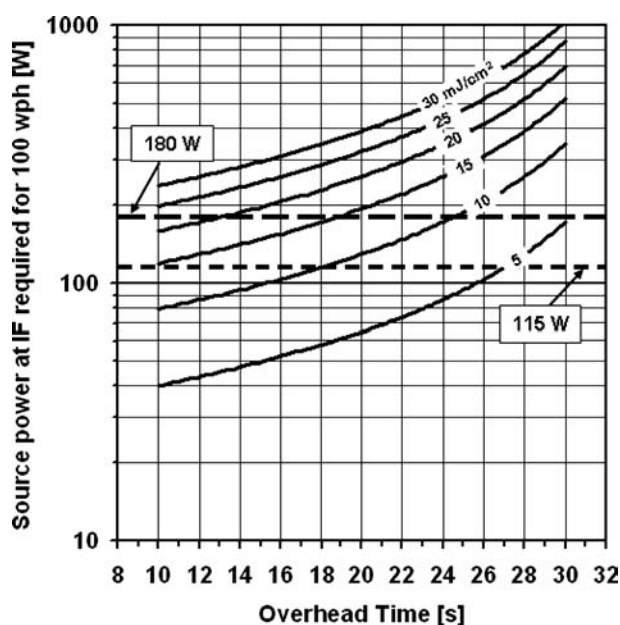


Figure 3.7 The tradeoff between exposure time and overhead time for a range of values for source power and resist sensitivities. (Reprinted from Ref. 6 with permission from Elsevier.)

available, they have been used over burst values. For continuous or burst mode, it is desirable to know the duration over which the data were collected. Note that a “showstopper” is defined as a technical problem that cannot be solved in a cost-effective and timely manner; a technical challenge, on the other hand, is one that can be so addressed. In many cases, researchers must address a technical challenge to know that it is a showstopper.

3.4.2.3.1 DPP

3.4.2.3.1.1 Xe DPP EUV sources for existing EUV microscanners are based on Xe DPP technology. They provide about 1 W of power at the IF.¹⁹ However, the showstopper for Xe DPP is thermal extraction. It is now widely agreed that this technology cannot meet the power needs of HVM sources, because the upper limit for thermal mitigation is expected to be 30 kW. Therefore, all current Xe DPP projects^{18,19} are focused on delivering a low-power source for an alpha-level scanner. No further efforts are planned to significantly increase the Xe DPP power level. Instead, efforts are now focused on increasing the reliability of existing sources.⁴⁹

The current data for thermal extraction indicate that up to 30 kW of input power can be mitigated and 230 W of EUV power can be generated.⁵⁴ However, only 4 to 8 W of power can be collected and delivered to the IF in a 100 % duty cycle.⁴⁹ Note that significant development in the past has allowed the present level of thermal mitigation for Xe DPP. The use of porous metal cooling technology,⁶⁵ in which high-pressure water is forced through porous metal electrodes to cool them, has increased power input to the sources in one source configuration. To reduce the

thermal heat load on the electrodes, the distance between the plasma and electrode also must be increased to allow for higher power generation.^{19,23,29} An electrode configuration called Star Pinch has been demonstrated to allow a higher thermal load than other DPP sources.⁶⁶ The supplier has predicted a 10^{10} -pulse lifetime for this electrode configuration. Input energy to a DPP source is dissipated in various components of the system, from which the heat must be extracted. According to calorimetric measurements for the Star Pinch configuration,⁶⁶ in the cathode 8%, anode 6%, foil comb 13%, and chamber 73% of the input power is dissipated. Electrode thermal extraction is therefore only part of the issue, but it is the most important part because rising temperatures can increase the erosion of electrodes and reduce their lifetime. Sputtering is the next leading cause of electrode erosion. Today, a 500 million-pulse lifetime for the cathode and >4 billion-pulse lifetime for the anode have been demonstrated.⁴⁹

In Table 3.6, a best estimate has been made for the limit of Xe DPP technology, although no commercial programs are in place to further increase Xe DPP power to meet higher power requirements. For Xe DPP, it is reasonable to expect that close to 1% can be achieved for the upper limit of the CE. Most suppliers today are working with 1.8-sr collectors, and designs exist for 3.14-sr collectors. In Table 3.6, the transmission of the debris mitigation device is simply an estimate; the same is true for available SPF filters. With a 75% étendue match expected, effective collection can be potentially increased to 17% as the SPF and collector efficiency improve. With 30-kW power input and 17% collection, a maximum of 50 W of power at the IF can be expected for Xe DPP. In summary, thermal extraction is the showstopper for Xe DPP technology, limiting it to 50 W of maximum power at the IF—even if improvements are made to collect more EUV photons from the source and deliver them to the IF.

3.4.2.3.1.2 Sn DPP For Sn DPP, a higher CE of 2.5% has been measured and up to 3% CE has been predicted.⁶⁷ The same constraints on collection efficiency for Xe DPP apply to Sn DPP systems. Current collection efficiency is estimated to be 4%, and 17% is expected in the near future. With 200 W of power measured in $2 \text{ m}^2 \text{ sr}$ at the source, a minimum of 8 W of power can be expected at the IF. An upper limit of 150 W at the IF is expected for a 30-kW power input if CE is increased as indicated in Table 3.6. Thermal load is considered to be the technical showstopper for Sn DPP.

In Sn DPP systems, debris mitigation was expected to be a potential showstopper. However, it has been shown that for 1 billion shots, no loss of power at the IF is observed, indicating that debris has been successfully mitigated.⁶⁸ The supplier has in-situ cleaning capabilities to clean Sn debris deposited on a collector; however, in this case no cleaning was used. Based on these data, a lifetime of 10 billion pulses can be expected. Previously, the supplier had shown a 5% reflectivity loss for a sample collector material using over 100 million pulses for its debris mitigation system.²⁸ The supplier also showed that it could reclaim collector reflectivity with only a 4% reflectivity loss after 100 cleaning cycles. Thus, the supplier had expected to demonstrate a collector lifetime of up to 10 billion pulses. Although

such performance meets the needs for an alpha-level EUVL scanner, much work is still needed before a manufacturing scanner will meet the expected requirement of 80 billion pulses.

3.4.2.3.1.3 Li DPP Recently a high-power Li DPP system was proposed.³¹ With the present estimate of 2.5% CE for a Li DPP source, the collection efficiency and technology limits are expected to be similar to those of a Sn DPP system. However, no power performance data are currently available to assess the potential technical challenges or showstoppers for this technology.

3.4.2.3.2 LPP

3.4.2.3.2.1 Laser power High-power lasers are the key enablers of LPP EUV source technology. Consequently, their limitations must be fully understood to understand the limitations of LPP EUV sources. A high average power (15-kW range) and high peak power (pulses from hundreds of millijoules to 1 J with a width of ~tens of ns)^{69–71} are needed. It is also believed that an ~10-ns pulse length may be needed for Xe LPP only, while large pulse lengths of ~tens of ns may be sufficient for Sn LPP. It will be difficult for a single laser module to meet these laser power requirements. Laser modules will need to be multiplexed to deliver such power. Multiplexing of high-power lasers has been demonstrated, in which three 1-kW lasers were spatially and temporally multiplexed.²¹ Although there is no hard technical basis for predicting how many chains can be used for multiplexing, a good estimate is that up to 15 kW of laser power can be achieved. In principle, higher laser power can be achieved by further multiplexing, thus giving this technology the scalability to enable higher EUV power than current specifications. Nd:YAG lasers, CO₂ lasers, and fiber-based lasers are being considered for LPP-based EUV sources for HVM. Table 3.7 gives the present status and future prospects for these lasers. Excimer lasers were previously being considered for LPP; however, due to their low CE and the possibility of unreasonable utility requirements, these lasers are no longer being considered for LPP-based EUV sources.

One supplier developed a 1.5-kW Nd:YAG laser module using master oscillator–power amplifier (MOPA) architecture and demonstrated reliable operation of

Table 3.7 High-power laser status.

Parameters	Units	Lasers		
		Pulsed CO ₂	Nd: YAG	Fiber
<i>Power</i>				
Today	kW	7	1.5	0.045–0.100
Duty cycle	%	10	100	100
Near future	kW	10–20	2.5	1–10
<i>Operation frequency</i>				
Today	kHz	50–100	1–6	50–100
Near future	kHz	50–100	>10	>1000
<i>Efficiency</i>				
Today	%	2.5–4	6–13	10–30
Near future	%	5	13	40

1.5-kW lasers.⁶¹ The supplier was then able to combine up to three such chains and deliver 4.5 kW of power. Such laser power output is the current record for high-power Nd:YAG lasers, but the system was not run long enough to obtain reliable data.⁷² A second supplier demonstrated Nd:YAG lasers with a 2.5-kW power, 6-ns, 10-kHz system that yields 4 W of power at the IF.²⁰ Plans exist to increase the power to 5 kW to demonstrate 10-W systems. However, because further increases in Nd:YAG laser power are not deemed feasible and cost effective,²⁰ this supplier plans to use pulsed CO₂ lasers as drivers for high-power sources. A third supplier has demonstrated a 1.2-kW, 16.6-ns Nd:YAG pulse laser¹⁹ that gives a 1% CE and produces 12 W of power at the IF. A fourth supplier²¹ demonstrated the operation of a 1.5-kW Nd:YAG laser module. The supplier expects to increase the laser power per module to 2500 W. In addition, this supplier demonstrated multiplexing of three lasers to realize 3 kW of laser power. The supplier believes that even higher power can be achieved by multiplexing. Reliable CO₂ lasers with a continuous output of 10 to 20 kW are commercially available. However, they must be switched to produce the desired pulse shapes. A 30 to 40% switching efficiency is expected for these lasers. An 8-kW pulsed CO₂ laser in continuous wave (CW) mode with a 20-ns pulse width and 100-KHz operation,³⁰ and a 12-KW laser in burst mode, are available.²⁹ Continuous performance improvement over the last few years means that 10+ kW class CO₂ lasers will be available in the near future. Fiber lasers have the advantage of the best wall-plug-to-laser-light efficiency, and they allow ease of multiplexing. However, the power of these lasers remains only ~100 W today. A laser power density of 1×10^{11} W/cm² is now believed to be optimum for generating Sn LPP plasmas with Nd:YAG lasers. This was recently demonstrated in experiments⁶⁵ by scanning Sn targets through the minimal focus of a laser beam (with a maximum intensity of 1×10^{12} W/cm²), which produced double peaks that correspond to CE maxima.⁷³ Experimental and modeling efforts are underway to understand these power density limits and develop ways to achieve the maximum CE for Sn LPP.⁷³ Experimental and modeling results indicate that the required optimum laser power density increases with decreasing laser wavelength.¹⁰

3.4.2.3.2.2 Xe LPP Assuming 15 kW is the highest feasible laser power that can be made available, Xe LPP technology has the potential to deliver a minimum of 60 W of power at the IF. Due to the low CE of Xe fuel (similar to that in Xe DPP), this technology is not expected to deliver the power required for EUV sources in HVM. Currently, no commercial supplier is developing this technology for EUV sources. For Xe LPP with 2.5-kW Nd:YAG lasers, a Xe jet target, and 0.8% CE, one supplier has measured 9.1 W of power at the source and is expected to collect 2 W at the IF.²⁰ A second supplier, using a 1.2-kW Nd:YAG laser, a Xe droplet target, and 1% CE, measured 12 W at the source.¹⁹ A third supplier, using a 1-kW Nd:YAG laser and Xe jet, has measured 0.8% CE and 8 W at the source. A combined laser system has also been demonstrated, with 0.5% CE and 3 kW, and 15 W measured at the source.²¹ Additional information on this technology can be found in Ref. 4.

3.4.2.3.2.3 Sn LPP Due to its higher efficiency, Sn is also favored as a fuel in LPP EUV sources. Initial experiments have shown CEs of 4 to 5% with droplet targets for CO₂ laser pulses.²⁹ One supplier has reported an estimated power of 100 W in burst mode and 5 W of average power.²⁹ Another supplier of a rotating Sn plate target and 6 kW of CE for a CO₂ laser has reported measured power of 16 W at the IF with a 1-sr collector.⁷⁴ Today the estimated collection efficiency for LPP system is 11%, but progress in collector design and improved SPF will increase that to 33%. This means that for a 15-kW laser, up to 149 W of power can be obtained at the IF for Sn LPP. In summary, the remaining technical challenges for Sn LPP technology are laser power, debris mitigation, and collector lifetime. Although good progress has been shown in Sn LPP-based EUV sources, long-term performance of an integrated system is needed to increase confidence in this technology.

3.4.3 Source components and their lifetimes

An important factor in the viability of EUV sources is the lifetimes of their components. Electrode lifetime is important for DPP, and collector lifetime is important for both DPP and LPP.

Critical component lifetime is measured as the number of pulses that a component can accept without its performance degrading to an unacceptable level. For collectors, up to a 10% loss of reflectivity is acceptable.⁷⁴ For electrodes, choosing lifetime measurement criteria is not straightforward. A loss of 10% power in the source has been proposed as a criterion for replacing electrodes.⁷⁵ Previously, scanner suppliers had lifetime requirements for components of 30,000 h tied to cleanliness requirements for sources. Later, however, these suppliers clarified this requirement by stating that the lifetime of critical components will be decided by the CoO.⁷⁴ This means that if collectors and electrodes can be cost-effectively replaced with an acceptable component cost, down time, and requalification time, the lifetime of the source components can be lowered. This is good news for source suppliers, since the lifetime of 30,000 h could be a showstopper for EUV sources.³⁰ Because there are no widely accepted CoO models of EUV sources for EUV scanners today, an agreement was reached between scanner manufacturers and source suppliers in an industry forum on this topic.³ Currently, the general guideline for lifetime requirements (Table 3.1) of an alpha tool operating at 2 kHz is 1 month or 10 billion pulses; the lifetime of a beta tool operating at 5 kHz is 3 months or 10 billion pulses; and the lifetime of a production tool is 12 months or 80 billion pulses.

As mentioned in Sec. 3.4.3.2.1, electrode lifetime in Xe DPP is limited primarily by thermal load and sputtering. Today, for Xe DPP for microscanners, the electrode lifetime is >500 million pulses for the cathode and >4 billion pulses for the anode.⁴⁹ A much higher electrode lifetime of 10 billion pulses was previously projected for another design of Xe DPP.⁶⁶ Continued improvement in electrode lifetime can be expected.

For Sn DPP, an electrode lifetime is no longer an issue due to the use of rotating electrodes with regenerating Sn surfaces.⁶⁸ This electrode design has also addressed the thermal management issue for electrodes, and the supplier projects that up to 100 kW of thermal load can be handled by its electrodes.

The cost and time to replace electrodes are lesser issues than the collector lifetime. Collector lifetime is generally measured with a sample made of collector materials using measurements of its reflectivity over time or a quartz crystal microbalance (QCM).¹⁹ For Xe DPP, lifetimes of 1 billion pulses have been demonstrated, and a range of 5 to 10 billion is expected.¹⁹ With effective debris mitigation, collector lifetime for Sn DPP may be addressed. The supplier has shown a lifetime of 1 billion pulses and expects a 10 billion-pulse lifetime.

The geometrical arrangement in Sn LPP allows for a large collection angle; however, this geometry does not allow debris mitigation devices (e.g., a foil trap) between the source and the collector. By using alternative debris mitigation technologies and a large number of sacrificial layers on ML collectors, a lifetime of 100 billion pulses has been projected for Sn LPP collectors. Since LPP operates at $10\times$ frequency, effective lifetime projections are comparable to those made for Sn DPP.

The collector lifetime is the second leading challenge, after source power, to the implementation of EUVL. It appears that eventually this will be a CoO issue and not a potential showstopper for EUV sources.

3.5 Summary and Future Outlook

Today, Sn DPP technology is the leading technology for supporting high power EUV sources for alpha level scanners; sources based on this technology can deliver up to 8 W of power at the IF in continuous mode and twice this amount in burst mode. Based on 30 kW of maximum input power and an increased CE of 3%, Sn DPP can be expected to deliver up to 150 W of power at the IF, provided the thermal load can be managed and the collection efficiency can be increased to 17%. Based on present data on Sn debris mitigation efficiency and an estimated collector lifetime of 10 billion pulses, further improvement in collector lifetime will be needed to meet HVM goals. The existing technical challenges facing Sn DPP EUV sources include thermal management of the entire system and continued progress in debris mitigation and collector lifetime. Without this progress, further power scaling for Sn DPP cannot be achieved.

Xe fuel is not expected to deliver the required power for HVM by either DPP or LPP technology. However, Xe DPP sources will continue to be used in METs and alpha-level scanners, with continued increase in their reliability.

For LPP technology in general, high-power lasers are the leading technical challenge and a potential showstopper. Sn LPP technology has the advantage of

potential power scaling; however, an integrated system must first be demonstrated to increase confidence in this technology.

References

1. *International Technology Roadmap for Semiconductors* (ITRS), SEMATECH, Inc. Available at <http://www.sematech.org>.
2. K. Ota, Y. Watanabe, V. Banine, and H. Franken, "EUV source requirements for EUV lithography," Chapter 1.2 in *EUV Sources for Lithography*, V. Bakshi, Ed., SPIE Press, Bellingham, WA (2005).
3. V. Bakshi, "EUV Source Technology Status," in *IEUVI Source TWG*, Sapporo, Japan (Nov. 2007). Proc. available at <http://www.ieuvi.org>.
4. V. Bakshi, Ed., *EUV Sources for Lithography*, SPIE Press, Bellingham, WA (2005).
5. Summary of EUVL CoO calculations by P. Seidel and V. Bakshi from "EUV source technology status," EUV Source Workshop Summary, Baltimore, MD (May 2007). Proc. available at <http://www.sematech.org>.
6. K. Kemp and S. Wurm, EUV Lithography, *C. R. Physique* **7**, 875–886 (2006).
7. S. Wurm, "Outlook: EUVL Manufacturing Insertion," *Solid State Technology*, October 2006.
8. K. N. Koshelev, et al., "Radiative collapse in Z pinches," Chapter 6 in *EUV Sources for Lithography*, V. Bakshi, Ed., SPIE Press, Bellingham, WA (2005).
9. M. Al-Rabban, M. Richardson, H. Scott, et al., "Modeling LPP sources," Chapter 10 in *EUV Sources for Lithography*, V. Bakshi, Ed., SPIE Press, Bellingham, WA (2005).
10. K. Nishihara, A. Sasaki, A. Sunahara, et al., "Conversion efficiency of LPP sources," Chapter 11 in *EUV Sources for Lithography*, V. Bakshi, Ed., SPIE Press, Bellingham, WA (2005).
11. S. A. van der Westen, C. Bruineman, F. Bijkerk, and V. Bakshi, "Flying Circus 2 (FC2): Calibration of an extreme ultraviolet (EUV) source at PLEX LLC," *ISMT Technology Transfer Report #04024490A-TR* (April 2, 2004). Available at <http://www.sematech.org>.
12. A. Hassanein, V. Sizyuk, V. Tolkach, et al., "Simulation of DPP/LPP hydrodynamics and radiation transport for EUV," presented at the EUVL Symposium, Miyazaki, Japan (Nov. 2005). Proc. available at <http://www.sematech.org>.
13. R. Spitzer, T. Orzechowski, D. Phillion, R. Kauffman, and C. Cerjan, "Conversion efficiencies from laser-produced plasmas in the extreme ultraviolet regime," *J. Appl. Phys.* **79**, 2251–2258 (1996).
14. J. D. Gillaspay, "Atomic xenon data," Chapter 2.1 in *EUV Sources for Lithography*, V. Bakshi, Ed., SPIE Press, Bellingham, WA (2005).
15. Section III (Plasma Pinch Sources) and Section IV (Laser Produced Plasma Sources) in *EUV Sources for Lithography*, V. Bakshi, Ed., SPIE Press, Bellingham, WA (2005).

16. V. Bakshi, J. Gillaspay, and B. Rice, "EUV modeling source workshop summary," presented at the EUV Source Workshop, Antwerp, Belgium (Sep. 28, 2003). Proc. available at <http://www.sematech.org>.
17. I. Fomenkov, et al., "Progress in development of a high power source for EUV lithography," presented at the EUV Source Workshop, Miyazaki, Japan (Nov. 5, 2004). Proc. edited by V. Bakshi.
18. J. Pankert, "Philips's EUV source: Main messages," presented at the EUV Source Workshop, Miyazaki, Japan (Nov. 6, 2004). Proc. edited by V. Bakshi.
19. U. Stamm, "EUV source development at XTREME technologies: An update," presented at the EUV Source Workshop, San Jose, CA (Feb. 27, 2005). Proc. edited by V. Bakshi.
20. A. Endo, "Performance and concepts of EUVA LPP and GDPP technologies," presented at the EUV Source Workshop, San Jose, CA (Feb. 27, 2005). Proc. edited by V. Bakshi.
21. S. Ellwi, "Performance of kilowatt-class laser modules in scaling up laser produced plasma (LPP) EUV source," presented at the EUV Source Workshop, San Jose, CA (Feb. 27, 2005). Proc. edited by V. Bakshi.
22. H. Milchberg, "Modeling laser heating of condensed xenon and extreme ultra-violet (EUV) emissions," *ISMT Technology Transfer Report #04024496A-TR* (April 2, 2004).
23. U. Stamm, "EUV source development at XTREME technologies: An update," presented at the EUV Source Workshop, Miyazaki, Japan (Nov. 6, 2004). Proc. edited by V. Bakshi.
24. I. Yu. Tolstikhina, S. S. Churilov, A. N. Ryabtsev, and K. N. Koshelev, "Atomic tin data," Chapter 2.2 in *EUV Sources for Lithography*, V. Bakshi, Ed., SPIE Press, Bellingham, WA (2005).
25. A. Cummings, G. O'Sullivan, P. Dunne, et al., "Conversion efficiency of a laser-produced Sn plasma at 13.5 nm, simulated with a one-dimensional hydrodynamics model and treated as a multi-component blackbody," *J. Physics D: Appl. Phys.* **38**, 604–616 (2005).
26. J. Pankert, "Philips EUV results and roadmap," presented at the EUV Source Workshop, Santa Clara, CA (Feb. 22, 2004). Proc. edited by V. Bakshi.
27. J. Pankert, "Status of Philips Extreme's EUV source," *Proc. SPIE* **5374**, 152–159 (2004).
28. J. Pankert, "Philips EUV source: Update and issues," presented at the EUV Source Workshop, San Jose, CA (Feb. 27, 2005). Proc. edited by V. Bakshi.
29. D. C. Brandt, I. V. Fomenkov, N. R. Böwering, et al., "LPP source development for HVM EUV lithography," presented at the EUVL Symposium, Sapporo, Japan (Nov. 2007). Proc. available at <http://www.sematech.org>.
30. A. Endo, H. Hoshino, T. Suganuma, et al., "Laser produced plasma light source for HVM-EUVL," presented at the EUVL Symposium, Sapporo, Japan (Nov. 2007). Proc. available at <http://www.sematech.org>.

31. M. McGeoch, "PLEX source update," presented at the EUV Source Workshop, San Jose, CA (Feb. 27, 2005). Proc. edited by V. Bakshi.
32. M. A. Klosner, H. A. Bender, W. T. Silfvast, and J. J. Rocca, "Intense plasma discharge source at 13.5 nm for extreme-ultraviolet lithography," *Opt. Lett.* **22**(1), 34–36 (Jan. 1997).
33. W. Partlo, I. Fomenkov, R. Olive, and D. Birx, "Development of an EUVL (13.5 nm) light source employing a dense plasma focus in lithium vapor," *Proc. SPIE* **3997**, 136–156 (2000).
34. P. Naughton, Freescale Semiconductors, private communication.
35. W. Worth, International SEMATECH Manufacturing Initiative (ISMI), private communication.
36. D. Brandt, Cymer, private communication.
37. M. Gower, Exitech, private communication.
38. H. Kanazawa, M. Amemiya, K. Fujimoto, J. Ito, and Y. Watanabe, "EUV source evaluation at intermediate focus," presented at the EUVL Symposium, Miyazaki, Japan (Nov. 2004). Proc. available at <http://www.sematech.org>.
39. T. Missalla and M. Schurmann, "Characterization of intermediate focus," presented at the EUV Source Workshop, San Jose, CA (Feb. 2004).
40. L. Schmaenok, "Intermediate focus metrology development results," presented at the EUV Source Workshop, San Jose, CA (Feb. 2004).
41. N. R. Böwering, I. V. Fomenkov, B. A. M. Hansson, et al., "Measurement of EUV radiation at the intermediate focus," presented at the EUV Source Workshop, San Diego, CA (Nov. 10, 2005).
42. S. A. van der Westen, R. de Bruijn, F. Bijkerk, and V. Bakshi, "Flying Circus 2 milestone #2 report: Diagnostic performance," ISMT Technology Transfer Report **#03044396A-ENG** (May 9, 2003).
43. S. A. van der Westen, R. de Bruijn, F. Bijkerk, et al., "Cross-calibration of extreme ultraviolet (EUV) energy sensors," ISMT Technology Transfer Report **#04024498A-TR** (April 2, 2004).
44. S. Grantham, "EUV source metrology for EUV source development," *SEMATECH Technology Transfer Report* **#04024494A**, available at <http://www.sematech.org> (2004).
45. L. A. Shmaenok, N. N. Salashchenko, N. I. Chkhalo, et al., "Multilayer based instrumentation developments for EUVL source metrology," presented at the EUV Source Workshop, Santa Clara, CA (Feb. 23, 2003).
46. P. Marczuk, "EUV collectors: Design, development, fabrication and testing," *Proc. SPIE* **5193**, 39–49 (2004).
47. P. Marczuk, "Collector optics for EUV lithography," presented at the EUV Source Workshop, Santa Clara, CA (Feb. 22, 2004).
48. B. Nikolaus, J. Kleinschmidt, D. Bolshukhin, et al., "Collector optics integration into medium power EUV source systems," presented at the EUVL Symposium, Barcelona, Spain (Oct. 2006). Proc. available at <http://www.sematech.org>.

49. M. Yoshioka, "Progress on DPP source development towards HVM," presented at the EUVL Symposium, Sapporo, Japan (Nov. 2007). Proc. available at <http://www.semtech.org>.
50. CXRO Web site (<http://www-cxro.lbl.gov>).
51. G. Derra, P. Zink, T. Krücken, A. Weber, and J. Pankert, "Tin delivery systems for gas discharge sources," presented at the EUV Source Workshop, San Jose, CA (Feb. 27, 2005).
52. Y. Watanabe, "Out of band radiation" (out-of band panel discussion presentation), EUV Source Workshop, Miyazaki, Japan (Nov. 5, 2004).
53. H. Kondo, "Out of band radiation" (out-of band panel discussion presentation), EUV Source Workshop, Miyazaki, Japan (Nov. 5, 2004).
54. U. Stamm, "Development of commercial EUV sources at XTREME Technologies—An update," presented at the EUV Source Workshop, Baltimore, MD (May 6, 2007).
55. L. Shmaenok, N. Salashchenko, V. I. Luchin, A. Ya. Lopatin, and N. N. Zybin, "Free-standing spectral purity filters," presented at the EUV Source Workshop, Barcelona, Spain (Oct. 19, 2006).
56. U. Stamm, et al., "EUV source power and lifetime: The most critical issues for EUV lithography," presented at SPIE's 29th Annual International Symposium on Microlithography, Santa Clara, CA (Feb. 22–27, 2004).
57. G. Derra and W. Singer, "Collection efficiency of EUV sources," *Proc. SPIE* **5037**, 728–741 (2003).
58. S. A. De Westen, C. Bruineman, E. Louis, et al., "FC Flying Circus 2: Status and update," presented at the EUV Source Workshop, Santa Clara, CA (Feb. 2004).
59. F. Bijkerk, et al., "FC2 project status and metrology survey," presented at the EUV Source Workshop, Santa Clara, CA, (Feb. 23, 2003). Proc. edited by V. Bakshi.
60. M. Goldstein and V. Bakshi, "Optical Design for Affordable EUV Lithography," presented at EUVL Symposium, Sapporo, Japan (Nov. 2007). Proc. available at <http://www.semtech.org>.
61. R. Brainard, K. Dean, and T. Koehler, "EUV resist performance trade-offs," presented at the EUV Source Workshop, San Jose, CA (Feb. 27, 2005). Proc. edited by V. Bakshi.
62. A. M. Goethals, G. F. Lorusso, R. Jonckheere, et al., "Progress in full field EUV lithography program at IMEC," presented at the EUVL Symposium, Sapporo, Japan (Nov. 2007). Proc. available at <http://www.semtech.org>.
63. K. Dean and S. Tedesco, report to the IEUVI International EUV Initiative Resist Technical Working Group, Sapporo, Japan (Nov. 1, 2007). Proc. available at <http://www.ieuvi.org>.
64. H. Meiling, H. Meijer, V. Banine, et al., "First performance results of the ASML alpha demo tool," *Proc. SPIE* **6151**, 615108 (2006).
65. I. Fomenkov et al., "Performance and properties of a high power light source for EUV Lithography," presented at the EUV Source Workshop, Santa Clara, CA (Feb. 22, 2004).

66. M. McGeoch, et al., "Star Pinch power and lifetime scaling," presented at the EUV Source Workshop, Santa Clara, CA (Feb. 22, 2004). Proc. edited by V. Bakshi.
67. K. Nishihara, "On the conversion efficiency of LPP-EUV light source," presented at the EUV Source Workshop, Santa Clara, CA (Feb. 22, 2004). Proc. edited by V. Bakshi.
68. M. Corthout, "Lessons learnt on Sn DPP sources in Alpha tool and the road to HVM," presented at the EUVL Symposium, Sapporo, Japan (Nov. 2007). Proc. available at <http://www.semtech.org>.
69. R. Moyer, et al., "Multi-kilowatt solid state lasers for extreme ultraviolet light sources," *HPAPP-5, Solid State and Diode Laser Technology Review* (2003).
70. D. Moyer, "Laser produced plasma EUV source program," presented at the EUV Source Workshop, Santa Clara, CA (Feb. 23, 2003). Proc. edited by V. Bakshi.
71. H. Shields, S. W. Fornaca, M. B. Petach, et al., "Xenon target performance characteristics for laser-produced plasma EUV sources," *Proc. SPIE* **4688**, 94–101 (2002).
72. R. H. Moyer, Northrop Grumman Corporation, private communication.
73. M. Richardson, C.-S. Koay, S. George, et al., "The tin-doped micro-droplet laser-plasma EUV source," presented at the 3rd International Symposium on EUV Lithography, Miyazaki, Japan (Nov. 1–5, 2004).
74. Y. Watanabe, "Joint requirements—ASML, Nikon, and Canon," presented at the EUV Source Workshop, Santa Clara, CA (Feb. 22, 2004).
75. V. Bakshi, "EUV source workshop summary," presented at the EUV Source Workshop, Antwerp, Belgium (Sep. 29, 2003). Proc. edited by V. Bakshi.



Vivek Bakshi is president of EUV Litho, Inc., an organization that he formed to promote EUV Lithography via workshops and courses. Previously, he was a senior member of the technical staff in SEMATECH's Lithography Division. In 1983 he received his MS in physics from the Indian Institute of Technology at Kanpur, India, and a PhD in physics from the University of Idaho in 1988. He also received an MS in Science and Technology Commercialization from the IC² Institute at the University of Texas at Austin in 1997. He did his postdoctoral work at the University of Texas at Austin, where he also held the position of Research Associate. He was a Visiting Assistant Professor at the University of Texas at Arlington for three years before joining SEMATECH in 1996. From 2003–2007 he lead EUV Source and EUV Source Metrology projects at SEMATECH. In his early days at SEMATECH he managed projects in the area of plasma etch, advanced process control, and 300-mm tool performance assessment. Dr. Bakshi has authored/co-authored over 125 technical publications, including book chapters and articles in peer-reviewed journals and trade publications. In addition to this volume, he's edited another book on EUV Lithography: *EUV Sources for Lithography* (SPIE Press, 2006). Contact e-mail: vivek.bakshi@euvlitho.com.

Chapter 2

EUV LLC: An Historical Perspective

Chuck Gwyn and Stefan Wurm

Contents

2.1	Introduction	56
2.1.1	Background	57
2.1.2	Need for a revolutionary approach	58
2.2	Formation of the LLC	59
2.2.1	Vision	59
2.2.2	Implementation	60
2.2.2.1	Business model	60
2.2.2.2	Goals and objectives	61
2.2.2.3	Resources	62
2.2.3	Organizational structure	62
2.2.3.1	Management board	62
2.2.3.2	EUV LLC office	63
2.2.3.3	Committees	63
2.2.3.4	Working groups	64
2.2.3.5	VNL	64
2.2.3.6	External advisory group coordination	65
2.2.3.6.1	Advisory board	65
2.2.3.6.2	SEMATECH/SIA coordination	65
2.2.3.7	Suppliers	66
2.3	Program Structure	66
2.3.1	Organization	67
2.3.2	Risk management	68
2.3.3	Reporting	69
2.3.3.1	Weekly meetings	69
2.3.3.2	Monthly and quarterly reviews	69
2.3.3.3	NGL review	70
2.3.3.4	International meetings	70
2.3.4	Documentation	70
2.3.4.1	White papers	70
2.3.4.2	Quarterly reports	70
2.3.4.3	Conference presentations and journal publications	70
2.3.4.4	Website	71

2.4 Program Results	72
2.4.1 Technical accomplishments	72
2.4.2 IP portfolio	76
2.4.3 Program statistics	76
2.4.4 Delays	77
2.4.4.1 Extension of DUV	78
2.4.4.2 Competitive technologies	78
2.4.4.3 Economic downturn	78
2.4.4.4 Industry indecision	79
2.5 Retrospective Observations	79
2.5.1 Improvements	79
2.5.1.1 Additional planning and slower ramp	79
2.5.1.2 Additional member company involvement	79
2.5.1.3 Additional semiconductor equipment manufacturing involvement	80
2.5.1.4 Supplier involvement	80
2.5.1.5 DOE support	80
2.5.1.6 Program termination	81
2.5.1.7 Missed opportunities	81
2.5.2 External issues	82
2.5.2.1 Washington D.C. involvement	82
2.5.2.2 CRADA negotiations	82
2.5.3 Benefits	83
2.5.3.1 VNL	83
2.5.3.2 Industry	83
2.6 Status of EUV Development at the End of LLC	84
2.6.1 Risk reduction	84
2.6.2 Industry involvement	85
2.7 Summary	85
Appendix A: Major Accomplishments of the EUV LLC Program	87
Appendix B: EUV LLC Program Patents	92
Acknowledgments	96
References	99

2.1 Introduction

The Extreme Ultraviolet Limited Liability Company (EUV LLC) was formed in 1997 to advance the R&D for EUV lithography. The company contracted with the Department of Energy (DOE) Virtual National Laboratories (VNL) consisting of Lawrence Berkeley, Lawrence Livermore and Sandia National Laboratories to accelerate the EUV technology development and to reduce the risks associated with developing manufacturing tools and transferring the technology to industry for commercialization. The program started as a three-year program and later was extended to six years.

It can be stated with a significant level of confidence that the EUV technology as applied to lithography would not be a future contender for IC manufacturing

if it had not been for the formation and pursuit of the technology by the LLC. EUVL research would have stopped within the U.S. in the 1997 time frame and the technology would not have provided a future manufacturing option.

The EUV LLC program demonstrated the viability of EUV lithography, reduced the commercialization risks for EUVL to an acceptable level, and enabled the following key accomplishments:

- Design and fabrication of a complete, integrated, full-field (24×32.5 mm), scanning, alpha-class lithography tool denoted as the Engineering Test Stand (ETS).
- Development and integration of computer-aided design methods to support thermal, dynamic, and vibration design and analysis of individual components, subsystems, and complete system operation.
- Development of a reflective EUV mask technology including multilayer (ML) coated, low thermal expansion material (LTEM) mask blanks complete with metrology, ML defect repair methods, patterning inspection, and repair processes.
- Implementation of EUV optics fabrication projects with industry to demonstrate continuous optics fabrication technology improvement and development of engineered MLs with capping layers to provide good reflectivity and stability.
- Demonstration of extensive EUV lithographic printing using extended deep ultraviolet (DUV) resists.
- Collection of over 150 domestic and foreign patents and numerous technical/trade secrets.

This chapter summarizes the initial EUV LLC program vision, history, successes, delays, and issues. Included are comments regarding changes that could have been made during the early phases of the program to improve technological success and commercial implementation.

2.1.1 Background

During the late 1990s, the semiconductor industry was rapidly growing, and companies were implementing aggressive plans to maintain or accelerate the technology for integrated circuits (IC) following Moore's law, e.g., doubling the number of transistors on an IC device every 18 months. Although extensions of conventional optical lithography methods using DUV light were expected to continue for printing dimensions below 100 nm, manufacturing projections indicated that a new lithography technology would be needed to print features < 70 nm without manufacturing throughput loss. Several technologies were pursued, including proximity x-ray, projection electron and ion beams, and shorter DUV wavelengths. EUVL using 13 to 14 nm EUV light was considered a promising technology, although many challenges had to be addressed before the technology could be considered mature

enough to be used in commercial lithography tools for manufacturing. These challenges included demonstrating a complete EUV tool with an illumination system consisting of a radiation source and condenser system, a reduction camera with precision ML-coated mirrors, defect-free reflective masks, an EUV-sensitive resist, metrology to support manufacturing and inspection of reticles, and non-EUV specific subsystems consisting of the focus and overlay systems, scanning mask and wafer stages, optics housing, wafer- and reticle-handling interfaces, robotics, and issues related to operating in the vacuum environment required for an EUVL tool.

As noted in Chapter 1, in 1988 imaging using x-ray wavelength light had been proposed by Hawryluk and Seppala¹ at the Lawrence Livermore National Laboratory (LLNL) and by Silfvast and Wood² at AT&T; and in 1989, the first imaging was demonstrated by Kinoshita, et al. at NTT.³ Continued work was pursued by AT&T and the U.S. national laboratories during the early 1990s, and many of the basic imaging concepts were demonstrated. During the mid-1990s, several industrial companies, including Intel, AMD, Ultratech, Tropel, JMAR, and others, partnered with the U.S. Department of Energy (DOE) national laboratories through cooperative research and development agreements (CRADAs) to study the semiconductor industry's possible use of 13-nm EUV light in lithography.

While the IC industry was expanding at a rapid rate during the mid-1990s, the DOE faced substantial budget reductions when the U.S. Congress eliminated programs it deemed unnecessary, especially R&D projects at the national laboratories that were not directly tied to weapons or defense programs. In addition, the national laboratories had gone through several voluntary reductions in work force. In 1996, the DOE decided to stop all work on the EUV program, including the projects that had been co-funded during the mid-1990s through CRADAs with the industrial companies. However, based on early lithographic demonstrations using EUV wavelengths at the DOE labs and in Japan, Intel decided that EUVL had sufficient potential to warrant continued R&D work. Since the DOE was discontinuing the program and personnel would be immediately assigned to other programs, there was an urgency to keep the R&D team together to maintain momentum. Therefore, in late 1996, Intel provided bridge funding to maintain the EUV research while a more extensive program was developed and CRADAs were signed with these three national laboratories: LLNL,⁴ Lawrence Berkeley National Laboratory (LBNL),⁵ and Sandia National Laboratory (SNL).⁶

2.1.2 Need for a revolutionary approach

The R&D necessary to successfully demonstrate EUVL was projected to be very expensive, much greater than any of the individual lithography equipment manufacturers could afford. This was especially true if the technology were to be made available by 2005, when a new lithography would be required to support IC manufacturing at the smaller features sizes predicted by the *International Technology Roadmap for Semiconductors* (ITRS).⁷ Early estimates by Intel and the

national laboratories indicated that a funding level of approximately \$60 million per year would be needed to maintain and accelerate the R&D program at the three national laboratories.

Even though a new start-up company could conceivably have been established to perform EUV R&D, the time to organize a company, acquire a facility, obtain and install equipment, and recruit experienced staff would have caused substantial delays. In addition, the urgency required an immediate decision and prevented a lengthy study of alternative methods of development. As a result, an Intel committee led by Gerry Parker, Intel Senior Vice President; John Carruthers, Director of Components Research at Intel; and Jack Salvador, Intel Legal Counsel, recommended the formation of a “virtual” company using the resources available at the national laboratories to continue the development of EUV technology.

2.2 Formation of the LLC

2.2.1 Vision

Intel’s initial vision for EUVL development, with input from each of the three DOE laboratories, involved establishing a virtual company called the EUV Limited Liability Company (EUV LLC) that would consist of a consortium of IC companies. The vision included obtaining funding for the company by selling shares of stock to IC companies that would manage the company and would share in the technology achievements. The EUV LLC would contract with the DOE laboratories, which were to be combined to form the Virtual National Laboratory (VNL), for a majority of the R&D related to demonstrating EUVL technology. In addition, the EUV LLC would develop partnerships to transfer the technology and intellectual property (IP) to the semiconductor equipment manufacturing companies to manufacture beta and production tools. In return for early access to the technology and IP licenses, the SEMs would provide rights of first refusal (ROFR) to the EUV LLC member companies for beta and production EUVL tools and would pay royalties to the EUV LLC for tools sold to non-LLC member companies. The EUV LLC would also establish joint development programs (JDPs) with other commercial companies to produce major components or subsystems for the lithography tools and the infrastructure for masks, resists, metrology tools, etc., to support EUVL in commercial IC manufacturing.

The EUV LLC would be responsible for obtaining funding and managing the program. Detailed goals and objectives would be established to accelerate the technology development and to reduce risks associated with developing manufacturing tools. The success of the virtual company in cooperatively funding an expensive project and accelerating the technology development and transfer to industry could provide a new paradigm for the future development of enabling technologies for high-technology industries.

Since one of the major technical objectives of the program was to accelerate the technology development and transfer the results to industry for commercialization,

the initial planning indicated a three-year development program beginning in 1997, with the transfer of the technology to commercialization in 2000–2001.

2.2.2 Implementation

The EUV LLC, under Intel leadership, was incorporated in late 1996; in April 1997, it signed a three-year CRADA with the VNL. Motorola and AMD joined the LLC as founding members. Subsequently, Micron, Infineon, and IBM joined the virtual company. Although the investment levels by the members varied, the organization achieved a major goal of providing broad IC industry support for EUVL.

The EUV LLC/VNL CRADA had at least three unique characteristics. First, a single CRADA with the VNL incorporated the resources of each of the three laboratories. Second, the CRADA was completely funded by private industry and did not contain any matching funds from the DOE. Third, the provisions of the CRADA gave the EUV LLC complete ownership of the IP developed within the program and the right to patent the IP. The DOE retained the right to use the technology, royalty-free, for use in defense applications.

2.2.2.1 Business model

The business model involved four organizational components—the EUV LLC, the VNL, SEMs, and suppliers—as shown in Fig. 2.1. The basic model involved the VNL providing research, development, and engineering, along with the EUV LLC providing program direction. In return for funding the technology development, IP was harvested from the VNL in the form of knowledge, U.S. and foreign patents, and other IP such as trade secrets consisting of technology learning. The IP and licenses were transferred to the SEMs and suppliers in return for early access to beta

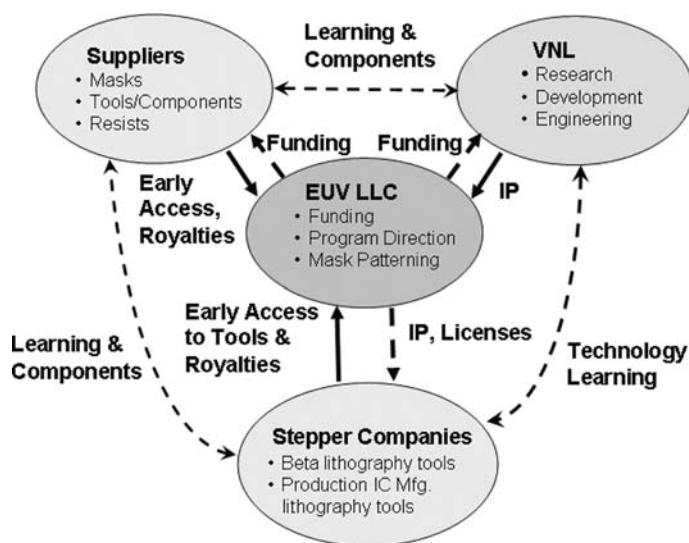


Figure 2.1 LLC business model showing the four major entities.

and production lithography tools and components, and royalty payments obtained from sales to nonmember companies. In addition to providing program funding, the EUV LLC provided program direction to the VNL and suppliers. Mask patterning technology was developed through separate agreements with the suppliers.

Funding was to be obtained by the sale of EUV LLC shares to the member companies at \$5,000,000 per share. Each share provided access to a beta or production lithography tool through a ROFR in the order that the shares were purchased. If a company did not exercise its ROFR, the right to purchase a tool was transferred to the next member in the priority sequence until the members' tool needs were satisfied. After the member companies had their development and manufacturing tools, the semiconductor equipment manufacturing companies could sell tools to nonmembers and transfer the royalties to the EUV LLC. The EUV LLC business model provided infrastructure suppliers with access to the technology and a use license with low upfront costs, small royalties based on sales, and ROFRs for EUV LLC member companies.

In late 1997, an agreement was signed with the first semiconductor equipment manufacturing company, Silicon Valley Group Lithography (SVGL), which was acquired in 2002 by ASML of The Netherlands, to participate in the program with the objective of developing beta and production tools to the EUV LLC members that were subject to ROFR assignments. In 1998, similar agreements were signed with ASML and United States Advanced Lithography (USAL).

The legal structure of the EUV LLC was flexible and allowed a corporate structure that was attractive to the various participants. When necessary, the structure was modified to accommodate changing issues and circumstances. The number and variety of EUV LLC members provided critical support to demonstrate the value of the program to the industrial community and to the U.S. government.

2.2.2.2 Goals and objectives

The EUV LLC program goals included the following:

- To facilitate research, development, and engineering, and enable SEMs to provide beta and early production exposure tools to support IC manufacturing by 2005;
- To design and fabricate an integrated scanning alpha exposure tool to provide EUV learning and early process development;
- To assist in the development of the supplier and process infrastructure to assure the availability of masks, optics, coatings, photoresists, EUV sources, and metrology for successful technology implementation in manufacturing.

A major underlying objective throughout the program was to reduce the risks associated with implementing a new lithography technology into manufacturing.

2.2.2.3 Resources

To the extent allowed by funding, the EUV LLC had access to almost unlimited resources through the VNL in a number of fields of expertise, including optics design, at-wavelength and visible wavelength metrology, ML engineering and deposition, vacuum engineering, precision engineering design and component fabrication, magnetic levitation stage design and fabrication, control software, and associated support technologies.

The decision to use the R&D resources at the DOE laboratories provided an optimum way to establish a virtual company with access to world-class talent in a very short period of time. The team that was assembled provided extensive background knowledge for EUV research, materials analysis, environmental issues, and metrology. In addition, the physical laboratories were already established for most of the initial work. If a new company had been formed, extensive delays would have been encountered in recruiting the required talent, locating and facilitating the laboratories, and establishing the management and support infrastructure. In addition, laboratory personnel were anxious to participate in a “new” nonconventional, industry-led R&D program.

In addition to the VNL, each member company selected specific projects for advanced internal work to enable the technology and to gain advanced development experience. Much of the work was envisioned to provide a working knowledge of the technology within the company and therefore to accelerate the transfer of EUV technology into manufacturing at the appropriate time.

The unique combination of expertise at the national laboratories could not have been found anywhere else, specifically in technology areas where SEMs had little or no experience. The industry expertise of the EUV LLC members provided the critical mass to succeed in demonstrating the complex, challenging EUV technology. This is most evident by comparing the EUV technology effort with competing next-generation lithography (NGL) technologies, which lacked resources required in science, engineering, and manpower to achieve the required critical investment.

2.2.3 Organizational structure

The EUV LLC organization consisted of a central business office, a management board, an advisory board, a number of coordinating committees and working groups, representatives from the SEMs and component and subsystem suppliers, and the VNL, as shown in Fig. 2.2. Although some of the key personnel changed during the five-year program, the figure includes the responsible personnel in the various positions at the end of the program in early 2003.

2.2.3.1 Management board

The management board, consisting of high-level representatives from each of the member companies and chaired by Intel Senior Vice President Sunlin Chou, was responsible for funding and overseeing the operation of the EUV LLC. The management board provided overall guidance for program objectives, budget, and

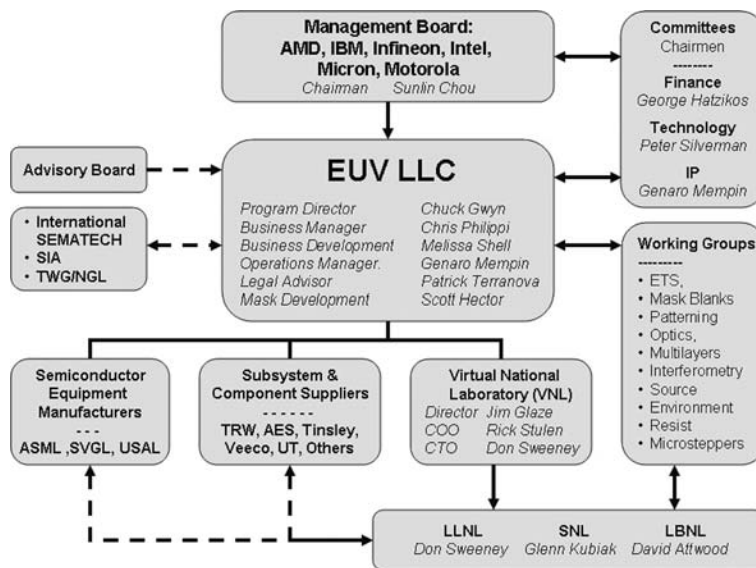


Figure 2.2 EUV LLC organizational structure with the committee chairpersons and staff positions at the end of the main program in early 2003. During the program extension, John Taylor (LLNL), John Goldsmith (SNL), and Erik Anderson (LBNL) provided management for the VNL.

spending plans and evaluated the technical progress of the program. Formal meetings were held monthly in Santa Clara, California, where technical progress was reviewed and business and supplier issues were discussed. Detailed reports were presented by the finance, technology, and IP committees.

2.2.3.2 EUV LLC office

The EUV LLC office was responsible for providing program direction, funding, resist evaluation, mask patterning, and process development. The EUV LLC office ran the daily operations using personnel from the member companies consisting of a program director, business manager, business development manager, operations manager, legal advisor, and mask development manager. The office held weekly project status meetings and scheduled and organized workshops, review meetings, and press meetings as required. The office director reported to the management board and provided all interfaces between the EUV LLC representatives and the VNL.

The EUV LLC member company assignees provided on-site management and support. EUV LLC team representatives participated in all working group meetings, assisted in technical analysis and design projects, and served as an industry sounding board for the laboratory staff.

2.2.3.3 Committees

The three key committees consisted of the finance, technology, and IP committees with the following responsibilities:

Finance: Tracked expenditures by the VNL, industrial subcontractors, and the EUV LLC operations office; reviewed proposed budgets; and solicited the sale of additional shares in the EUV LLC to meet budget requirements.

Technology: Identified technical goals and objectives; reviewed technical progress; allocated funding; and identified risks for each of the technical projects.

Intellectual Property (IP): Reviewed invention and technical advances by each of the VNL laboratories and classified the invention disclosure items for patent applications (either domestic or foreign or both) or as a trade secret.

Each committee contained one or more members from each of the EUV LLC member companies. They met monthly to discuss progress, status, and critical issues and to develop a set of action requirements (ARs) directed to the EUV LLC office or management board for follow-up.

2.2.3.4 Working groups

Working groups were established in all of the key technology areas:

- Engineering Test Stand (ETS)
- mask blanks
- mask patterning
- optics design and fabrication
- ML coatings
- interferometry (visible and at-wavelength)
- EUV source development
- operational environment
- photoresist development and evaluation
- microsteppers

Additional working groups or subgroups were formed as needed to address other key issues and were dissolved when the problems were solved.

2.2.3.5 VNL

The VNL consisted of the combined activities of the three DOE laboratories plus an overall management team consisting of a director, chief operations officer, and chief technical officer. This team was responsible for oversight of the work at the three laboratories and for directing the work through the program managers at each of the laboratories. The VNL team was responsible for developing detailed program plans, including schedules and the work breakdown structure, to accomplish the program objectives established by the EUV LLC. Each of the laboratories and the VNL management team held regular weekly and monthly program management meetings. The VNL team was also responsible for planning, organizing, and preparing the quarterly, full-day program review meetings. Although interlaboratory teams worked on some projects, R&D was divided among the three

laboratories as follows: LBNL was responsible for EUV interferometry of individual optics and projection optics (PO) boxes for microexposure tools (METs) and ETS PO boxes, defect inspection and analysis, and EUV scattering; LLNL was responsible for optics design, ML coatings, mask blanks, visible light metrology of optics and PO boxes, PO box engineering, and condenser design; and SNL was responsible for systems engineering, environmental controls, source development, 10×-reduction microstepper experiments, modeling, and resist development.

2.2.3.6 External advisory group coordination

In addition to guidance provided by the member companies, the EUV LLC sought advice from external organizations on program directions, political issues, and management input.

2.2.3.6.1 Advisory board The advisory board consisted of key representatives from industrial and government agencies. The advisory board membership consisted of representatives from the following:

- The six EUV LLC member companies: AMD, IBM, Infineon, Intel, Micron, and Motorola;
- Nonmember IC companies: Texas Instruments and Lucent;
- Six U.S. government agencies: the DOE, the Department of Defense (DOD),⁸ the Defense Advanced Research Projects Agency (DARPA),⁹ the Office of the Director of Defense Research & Engineering (DDR&E),¹⁰ the Department of Commerce (DOC),¹¹ and the National Institute for Standards and Technology (NIST);¹²
- The VNL;
- International SEMATECH (now called just SEMATECH, which is how it will be referred to throughout this chapter);¹³
- The Semiconductor Industry Association (SIA),¹⁴ and
- The Semiconductor Research Corporation (SRC).¹⁵

The purpose of the advisory board was to critique the broad technical progress and objectives of the EUV LLC and to provide feedback to the EUV LLC on its assessment of overall program progress, schedules, potential political issues and interactions, and possible conflicts that should be addressed. Voluntary help was also solicited from specific members of the advisory board to help mitigate potential issues within various government agencies.

2.2.3.6.2 SEMATECH/SIA coordination The SEMATECH and SIA organizations held semiannual NGL review meetings that were attended by industry, university, and government personnel. Their objective was to evaluate the progress toward developing several potential advanced lithography technologies to be used by the IC industry and to select the NGL technology at the appropriate time. The

potential lithography technologies included proximity x-ray, electron-beam projection lithography (EPL), ion-beam projection lithography (IPL), 157 nm, and EUV. Each of these technologies faced a number of potential showstoppers and issues that needed to be resolved before the industry could implement the technology into a manufacturing tool. The technologies were competing for funding and against a timeline to become the technology of choice by the industry, and SEMATECH provided the evaluation forum. In addition, SEMATECH provided funding support for critical industrial and university projects.

2.2.3.7 Suppliers

The initial SEMs consisted of SVGL, ASML, and USAL. Although invited to participate in design reviews and working groups, Nikon and Canon were not invited to join as official EUV LLC-sponsored SEMs because of U.S. government restrictions on foreign participation. The SEMs were responsible for developing beta and production lithography tools using R&D from the EUV LLC program.

Joint development agreements (JDAs) and contracts were established with several companies, including TRW, Tinsley, Veeco, AES, Ultratech, and others to develop EUV sources, optics, and ML coating tools. Initial agreements involved the development of a 1.5-kW laser by TRW, advanced ML coating tools by Veeco, advanced optics polishing and manufacture by Tinsley, source hardware by AES, and magnetic stage components by Ultratech. These companies were involved in specific working groups and participated in the quarterly reviews.

The rigid restrictions imposed by CRADA Article XXII caused problems for foreign suppliers because they were required to demonstrate a U.S. benefit. This requirement tended to discourage normal commercial interactions between these suppliers and the VNL. The early failure to recognize that the U.S. government would prevent the EUV LLC from licensing lithography suppliers in Japan prevented the development of a robust competitive environment for the development of EUVL. Addressing this issue early in the program is one area in which the EUV LLC could have been more successful.

2.3 Program Structure

The initial EUV LLC overall program objective was to develop enabling EUVL technology to increase knowledge and reduce the risks for suppliers who were developing beta stepper/scanners in 2004 and production tools in 2006. This objective focused on three areas: (1) technology development for a laser-produced plasma (LPP) source, precision ML-coated optics, defect-free mask blanks, and supporting metrology; (2) design and fabrication of the ETS to demonstrate full-field imaging using a 0.1-numerical aperture (NA), 4 $\times$ magnification system with the equivalent EUV flux for a 10-wafer/hour throughput (200-mm wafers); and (3) development of supporting technologies for mask patterning, resist development/evaluation, and microstepper experiments.

2.3.1 Organization

The technical program was divided into seven major tasks with subtasks to support the overall program objectives (see Table 2.1). Each of the tasks was assigned to program managers at specific laboratories within the VNL, and a detailed work breakdown structure was developed that described the schedule, resources, and activities to be performed. Microsoft Project software was used for planning and documentation.

Table 2.1 EUV LLC program tasks.

Major task		Subtasks	
1	EUV Optics	1.1	EUV optic design
		1.2	Projection optics substrates
		1.3	Mounted projection optics
		1.4	Projection optics box
		1.5	Condenser optics substrates
2	ML Coating	2.1	ML coatings reflective improvement
		2.2	ML stress and substrate effects
		2.3	Uniform graded coatings
		2.4	ETS coatings samples evaluation
		2.5	Mo ₂ C/Si coatings
		2.6	Mo/Be reflectivity optimization
		2.7	Deposition equipment upgrades and controls
		2.8	Projection optics coating facilities
		2.9	Condenser coating facilities
		2.10	Other optics coatings
3	Metrology	3.1	100-pm phase-shifting point diffraction interferometer (PSPDI)
		3.2	Reflectometry and scattering
		3.3	At-wavelength interferometry
		3.4	At-wavelength defect inspection
4	Masks	4.1	150-mm reflection mask substrates
		4.2	Low defect deposition (LDD) tool facility
		4.3	150-mm mask blanks with < 0.1 defects/cm ²
		4.4	Defect reduction in EUVL mask blanks
		4.5	Defect smoothing and repair for EUVL mask blanks
5	EUV Source	5.1	Advanced source for ETS illuminator
		5.2	Discharge source
		5.3	ETS illuminator
6	Resist	6.1	10× microsteppers
		6.2	Resist, imaging and processing
7	ETS	7.1	PO box integration
		7.2	ETS illuminator
		7.3	ETS system, body and robotics
		7.4	ETS environment
		7.5	Stage subsystem
		7.6	Control subsystem
		7.7	System modeling
		7.8	System design environment

2.3.2 Risk management

Formal risk management was imposed early in the program for all technical and business areas. A rank-ordered list of technical and interaction risks that could delay or prevent completion of the R&D and timely commercialization of the technology was developed for each major technology area. The R&D risks were associated with technical issues or problems that needed to be solved. The interaction risks included intermeshing the individual technical accomplishments by the different teams into a composite schedule and specific team interface issues that needed to be addressed early in the development schedule to assure simultaneous completion of critical elements of the program. Interaction risks also included issues that needed to be addressed with the industry partners associated with the technology commercialization.

The formal risk-reduction process involved five distinct steps: (1) identifying the technical or implementation risks for each task both from a top-down and bottom-up approach by the teams involved; (2) scoring each risk according to scores listed in Table 2.2 and prioritizing the issues; (3) developing action plans to reduce each risk; (4) tracking and reporting progress in reducing the risks; and (5) repeating the process by refining the risk list through modification, elimination, or addition of a new risk.

Each of the risks was listed on a “score card” by each of the working groups and scored on a three-point system according to solution status or schedule impact. Later in the program, half-point scoring was incorporated to recognize progress in reducing the risks, as shown in Table 2.2. The individual working group lists were combined into a high-level list of risks to designate the top 15 to 20 risks. These lists were reviewed and updated at the quarterly reviews. The entire risk list for subprojects frequently contained several hundred items at the lowest level of the hierarchy.

During the formal quarterly reviews, a risk scorecard was presented for each project. The scorecard listed each specific risk and briefly described the issues and progress associated with that risk. Numerical scores were summarized for each risk. During each review, the current scores were compared with the previous review scores to measure the level of progress, and a target date was established to indicate when the risk needed to be resolved. Color coding was used to emphasize any lack of progress and the severity of the risk within the program.

Table 2.2 EUV LLC risk level definitions.

Risk level	Designation
1.0	Problem defined (no solution identified)
1.5	Possible solution identified, research and development being performed
2.0	Basic solution in development
2.5	Solution demonstrated
3.0	Proven solution or supplier engaged for commercialization

2.3.3 Reporting

Aggressive program management methods and oversight were provided by the industrial partners. In addition to developing a detailed work breakdown structure for all aspects of the program, the VNL set detailed milestones and deliverable schedules. Auxiliary goals were established to coincide with technical presentations at conferences to highlight EUV progress and to increase industry awareness and interest in the technology. Once the decision was made to report on EUVL advances and to directly compete with the other NGL technologies at the SEMATECH/SIA NGL meetings, additional milestones were established to demonstrate the technology advances at those NGL meetings and to demonstrate progress toward resolving the critical issues defined by the NGL task force.

The high level of program visibility provided at technical conferences, leadership by Intel, and program progress generated good press coverage in the technical journals and general news publications. Over 100 press and news articles enabled various interest groups within the political and industrial communities to identify with the program and support it for their own success.

2.3.3.1 Weekly meetings

Status update meetings for the program managers and EUV LLC representatives were held weekly in the EUV LLC office at SNL in Livermore, California. Call-in options were available for the EUV LCC members who could not attend the meeting and for managers who were traveling. Key technical and business highlights were discussed and appropriate actions were identified to address problem areas. Five- to ten-page written reports summarizing activities in the EUV LLC office, technical highlights within the VNL, plans, and required actions were published weekly and distributed to approximately 60 EUV LLC representatives and VNL program managers.

2.3.3.2 Monthly and quarterly reviews

Formal reviews were presented each month to the technology committee. In addition to providing updates on critical issues, specific topic presentations were provided by key technical personnel on an as-requested basis. Also, business and IP issues were discussed at the regular monthly committee meetings.

Formal eight-hour quarterly reviews were held at an off-site hotel in Pleasanton, California. These reviews were attended by approximately 80 representatives from member companies, suppliers, and VNL personnel. Besides reviews at each meeting of general technical progress in key areas like the ETS design and fabrication, other topics were reviewed at alternating meetings to ensure in-depth coverage of all aspects of the program. During each review, attendees identified action items for attention during the next quarter. Copies of all foils used in the presentations were provided to the attendees.

2.3.3.3 NGL review

Annual technology status reports were presented at the SEMATECH NGL technology reviews. Critical issues and potential showstopper problems were identified by the attendees for action by the EUV LLC/VNL.

2.3.3.4 International meetings

The EUV LLC, working with SEMATECH and ASET,¹⁶ established an Annual International EUV Workshop that was held each autumn.¹⁷ The first workshop was held on October 13, 1999, in Monterey, California, with succeeding workshops rotating among the U.S., Europe, and Japan. Progress in developing the EUV technology was reported worldwide; separate international coordinating meetings and workshops were held for various topics in conjunction with the workshop.

2.3.4 Documentation

A variety of reporting mechanisms were used to document the program results, including monthly committee meetings and weekly status meetings. Minutes were written for all meetings and distributed to the EUV LLC members and interested EUV LLC managers.

2.3.4.1 White papers

In response to SEMATECH requests, several white papers were published during the early phases of the program to summarize the technology status and challenges. These 200-page reports introduced the technology; outlined the program organization; and documented the technical progress, remaining problems, cost of ownership model, and plans for resolving the remaining technical issues.

2.3.4.2 Quarterly reports

Formal quarterly reports were prepared by the VNL program and project managers. These reports discussed the technical projects in detail, including problem areas, and disclosed possible inventions to be considered for patents or trade-secret classification.

2.3.4.3 Conference presentations and journal publications

The program supported the presentation of technical results at national and international conferences and the publication of articles in technical periodicals. This motivated laboratory research personnel and generated good public relations for the program. A formal process was used to review proposed presentations and publications. During the six-year EUV LLC program, the review committees examined 590 abstracts and papers, as shown in Fig. 2.3, and provided feedback to the authors to improve the quality of material recommended for presentation or publication. A large majority of the proposals was recommended for publication.

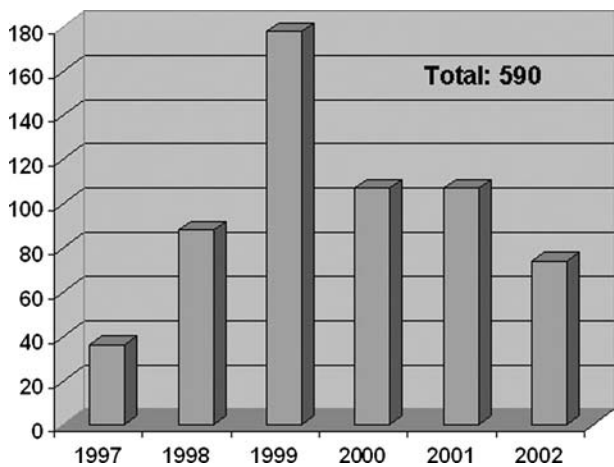


Figure 2.3 Abstracts and papers reviewed by the EUV LLC review committee.

Table 2.3 Representative conferences and journals.

Conferences	Journals
American Society for Precision Engineering	<i>Applied Physics Letters</i>
Applied Optics	<i>American Society for Precision Engineering</i>
Annual International Symposium on Microlithography	<i>Future Fab International</i>
Conference of Photopolymer Science and Technology	<i>Encyclopedia of Optical Engineering</i>
International Conference on Electron, Ion, and Photon Beam Technology and Nanofabrication (EIPBN)	<i>Information Science and Technology</i>
First International EUV Lithography Symposium	<i>Japanese Journal of Applied Physics</i>
IEEE Lithography Workshop	<i>Japanese Society of Applied Physics</i>
International Optics Design Conference	<i>Journal of Applied Physics</i>
International EUVL Workshop	<i>Journal of the Optical Society of America</i>
International Symposium of VLSI Technology	<i>Journal of Synchrotron Radiation</i>
Microprocessors and Nanotechnology	<i>Journal of Vacuum Science and Technology</i>
Optical Society of America	<i>Material Research Society</i>
Photomask Technology BACUS	<i>Micro and Nano Engineering</i>
Semicon West	<i>Optical Engineering Magazine</i>
	<i>Optics Communications</i>
	<i>Physics of X-ray Multilayer Structures</i>
	<i>Review of Scientific Instruments</i>
	<i>Science and Technology Review</i>

Table 2.3 is a representative list of the conferences and journals that contain EUV articles by the VNL and EUV LLC personnel from 1997 to 2003.

2.3.4.4 Website

Midway through the program, a password-controlled website was established for the EUV LLC member companies and VNL personnel. The site contained copies

of the foils presented at the quarterly reviews, minutes from the working groups, selected abstracts and written versions of published papers, calendars, and personnel listings with contact information. It also provided access to reference material, and in many instances the foils and illustrations from the site were used by the EUV LLC member company personnel to prepare presentations at their facilities.

2.4 Program Results

2.4.1 Technical accomplishments

By most measures, the program accomplished every technical goal established by the EUV LLC by providing excellent technology advances and an enormous amount of technical information.

One major goal was to design and fabricate an integrated full-field (24×32.5 mm) 0.1-NA scanning lithography tool that demonstrated all aspects of EUV technology, including the EUV source, optical collection and focusing system, synchronized scanning stages, environmental control system, and computer control complete with low-defect reflective masks. This lithography system, the Engineering Test Stand (ETS), is shown in Figs. 2.4 through 2.8 along with representative images in Fig. 2.9.

One highly significant measure of the success of the EUV LLC program is that no technical surprises have been uncovered during the commercialization of EUV technology. This is in strong contrast to the experience of other NGL technologies in which major showstoppers were uncovered. For example, the development of 157-nm lithography failed because of the late discovery of CaF_2 birefringence.

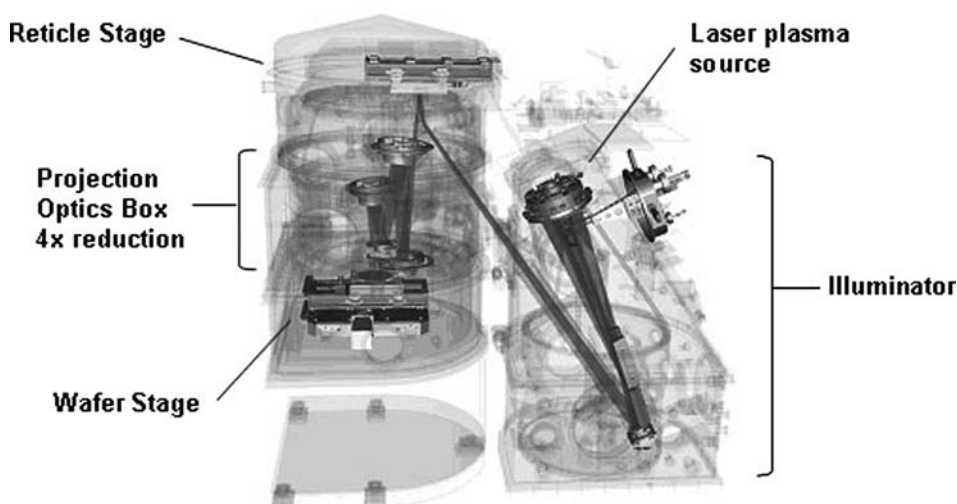


Figure 2.4 Schematic drawing of the optics path in the ETS identifying major system components. (Reprinted with permission from Intel.)

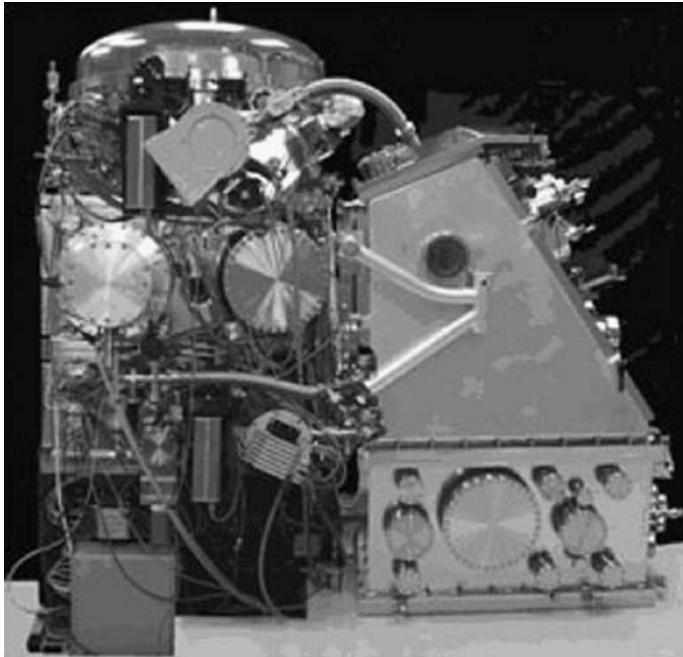


Figure 2.5 Initial assembly of ETS illuminator and wafer exposure chambers. (Reprinted with permission from Intel.)



Figure 2.6 Right-side view of fully assembled ETS showing the source chamber and wafer exposure chambers with associated control and utility connections. (Reprinted with permission from Intel.)

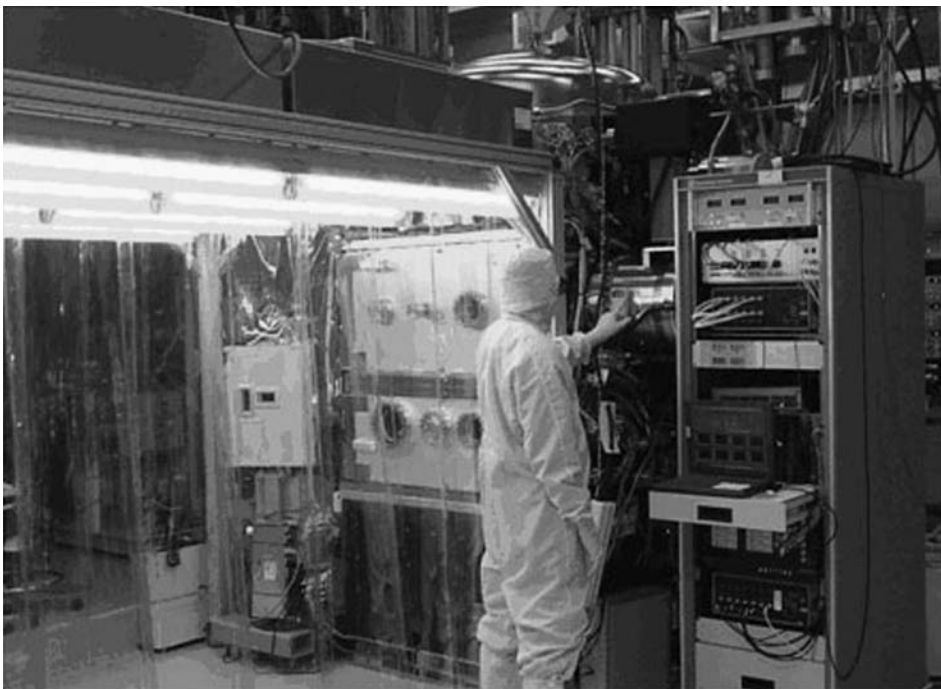


Figure 2.7 Front view of the completed ETS showing the wafer exposure chamber. (Reprinted with permission from Intel.)



Figure 2.8 Control console for the ETS with graphic displays to control the wafer exposure and monitor the status of the LPP source, condenser, and PO flux systems. (Reprinted with permission from Intel.)

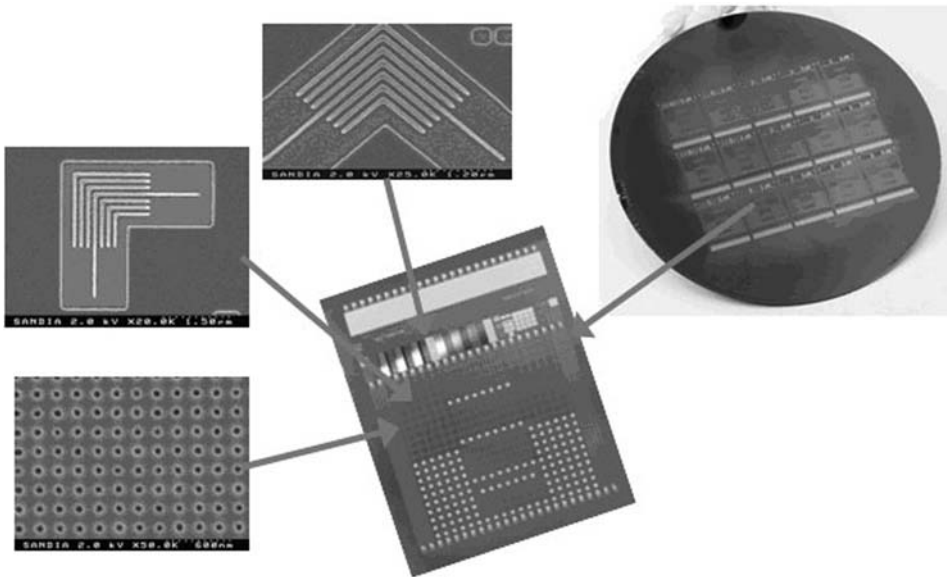


Figure 2.9 Representative printed test patterns and wafer obtained using the ETS. (Reprinted with permission from Intel.)

A detailed description of the EUVL technology development status in 2003, reflecting the signature contributions made by the EUV LLC/VNL, has been given in Ref. 18. Most of the technical program accomplishments are summarized in Appendix A. Highlights of the program include the following:

- Designed and fabricated a complete, integrated, full-field (24×32.5 mm), scanning alpha-class lithography tool, the ETS, complete with a computer-controlled system;
- Pioneered the development of both LPP sources and electrical discharge-produced plasma (DPP) sources;
- Developed and integrated computer-aided design methods to support thermal, dynamic, and vibration design and analysis of individual components, subsystems, and complete system operation;
- Developed reflective EUV mask technology, including ML-coated low thermal expansion material (LTEM) mask blanks complete with metrology, ML defect repair methods, patterning inspection, and repair processes;
- Implemented EUV optics fabrication projects with the industry to demonstrate continuous improvement in optics fabrication technology;
- Developed and engineered MLs with capping layers to provide good reflectivity and stability;
- Pioneered environmental mitigation techniques to maintain PO box optics in pristine conditions, and pioneered optics cleaning technologies to remove carbon and oxide from optics surfaces;
- Demonstrated extensive EUVL printing using extended DUV resists;

- Obtained SEMATECH support for the infrastructure technology;
- Provided formal program management and reporting; and
- Reviewed and collected over 300 IP items, including ~150 awarded or pending patents and numerous technical/trade secrets.

2.4.2 IP portfolio

During the development of the initial EUV LLC concept, a key decision was to capture an extensive IP portfolio from the work at the VNL and the member companies. This goal did two things: (1) it supported assembling a large patent portfolio for use by suppliers, and (2) it minimized the possibility that a single development organization would capture blocking IP that could inhibit or prevent efficient implementation of the technology. Individual VNL researchers were encouraged to disclose new ideas, and a formal VNL team of consultants was established to process the disclosures and develop the formal patent applications. Because of differences within the DOE management structure for the different laboratories (University of California versus Lockheed Martin), monetary IP disclosure incentives were provided only to SNL personnel. As patents were awarded, individual plaques were presented to each of the inventors at the quarterly reviews. Figure 2.10 summarizes the number of IP disclosures processed over time. Over 300 disclosures were reviewed; of this total, 145 were selected for patent filings, 17 were classified as copyright material, 116 were classified as CRADA-protected, and 22 were classified as trade secrets. Pending and awarded patents are listed in Appendix B. In several instances, multiple patents were awarded based on the initial disclosure.

2.4.3 Program statistics

During the six-year program, the EUV LLC's funding and manpower investment was responsible for substantial EUVL technical progress. The external investment

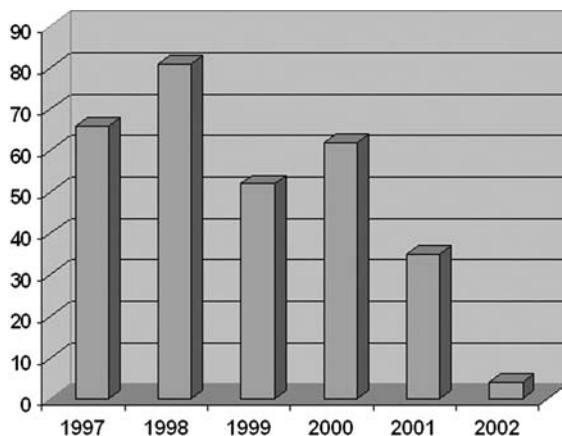


Figure 2.10 Number of processed IP disclosures.

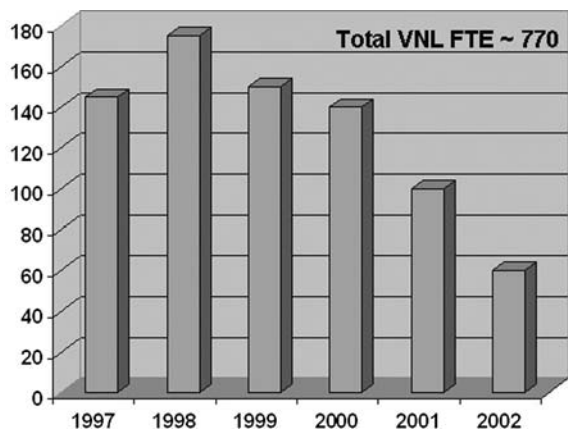


Figure 2.11 VNL personnel working on the EUV LLC program.

Table 2.4 Key program statistics.

Agreement	Three-year CRADA signed in 1997; extended twice for a total of six years
Financial investment	Over \$270M invested by the EUV LLC (~\$250M with the VNL)
Personnel	Total personnel included 387 at VNL and 160 at member companies
Risk issues	>400 risk issues tracked
Publications and presentations	600 publications and presentations (> 38 meetings/publications)
Quarterly reviews	24 quarterly reviews
Meetings	~250 weekly status update meetings; hundreds of working group meetings
Critical reviews	10 SEMATECH NGL critical reviews
Facility tours	~100 facility and laboratory tours and company reviews
Press	> 100 press articles
Documentation	3 white papers
	24 quarterly reports
	280 EUV LLC weekly reports (1400 pages)
	850 VNL weekly highlights
	~10,000 viewgraphs

by the EUV LLC in VNL and supplier-sponsored projects was well over \$270 million, including technical and management support. The full-time equivalent (FTE) personnel assigned to the program each year by the VNL are shown in Fig. 2.11. Some of the program statistics are summarized in Table 2.4.

2.4.4 Delays

In spite of the attractiveness of EUV technology and EUV LLC support, the technology encountered several implementation delays. Because of technology extensions, program delays, and the value of additional R&D to support EUVL, the CRADA with the VNL was extended initially for two additional years and then

subsequently for another three years (this later extension was terminated after 1½ years). These extensions provided a mechanism to continue the technology development as well as documentation and collection of IP. Some of the main reasons for the delays are discussed below.

2.4.4.1 Extension of DUV

One reason for the delay was a change in expectations for DUV technology: the expectations for existing DUV technologies were extended far beyond those of the mid-1990s, when EUVL was first proposed. Even though EUVL was first proposed for introduction at the 100-nm node, DUV is now expected to be the main technology, reaching down to the 45-nm half-pitch using water-based immersion technologies. Because the DUV extensions from 248-nm to 193-nm and 157-nm and then to immersion were viewed as simple extensions of the existing optical lithography, there was a widespread industry reluctance to divert resources to a new technology like EUVL. It has been estimated that the diversion caused by 157-nm technology, which was later proven unsatisfactory, caused at least a two-year delay in EUVL development. It is worth noting that the extensions of 248 nm and 193 nm were largely enabled by optical polishing and metrology technology, which was initially developed for EUV optics.

2.4.4.2 Competitive technologies

In addition to the 193-nm, 157-nm, and potentially 126-nm optical technologies, alternative IPL, EPL, and proximity x-ray lithography also had industry support as NGL technologies. Various alliances were established to support a specific technology—IBM and AT&T sponsored EPL, the Europeans focused on IPL, the EUV LLC championed EUVL, and Japan and separately IBM focused on proximity x-ray lithography. There was some disparity in the level of research and reporting for each of the technologies. The EUVL program reported technology challenges and risks in addition to technical progress, which gave EUV technology issues much higher visibility than problems with other technologies; consequently, risks for EUVL were often perceived as more severe. At various points during the program, EUVL issues such as optics finishing accuracy, the possibility of mask phase defects, critical dimension (CD) control, defect-free masks and mask costs, high source power, and high cost of ownership (CoO) were considered EUV technology showstoppers.

2.4.4.3 Economic downturn

Although the development of EUVL and other NGL technologies began in the mid-1990s when industry and technology advancement interests were high, the subsequent economic downturn caused many companies to delay investments in advanced lithography technologies. Economic fluctuations caused oscillations in the technology interest, the expected manufacturing insertion date, and development schedule, which also tended to increase costs. In addition, the projected high tool

cost, on the order of US\$25M, discouraged company commitments. Even though the cost was high by I-line and DUV standards, the projected cost was well in line with SEMATECH's predictions for an NGL technology based on the increasing cost trends associated with decreasing technology node dimensions and timelines.

2.4.4.4 Industry indecision

The lack of strong industry support for a specific NGL technology provided mixed messages for the manufacturing tool suppliers. Even though each technology had a strong sponsor, the levels of industry commitment varied. The semiconductor manufacturers' vacillation in making investments and the apparent lack of consensus for NGL technology caused the equipment development companies and their suppliers to delay the advanced investment required to establish the infrastructure, which led to additional cascading delays.

2.5 Retrospective Observations

Even though by most measures the EUV LLC program was very successful, activities could have been done differently in several areas.

2.5.1 Improvements

2.5.1.1 Additional planning and slower ramp

Because of the time pressures to implement the EUVL program, both to retain laboratory support and enthusiasm and to obtain industry support for the technology rather than other potential NGL technologies, the VNL program was scaled up during the first year from the minimal DOE investment to a higher level. As a result, various projects competed for personnel, and some projects were started prematurely. Later oscillations in funding resulted in personnel cutbacks with the accompanying reduction in morale. If more suppliers had been engaged before the program scaled up, and if a more uniform funding rate could have been supported, the funding could have been used more efficiently.

2.5.1.2 Additional member company involvement

Even though Intel deserves the major credit for starting and maintaining the program, an earlier, stronger marketing effort to enlist EUV LLC members could have had tremendous benefit. If all six members had been members of the EUV LLC before signing the CRADA, their influence could have been used with the government to modify the terms of the CRADA. In addition, a more unified investment by all members may have resulted in an increased interest in identifying technology problems, commercialization issues, and help in developing solutions for the problems. The early requirement for minimum percentage ownership in the EUV LLC, which was later removed, should have remained in effect in an attempt to provide more active participation. Even though a decision was made at the beginning of the

program to not count members' "in-kind" investments in the EUV LLC, perhaps an alternative "in-kind" investment with a specified number of on-site assignees could have helped ensure more active participation.

2.5.1.3 Additional semiconductor equipment manufacturing involvement

In retrospect, an ideal program could have been implemented differently. For example, a large investment was made to produce the ETS. A better investment would have been to develop the alpha tool for one of the stepper companies using VNL resources. For example, a partnership could have been developed with a single semiconductor equipment manufacturing company to use the VNL modeling, simulation, and design resources to develop its alpha tool. This would have involved a joint design by the semiconductor equipment manufacturing company and VNL engineers using VNL design tools. The alpha tool could have been assembled in off-site leased laboratory space in the Livermore area, which could have become a branch development center. Congruent with the alpha tool development, the semiconductor equipment manufacturing company could have refined the design (with SNL assistance) to build the beta or preproduction tool. Although a single semiconductor equipment manufacturing company is used as an example, with adequate planning several semiconductor equipment manufacturing companies could have bid on the alpha tool development, and the company offering the best support, business plan, and investment could have been awarded the VNL's support. In addition, since the total ETS investment was on the order of US\$100M, some funding assistance could have been provided to the semiconductor equipment manufacturing company in return for its active participation and assignment of on-site personnel. This approach also would have provided a good transition to ensure complete industry use and ownership of the tool after the VNL's formal program was completed.

The EUV LLC could have required more direct involvement by TRW/CEO to develop the LPP source at the VNL instead of in its facilities. In light of TRW/CEO's acquisition by Northrop Grumman in early 2003 and the subsequent decision to stop EUV source development work, this action would have protected some of the knowledge base for reapplication.

2.5.1.4 Supplier involvement

Suppliers were not as involved in the program as they could have been, resulting in less technology transfer and commercialization than planned. Varying levels of IC company interest discouraged suppliers from investing more aggressively. If suppliers had been more actively involved from the beginning and had assigned personnel on site at the VNL to be responsible for technology transfer and for providing inputs to the program on a continuing basis, more effort could have been directed toward solving the suppliers' specific problems.

2.5.1.5 DOE support

The laboratories' management always supported the program; however, the levels of support varied substantially during the six-year program. Initially, the program

had the attention of management at all levels, but the interest of new managers varied. In addition, several personnel were promoted during the program; some of the replacement personnel were more experienced than others and often the program results reflected those experience levels. During the later phases of the program, the DOE received substantial government support for homeland security. At this point, there was a lower level of interest in the EUV LLC contributions, and because of the internal competition for personnel within the laboratories and decreased funding from the EUV LLC, many of the pioneering EUV personnel left the program, creating gaps in the program expertise.

2.5.1.6 Program termination

The program termination could have been handled differently. Although the intent was to leave the EUVL research operations intact with an operating ETS for use by the VNL Resource Development Center (RDC), the transition did not go as smoothly as desired. First, even though SEMATECH funded a number of projects, the level of funding and difficulty in establishing formal projects resulted in smaller projects than the laboratories needed to maintain a critical resource base and support the technology development. Second, even though the VNL started a marketing program, the high VNL costs and the industry's ever-changing target for commercial implementation of EUVL discouraged suppliers from investing in VNL projects. Third, even though the EUV LLC companies purchased ETS usage shifts for their proprietary experiments, the shift subscriptions were not sufficient to guarantee the necessary support for the ETS for a full year. Instead, a compromise was made to operate the ETS for a partial year at a reduced level of support. This decision, coupled with the loss of key operating and engineering personnel, had a disastrous effect in early 2003 that resulted in operational errors and technical problems with EUV sources that could not be adequately solved. This experience with the ETS user facility was disappointing to the EUV LLC companies; most of them received fewer good operational shifts than purchased, and the imaging results were distorted by lack of experimental control. The net result was that the system was completely shut down at the end of June 2003 because of a lack of continuing demand by the EUV LLC members.

2.5.1.7 Missed opportunities

The VNL RDC user facility failed because the EUV LLC overestimated the technical readiness of the ETS to support a pilot line exposure service, and because the VNL underestimated the resources required to provide exposure to the ETS that could have retained current users and attracted potential new users. Many of the RDC problems were not EUV-specific and could have been avoided if, for example, the processing capabilities essential for the user facility had been integrated in a pilot line fashion. However, this would have required EUV LLC members to provide the personnel and material resources to run the RDC by themselves.

Another aspect of the RDC may have provided an even greater benefit than delivering exposed wafers to RDC customers: EUV technology learning. Although

EUV is an optical lithography technology, many of its subsystem technologies are different from those used in current 193-nm lithography tools. Significant learning could have been captured by running the ETS for customer use and by capturing and understanding all the EUV-specific problems in a systematic way. Semiconductor equipment manufacturing companies and EUV system subcomponent suppliers could have benefited from this learning.

2.5.2 External issues

2.5.2.1 Washington D.C. involvement

During the early phases of the program, the project generated conflicting interest within the Washington D.C. government agency community. The DOE supported the program as a demonstration of a large industry partnership and a continued focus on technology. The DOC interpreted the program as a way for foreign companies to gain access to leading U.S. technology from the national laboratories. This latter view was further emphasized by private company personnel visits to the Washington D.C. offices.

2.5.2.2 CRADA negotiations

Before the formal beginning of the program, additional time should have been spent to resolve CRADA issues. The IP patenting issue was resolved to the benefit of the EUV LLC in that the EUV LLC owns the titles to all patents, with certain use rights outside of lithography reserved by the DOE. This was a monumental accomplishment because CRADA participants generally obtain only a nonexclusive license. The issue of “net U.S. benefit” also should have been addressed more thoroughly before CRADA was signed. Since a large amount of political effort was invested to deal with some industry representatives and the DOC after signing CRADA, the time required to make a case for foreign involvement initially could have been a good investment. Perhaps a more complex partnership between the EUV LLC and Japan than with SVGL could have been proposed that would have provided a “net U.S. benefit” and supported competitive development.

Although time was urgent, in 1997 the EUV LLC was negotiating from a position of strength with a very anxious DOE in regard to implementing the program. Even though the DOE desired for this to be an industry-owned and supported program, the DOE may have been willing to provide some complementary or matching investment in related technologies (like metrology) to provide additional leverage for the EUV LLC funding. Although the DOE provided some overhead tax relief for capital purchases, they might have been willing to reduce other overhead rate charges or reduce the laboratory tax to extend the leverage of EUV LLC funding.

2.5.3 Benefits

2.5.3.1 VNL

The VNL obtained substantial benefit from the EUV LLC program. The program provided interesting research for its engineers and scientists and thus continued to build the knowledge base for the laboratories. It provided personnel with the opportunity to present and publish over 500 papers and to gain professional recognition, thus providing a good motivator for innovative research. The program exposed the laboratory personnel to industry management methods, cost controls, and daily environmental changes. It also gave the laboratories visibility within political, press, and industrial environments. The DOE highlighted the program as one of the most successful projects with industry, and in 2003, the VNL received an R&D 100 award for the design and fabrication of the ETS.

2.5.3.2 Industry

The EUV LLC program benefited industry in the form of proof-of-concept for EUVL system design and the fundamental engineering associated with using EUV for imaging. The SEMs benefited from the learning associated with optics fabrication and metrology by Tinsley and Zeiss, the vacuum materials qualification by VNL experiments, the environmental and contamination control methods (protection, mitigation, and thermophoresis) that were demonstrated, and the sensor development in such areas as dose control, thermal management, and optics alignment, which can be used in numerous areas of system design and fabrication. Basic development has also been done for specialized components such as spectral purity filters, sensors for various metrology applications, and standards for component performance and metrology. In addition, the basic development and value of modeling software for application, visualization, and analysis has been demonstrated as applied to system, subsystem, and component design.

For subsystem design, both the LPP and DPP sources have been characterized, and the scalability of each has been evaluated; PO box design, engineering, and fabrication have been demonstrated, and thermal management and alignment methods have been developed. Precision ML-coated optics have been fabricated by several suppliers. In other infrastructure areas such as mask blank fabrication with defect-free absorbers and buffer layers, and patterning with defect repair and inspection, the commercialization risks have been reduced.

Finally, for IC manufacturers, the proof-of-concept ETS demonstrated both small-field and scanned images, thus reducing the engineering risk associated with developing complete alpha and beta tools. The ETS provided imaging experiences that can be used to project the level of difficulty in adapting EUVL to a manufacturing environment. In addition, basic mask manufacturing methods were demonstrated along with the necessary metrology for inspecting the reticles. The extension of DUV resists was evaluated, and the importance of line edge roughness (LER) and sensitivity has been highlighted and categorized for small images.

In summary, many of the system engineering risks and the issues associated with implementing EUVL into manufacturing have been reduced.

The technology proof-of-concept, the EUV LLC business model that targeted enabling suppliers, and the SEMATECH/EUV LLC relationship enabled SEMATECH in 2003 to ramp up its effort to drive infrastructure readiness at a scale that was beyond the EUV LLC/VNL scope. A significant portion of the critical infrastructure efforts that enable EUV commercialization can trace their beginnings back to technology developed by the EUV LLC/VNL or through collaboration with suppliers and SEMATECH. Prominent among those are the SEMATECH Mask Blank Development Center¹⁹ and the SEMATECH EUV Resist Test Center²⁰, both in Albany, New York; the SEMATECH MET exposure tool²¹ and actinic inspection tool²² in Berkeley, California; EUV exposure and mask tools at IC manufacturers and captive²³ and merchant mask shops²⁴; and much of the EUV-specific metrology that has been adopted by companies and consortia around the world.

Last of all, the written reports and conference presentations and papers generated during the EUV LLC program captured the discoveries for use by all development organizations. In addition, the patents provide adequate protection for companies continuing to pursue EUVL R&D.

2.6 Status of EUV Development at the End of LLC

2.6.1 Risk reduction

As another method for describing the technical accomplishments of the EUV LLC program, several important technology risks and potential showstoppers for technology implementation were eliminated. Early answers to specific questions about system engineering and commercialization were resolved. Some of the risks and resolved showstoppers included the following:

- The manufacture of production-quality EUV optics with controlled figure and finish was demonstrated in at least three laboratories.
- Precision, low-stress, graded ML optical coatings were fabricated.
- Visible and at-wavelength metrologies were developed for optical fabrication and alignment.
- Low-defect reticle blanks were fabricated.
- The repair of reticle defects was demonstrated.
- Stable EUVL LPP and DPP sources were demonstrated.
- Extended DUV photoresists were developed, screened, and evaluated for LER and sensitivity.
- An EUVL alpha-tool was fabricated and its operation demonstrated.
- PO boxes were fabricated, and optics were fabricated, coated, and aligned.
- A system assembled with thermal control of all critical surfaces and imaging was demonstrated.

- Systems engineering risk reduction was demonstrated with module partitioning and characterization.
- Environment and contamination control was demonstrated with thermophoresis protection and mitigation.
- Dose, thermal, and alignment sensors were developed, evaluated, and characterized.
- Mask blanks were fabricated.
- Mask patterning processes (including absorbers, buffer layers, repair, and inspection) were demonstrated.
- Thermal management (methods and materials) was demonstrated in all system areas.
- Extensive modeling software for engineering, visualization, and analysis was developed.
- A library of materials and components was vacuum-tested and qualified.
- A vacuum system was designed.
- Wafer and reticle chucking (heat transfer, deformation, clamping) was demonstrated.
- Spectral purity filters were developed.
- Standards (reticles, MLs, etc.) were developed.

With EUV LLC and VNL support focused on solid technology progress, including reducing technology risks and eliminating technology showstoppers, EUVL technology was selected in 2001 as the technology of choice on the NGL roadmap for the 45-nm half-pitch and below.¹

2.6.2 Industry involvement

Before the involvement of the EUV LLC, the emphasis and work on EUV R&D had been limited to the DOE laboratories, AT&T, and a few universities. During the EUV LLC program, the level of interest and work expanded to a large number of companies, laboratories, and universities world-wide, largely in the U.S., Europe, and Japan. Most of the active participating organizations are listed in Table 2.5.

2.7 Summary

Although expensive, the EUV LLC program by most measures was very successful in terms of technical accomplishments, the unique management of a large program, the speed of implementation, the teamwork achieved between the VNL and industry representatives, and the consolidation of IP. If the program had not been initiated by Intel, it is very likely that all EUVL research would have been stopped, first at the DOE laboratories and later at AT&T, the only industrial organizations in the U.S. working on EUVL in 1997 and 1998. It is likely that the advanced lithography work in Japan would have continued to focus on proximity x-ray, and work

Table 2.5 Worldwide EUV interest at the end of 2003.

Companies	IC companies	Laboratories and universities	Consortia
ADE	AMD	Argonne National	United States
AERONEX	IBM	Laboratory	EUV LLC
ASML	Infineon	LBNL	SEMATECH
ASML Optics	Intel	LLNL	SRC
CEO	Micron	MIT ²⁵	VNL RDC
Conexant	Motorola	NIST	
Corning Inc.		NRL ²⁶	Europe
Corning Tropel Corp		SNL	IMEC ²⁷
Cymer		Colorado State University	LETI ²⁸
DuPont Photomask		University of California-	MEDEA+ ²⁹
Etec		Berkeley	PREUVE ³⁰
EUV Technology		University of Illinois	
Invax		University of Maryland	Japan
Janos Tech.		University of Nevada	ASET
JMAR		University of Texas	EUVA ³¹
KLA-Tencor		University of Wisconsin	AIST ³²
Luxel			
Opimax			
ORA			
Osmic			
Paragon Optics			
Photronics			
Plex LLC			
QED			
REO			
Rohwedder			
RTC LLC			
Schott-Lithotech			
Shibley			
Thermacore			
TRW			
Veeco			
Wave Optics			
ORA			

in Europe would have continued on IPL. Both Japan and Europe would have gradually discontinued the small amount of work on EUVL, and major EUV programs within ASET and MEDEA+ would not have been started. In 1997, the SEMATECH NGL task force relegated EUVL to fourth place behind x-ray, EPL, and IPL technologies, so without the EUV LLC program, there would have been no resurgence of interest in EUVL.

Given that both a focused EUVL program and private investment were needed, the path chosen to implement a virtual company using the national laboratories was an efficient and cost-effective approach. Although the VNL personnel and associated overhead costs were high, creating a new company or subsidiary with adequate facilities, equipment, and expert staff would have taken much longer and been far more expensive.

Finally, the technical accomplishments demonstrated EUVL with a full-field scanning prototype tool, resolved all major technology problems, and reduced the technology commercialization risks to an acceptable level. Even though the commercial implementation of the technology has taken longer than initially postulated, alpha EUVL tools have been fabricated by companies in Europe and Japan, and two alpha tools were delivered in 2006 with two additional deliveries of alpha tools planned for 2007. With the maturing of the EUVL infrastructure and the delivery of the first alpha tools by the SEMs, lithography experts expect EUVL to be the high volume manufacturing (HVM) technology for the 32 nm half-pitch and below.³³ In retrospect, with the benefit of six years worth of experience, the program could have been improved by

- Performing additional upfront planning and enlistment of IC company and suppliers support;
- Ramping up the initial program more slowly; and
- Obtaining more supplier industry involvement and buy-in early in the program.

The success of the virtual company in cooperatively funding an expensive project and accelerating the technology development with transfer to the industry could provide a new paradigm for the future development of enabling technologies for high-technology industries.

Appendix A: Major Accomplishments of the EUV LLC Program

Essentially all of the initial EUV LLC program objectives were met, and the EUVL technology was demonstrated, including the module development and system integration. Extensive learning was obtained during the program. Some of the many program accomplishments are detailed below:

- **Designed and fabricated a complete, integrated, full-field (24 × 32.5 mm), scanning, alpha class lithography tool denoted as the Engineering Test Stand (ETS)**
 - Low jitter, full-speed scanning maglev reticle and wafer stages for use in a vacuum environment.
 - Complete control system incorporating 15 controllers and over 430 components.
 - Environmentally engineered vacuum system to control the buildup of hydrocarbons and to control oxidation within the illuminator, PO box, and wafer and reticle zones.
 - Thermally and dynamically stable mechanical structure commensurate with the small tolerances needed to support sub-100-nm lithography.
 - Active cooling for optics and components in the illuminator to maintain thermal stability during system operation.

- Illuminator with a high-brightness laser, a variety of Xe target nozzles, a diffuser for unused target material recovery, debris mitigation, beam-shaping optics, thermal management, a spectral purity filter, and dose control. The diffuser was developed by Northrop Grumman Corp. but was not used in the ETS.
- PO box alignment using a two-step process with coordinate measuring machine optics positioning and a visible light interferometric measurement of the wavefront aberrations using an array of pinholes to guide fine adjustments of the mirrors for optimum alignment.
- Integrated exposure chamber with vibration isolation, a PO box, metrology trays, a focus system, reticle and wafer handlers, and reticle and wafer stage framework.
- Reticle and wafer handling system including electrostatic chucking, mechanical fixturing, and thermal control.
- Summary of typical facility requirements consistent with power, cooling, and environmental requirements, and analysis extensions for manufacturing use.
- Two interchangeable super Invar PO boxes with exact constraint optics mounting and active alignment, complete with an environmentally controlled shipping container.
- Precise system instrumentation with >120 temperature, flux, imaging, alignment, and dose sensors.
- Passive thermophoretic protection method for protecting masks from particulate contamination.
- System and component operating vacuum environmental requirements with methods for selecting acceptable materials and components, including testing and qualification.
- **Pioneered the development of two types of plasma sources**
 - LPP source with a variety of gas, cluster, liquid, and solid Xe targets with diffuser collectors.
 - High-power (1500 W, 5000 Hz) laser with TRW.
 - Capillary discharge source tube with debris mitigation and thermal management.
 - High-current pulse power supply for discharge source.
- **Developed and integrated computer-aided design methods to support thermal, dynamic, and vibrational design and analysis of individual components, subsystems, and complete system operation**
 - Design aids used to support module and subsystem partitioning and analysis to optimize system interfaces.
 - Finite element analysis with extensive dynamical, thermal, and lithography modeling and simulation.
 - Validated design methods with experimental confirmation of system and component operation.
 - Applied extensive visualization techniques to optimize the design process and minimize design errors.

- **Developed reflective EUV mask technology including ML-coated, LTEM mask blanks complete with metrology, ML defect repair methods, patterning inspection, and repair processes**
 - ML repair methods for phase and amplitude defects with Monte-Carlo analysis predicting mask blank yield as a function of defect type and location.
 - Metrology for quantifying mask blank flatness.
 - Defect smoothing methods for covering up to 70-nm substrate defects, thus minimizing metrology and defect-removal requirements.
 - Optimized reflective ML stack with absorber and buffer layers.
 - Evaluated a number of absorbers, including Ti, TiN, AlCu, Cr, TaSiN, TaSi, Ta, and TaN, with selection of Cr and TaN providing the best characteristics.
 - Provided framework for EUVL Semiconductor Equipment and Materials International (SEMI) standards, including wavelength, mask materials and format, reticle handling, chucking and clamping, allowable thermal and deformation tolerances, etc.
- **Implemented EUV optics fabrication project with industry to demonstrate continuous improvement in the fabrication technology**
 - Developed process for production-quality figure, mid-spatial-frequency roughness (MSFR), and high-spatial-frequency roughness (HSFR) polishing with Tinsley using flat and spherical samples.
 - Fabricated two sets of ETS mirrors, three sets of 0.1-NA, 10× microstep-per optics, and two sets of 0.3-NA, 5× MET optics with demonstrated continuous improvement.
 - Precision visible-light PSPDI metrology system with initial accuracy < 0.25-nm rms, with extension to lens-less system having 0.1-nm rms accuracy to support optics fabrication.
 - Successful championing and fabrication of only the clear aperture of large aspheric optics to reduce tool size and optic blank manufacturing requirements.
- **Developed engineered MLs with capping layers to provide good reflectivity and stability**
 - Developed two-ion-beam and one-magnetron ML deposition systems with Veeco.
 - Fundamental Mo-Si and Mo-Be ML data to support decision to not use Be because of toxicity and to focus on Mo-Si for worldwide use.
 - ML coating process to obtain a sample mask blank with a record low of 0.008 defects/cm² @ 60-nm defect size.
 - Achieved 70% reflectivity with six-month stability using stable capping layers.
 - Mo-Si with up to 70% reflectivity and less than 1% reflectivity loss with aging.
 - Ru capping layer to provide optimum ML stability by preventing oxidation.

- Evaluated accelerated aging methods to simulate EUV flux with an electron beam to provide the equivalent secondary electron density at the surface.
- Processes for depositing precision uniform and graded coatings for flat and aspheric surfaces.
- Reflectometer using synchrotron radiation to characterize ML reflectivity as a function of wavelength with benchmarking by Japan and Europe.
- Implemented at-wavelength interferometry, alignment, and defect inspection.
- Achieved at-wavelength ML coating uniformity measured to 0.05-nm rms.
- Precision control of ML deposition processes to permit accurate ML matching for mirrors and mask coated at different times.
- **Demonstrated EUVL printing**
 - Applied extended DUV resists.
 - Evaluated various optimized ML and absorber stack structures.
 - Characterized EUVL flare and development of methods to control flare.
 - Characterized horizontal/vertical printing bias caused by asymmetry of ETS illumination.
 - Performed extensive static imaging using the ETS PO box and synchrotron imaging system with variable illumination configurations (variable coherence disk, dipole, rotated dipole, off axis, and annular).
- **Demonstrated extended DUV resists**
 - Applied ultra-thin, pinhole-free resist process as a replacement for top-surface-imaged (TSI) resists.
 - Evaluated trade-offs between LER, sensitivity, and resolution.
 - Evaluated >100 resist formulations.
 - Benchmarked a 6-nm LER 3σ @ 2 mJ/cm² resist.
 - Established a standard method for measuring LER.
 - Performed shot-noise print analysis that indicated shot noise is not a problem below 32-nm half-pitch.
 - Developed support for EUV resist testing using the MET at LBNL.
- **Obtained SEMATECH support for infrastructure technologies**
 - Reduced risks and demonstrated sufficient development progress to gain acceptance of EUVL by the SEMATECH/SIA NGL Task Force as the lithography of choice for 45-nm half-pitch manufacturing.
 - Provided technology transfer to support the SEMATECH Mask Blank Development Center (MBDC).
 - Assisted with development of Statements of Work (SOWs) with deliverables for infrastructure and SEMATECH MBDC projects.
- **Implemented formal program management**
 - Detailed work breakdown with over 50 major project elements.
 - Technology and interaction risk identification, scoring, and reporting.
 - Formal working groups for each project with regular reporting.

- **Program reporting**

- Held 24 eight-hour quarterly reviews over six years with approximately 80 attendees present at each review from LLC companies, VNL, and suppliers.
- Wrote quarterly reports to summarize technical accomplishments, issues, and plans.
- Reviewed over 590 articles and abstracts for conference presentations and publications (over 40 different conferences and periodicals).
- Over 100 press articles in a variety of technical publications, newspapers, and world-wide journals
- Participated in 10 SEMATECH NGL critical reviews.
- Conducted numerous on-site laboratory tours and company reviews.
- 280 EUV LLC written weekly reports (~1400 pages) with 850 weekly highlights.
- Presented over 10,000 viewgraphs.
- Tracked more than 400 risk issues.
- Approximately 250 weekly status update meetings.

- **Reviewed and collected program intellectual property**

- IP committee met quarterly and reviewed over 300 items.
- IP committee decisions: obtain patents for 146 items; classify 116 items as CRADA-protected (processes and trade secrets); and copyright 17 items.
- As of December 31, 2003, 98 patents had been awarded and 51 were pending; several patent applications resulted in multiple patents and 16 were abandoned for various reasons.

- **Personnel participation**

- Over 770 FTE personnel years with a peak of 170 FTE's in 1998 and a minimum of 58 FTE's in 2002.
- Program participation by approximately 250 different personnel at the VNL.
- Program participation by over 160 different personnel at member companies.

- **Intangible program strengths demonstrated**

- Technical breadth and teamwork across VNL laboratories.
- Superb VNL team quality (technical expertise and innovation, ownership of problems and issues, dedication to completing milestones, leadership by managers).
- Accelerated EUVL progress as a result of the competition provided by other NGL technologies.
- Optimum blending of commercial and laboratory cultures.
- Growth of EUVL development from work by a few laboratories in 1997 to a worldwide effort involving over 100 industrial companies, universities, and laboratories in 2003.

Appendix B: EUV LLC Program Patents

The EUV LLC program developed numerous intellectual property items that were classified as patentable in the U.S. The following tables summarize the information for 150 U.S. patents that have been awarded and 38 that are still pending. In several cases, the items could be listed in more than one category.

Table B.1 Metrology patents.

Title	U.S. Patent
Null-Test Fourier Domain Alignment Technique for Phase-Shifting Point-Diffraction Interferometer	6,111,646
Phase Shifting Point Diffraction Interferometer Mask Designs	6,307,635
Phase-Shifting Point Diffraction Interferometer Grating Designs	6,195,169
Phase-Shifting Point Diffraction Interferometer Focus-Aid Enhanced Mask	6,151,115
Method and Apparatus for Interferometer At-Wavelength Distortion Measurement	6,559,952
Dual Domain Diffraction Interferometer	6,100,978
In-situ alignment system for Phase-Shifting Point-Diffraction Interferometry	6,118,535
Fourier-transform and global contrast interferometer alignment methods	6,239,878
Phase-Shifting Point Diffraction Interferometer Phase Grating Designs	6,266,147
Miniature Self-Contained Vacuum Compatible Electronic Imaging Microscope	6,327,102
Dual-Domain Lateral Shearing Interferometer	6,707,560
Extended Surface Parallel Coating Inspection Method	In process
Monolithic Pattern-Sensitive Detector	6,130,431
EUV Mirror-Based Absolute Incident Flux Detector	6,710,351
EUV Universal In-Band Detector	6,781,135
Linear-array EUV Dosimeter	6,906,781
Laser Detection of Carbon and Oxide Films on Mo/Si Multilayer Mirrors	In process

Table B.2 Optics patents.

Title	U.S. Patent
Interferometric At-wavelength Flare Characterization of EUV Optical Systems	6,233,056
Method of Fabricating Reflection-Mode EUV Diffraction Elements	6,392,792
Method of Fabricating Reflection-Mode EUV Diffusers	In process
Apparatus for Generating Partially Coherent Radiation	In process
Diffraction Optical Element for Extreme Ultraviolet Wavefront Control	In process
Reflective Optical Imaging System with Balanced Distortion	5,973,826
Reflective Optical Imaging System with Balanced Distortion	6,226,346
High Numerical Aperture Projection System for EUV Projection Lithography	6,072,852
Deformable Mirror for Short Wavelength Applications	5,986,795
Cleaning Process for EUVL Optical Substrates	5,958,143
Pedestal Substrate for Coated Optics	6,206,966
Compact Multi-bounce Projection System for EUV Projection Lithography	6,426,506
Projection Optics Box	6,147,818
High NA Ring-Field Projection System for EUVL	6,033,079
High NA Ring-Field Projection System for EUVL	6,183,095
High NA Ring-Field Projection System for EUVL	6,318,869
High NA Ring-Field Projection System for EUVL	6,188,513
High NA Ring-Field Projection System for EUVL	6,262,836

Table B.2 Continued.

Title	U.S. Patent
Correction of Localized Shape Errors on Optical Surfaces by Altering the Localized Density of Surface or Near-Surface Layers	6,844,272
Fabrication of Precision Optics using an Imbedded Reference Surface	Pending
Correcting surface contour of a non-rigid object through control of surface residual stress	Pending
Low-Cost Method for Producing Extreme Ultraviolet Lithography Optics	6,634,760
Figure Correction of Multilayer Coated Optics	In process
Surface Figure Control for Coated Optics	6,206,528

Table B.3 Multilayer patents.

Title	U.S. Patent
Method to Adjust Multilayer Film Stress Induced Deformation of Optics	6,011,646
High Reflectance-Low Stress Mo/Si Multilayer Reflective Coatings for Extreme Ultraviolet Lithography	6,110,607
Process for Fabricating High Reflectance-Low Stress Mo/Si Multilayer Reflective Coatings	6,309,705
Improved Method to Adjust Multilayer Film Stress Induced Deformation of Optics	6,134,049
A Post Deposition Method to Adjust the Reflectance Peak Position of an EUV Multilayer Mirror	In process
High Reflectance and Low Stress Mo ₂ C/Be Multilayers	6,229,652
Method and System for Producing Sputtered Thin Films with Sub-Angstrom Thickness Uniformity or Custom Thickness Gradients	6,524,449
Electrostatic Particle Trap for Ion-Beam Sputter Deposition	6,451,176
MoRu/Be Multilayers for EUV Applications	6,228,512
A Dynamic Mask for Producing Uniform or Graded-Thickness Thin Films	In process
Coatings on Reflective Mask Substrates	6,352,803
Method and System Using Power Modulation for Maskless Vapor Deposition of Spatially Graded Thin Film and Multilayer Coatings with Atomic-Level Precision and Accuracy	6,425,988
Proper Method for Measuring Beam Current in Ion Beam Processing	6,554,968
Ion Beam Collimating Grid to Reduce Added Defects in an Ion Beam Sputter Deposition (IBSD) Tool	6,521,897
Method and System Using Power Modulation and Velocity Modulation for Producing Sputtered Thin Films with Sub-Angstrom Thickness Uniformity or Custom Thickness Gradients	6,668,207
A Method for Modifying and Monitoring the Structure of a Thin Film with High Spatial Resolution Using Resistance Heating Through a Contacting Electrode Incorporated in a Scanning Probe Microscope	In process
Optimized Capping Layers for EUV Multilayers	In process
Optimized Capping Layers for EUV Multilayers	6,780,496
The Growth of Multi-Component Alloy Films with Controlled Graded Chemical Composition on Sub-Nanometer Scale	In process
Multilayer Films with Sharp, Stable Interfaces for Use in EUV and Soft X-Ray Applications	6,396,900
Use of Ion Beams for Protecting Substrates from Particulate Defect Contamination in Ultra-Low-Defect Coating Processes	In process
Method of Removing Carbon Contamination from EUV Multilayer Optics	In process

Table B.4 Environment patents.

Title	U.S. Patent
Protection of Lithographic Components from Particle Contamination	6,153,044
Method for Protection of Lithographic Components from Particle Contamination	6,253,464
Mitigation of Radiation Induced Surface Contamination	6,533,952
Process for Producing Radiation-Induced Self-Terminating Protective Coatings on a Substrate	6,231,930
A Self-Cleaning Optic for Extreme Ultraviolet Lithography	6,664,554
Apparatus for In-situ Cleaning of Carbon Contaminated Surfaces	6,772,776
Method for Protection of C1 Optics	In process
Apparatus and Method for Reducing Particle Contamination of Semiconductor Processing Tools	In process
Method for Reducing Carbon Contamination of Multilayer Mirrors	In process

Table B.5 Mask patents.

Title	U.S. Patent
Multi-level Scanning Method for Defect Inspection	6,484,306
Method and Apparatus for Inspecting Reflective Masks for Defects	6,555,828
Method and Apparatus for Inspecting an EUV Mask Blank	In process
Hybrid Shearing and Phase-Shifting Point Diffraction Interferometer	6,573,997
The Mitigation of Substrate Defects in Reticles Using Multilayer Buffer Layers	6,319,635
Compensation of flare-induced CD changes in photolithography	6,815,129
Repair of Phase Defects in EUVL Mask Blanks Using Spatially-Resolved, Enhanced Interdiffusion in the Multilayer Coatings	6,821,682
A Direct Write Technique for EUV Mask Fabrication to Produce Phase and/or Amplitude Modulation without a Patterned Absorber	6,635,391
Mitigation of Substrate Defects on Reflective Reticles Using Sequential Coating and Annealing	6,489,066
Method to Repair Localized Amplitude Defects in an EUV Lithography Mask Blank	In process
Compliant Layer Chucking Surface	In process
Etched-multilayer phase shifting masks for EUV lithography	6,875,543
Method for the Manufacture of Phase Shifting Masks for EUV Lithography	In process
Ion-assisted Deposition Technique for the Planarization of Topological Defects	In process
Mask Fabrication Process	6,015,640
Low Thermal Distortion Extreme-UV Lithography Reticle	6,316,150
Low Thermal Distortion Extreme-UV Lithography Reticle (Photolithography System)	6,441,885
Low Thermal Distortion Extreme-UV Lithography Reticle (Imaging Process)	6,395,455
Method for Mask Repair Using Defect Compensation	6,235,434
Method for Fabricating an Ultra-Low Expansion Mask Blank Having a Crystalline Silicon Layer	6,368,942
Removable Pellicle for Lithographic Mask Protection & Handling	6,492,067

Table B.6 ETS and illuminator patents.

Title	U.S. Patent
A Holographic Illuminator for Synchrotron Based Projection Lithography Systems	6,927,887
Synchrotron-based EUV Lithography Illuminator Simulator	6,768,567
Drive Electronics for a Programmable, High-Speed, 2-D Mirror Tilt Stage Component of a Coherence Controlling Illuminator	In process
Scanning Coherence Controlling Kohler Illuminator for Microfield Lithography Applications (Apparatus for generating partially coherent radiation)	In process
Condenser for Ring-Field DUV and EUV Lithography	6,186,632
Constant Volume Gas Cell Optical Phase Shifter	6,421,130
Condenser for Ring-Field DUV and EUV Lithography	6,398,374
Diffraction Element in Extreme-UV Lithography Condenser	6,118,577
Extreme-UV Lithography Condenser	6,210,865
Diffraction Element in Extreme-UV Lithography Condenser	6,285,497
Diffraction Spectral Filter for Use in Extreme-UV Lithography Condenser	6,469,827
Condenser for Extreme-UV Lithography with Discharge Source	6,285,737
Illumination System Having a Plurality of Movable Sources	6,396,068
EUVL Condenser with Micromirror Array	6,700,644
Sacrificial Multilayers for Lifetime Extension of the Plasma-facing Condenser Element in a Plasma-based Illuminator	In process

Table B.7 Source patents.

Title	U.S. Patent
Erosion Resistant Nozzles for Laser Plasma EUV Sources	6,011,267
Extreme-UV Electrical Discharge Source	6,356,618
Radiation Source with Shaped Emission	6,563,907
Electrode Configuration for Extreme-UV Electrical Discharge Source	6,498,832
Capillary Discharge Source	6,654,446
Discharge Source with Gas Curtain for Protecting Optics from Particles	In process
Fluid Jet Electric Discharge Source	In process
A Device for the Production of a Stable Liquid Stream from a Gaseous Source	In process
Method and Apparatus for Debris Mitigation for EUV Discharge Lamp	6,888,297
Efficient Narrow Spectral Width Soft X-Ray Discharge Sources	5,499,282
Configurations, Materials, and Wavelengths for EUV Lithium Plasma Discharge Lamps	5,963,616
Capillary Discharge EUV Lamp Source for EUV Microlithography and other Related Applications	6,031,241
Debris/Blocker Collector and Emission Enhancer for Discharge Sources	6,232,613
Adjustable Bore Capillary Discharge	6,576,917
Discharge Lamp Sources, Apparatus, and Methods	6,188,076
Erosion Resistant Nozzles for Laser Plasma EUV Sources	6,011,267

Table B.8 Lithography patents.

Title	U.S. Patent
Thin Layer Imaging Process for Microlithography Using Radiation at Strongly Attenuated Wavelengths	6,673,525

Table B.9 Miscellaneous patents.

Title	U.S. Patent
Graphical User Interface for Image Acquisition and Processing	6,341,183
Vacuum-Compatible, High-Speed, Programmable 2-D Mirror Tilt Stage	In process
Extreme-UV Lithography System	6,225,027
Method and Apparatus for Interferometer At-Wavelength Distortion Measurement	6,559,952
Precision Tip-Tilt-Piston Actuator That Provides Exact Constraint	5,986,827
Highly Damped Kinematic Coupling for Precision Instruments	6,325,351
Extreme Ultraviolet Lithography Machine	6,031,598
Wafer Chamber Having a Gas Curtain for Extreme-UV Lithography	6,198,792
Extreme-UV Lithography Vacuum Chamber Zone Seal	6,333,775
Extreme-UV Lithography Vacuum Chamber Zone Seal (Vacuum Apparatus)	6,545,745
Extreme-UV Lithography Vacuum Chamber Zone Seal (Photolithographic System)	6,549,264
Light Weight High-Stiffness Stage Platen	6,188,150
Refractory Bilayer Photoresist for EUVL	In process
Apparatus for In-situ Cleaning of Resist Outgassing Windows	6,192,897
Thermophoretic Vacuum Wand	6,072,157
Thermophoretic Vacuum Wand (Method)	6,232,578
Electrostatically Screened Voltage Controlled Electrostatic Chuck	6,169,652
Projection Lithography with Distortion Compensation Using Reticle Chuck Contouring	6,229,871
Extreme UV Scanning Wafer & Reticle Stages	6,353,271
Mask-to-Wafer Alignment Systems	6,642,995
Liquid Zone Seal	6,279,601
In-vacuum Exposure Shutter	In process
Motorized Support Jack	6,328,282
Portable Outgas Detection Apparatus	In process
Motorized Support Jack	6,561,486

Acknowledgments

The EUVL program was supported by a large number of dedicated scientists, engineers, and managers at the VNL and the EUV LLC. A list of over 500 personnel involved within these two organizations is presented below. In addition, many individual contributors at a number of component, subsystem, and exposure tool suppliers, SEMATECH, U.S. and foreign universities, and foreign associations provided invaluable contributions to the EUV LLC program and have not been listed. The EUV LLC is indebted for all or their contributions.

AMD: Ercan Adem, Scott Bell, Joffre Bernard, Jacques Bertrand, Daniel Collopy, Yunfei Deng, K. Early, Pat Gabella, Calvin Gabriel, Angela Hui, Paul King, Jongwook Kye, David Kyser, Bruno La Fontaine, Harry Levinson, Chris Lyons, Khanh Nguyen, Uzodinma Okoroanyanwu, Adam Pawloski, Khoi Phan, Christopher Pike, Marina Plat, Dick Roddy, Craig Sander, Natalie Sidarous, Bill Siegle, and Christy Woo.

IBM: Greg Gallatin, George Gomba, Emily Fisch, Bill Hinsberg, Frances Houle, C. Huang, Shukla Kapur, M. Lawliss, Michael Lercel, Ken Racette, Martha Sanchez, and C. Williams.

Infineon: Wolf-Dieter Domke, Albrecht Ehrmann, Stefan Hien, Stefan Hirscher, Rainer.Kaesmaier, Frank-Michael Kamm, Karl Kragler, Klaus Lowack, Andreas Oelmann, Michael Sebal, Siegfried Schwarzl, Andreas Wolter, and Stefan Wurm.

Intel: Craig Barrett, Jonathan Bird, Robert Bristol, John Bjorkholm, Yan Borodovsky, Mary-Ellin Brooks, Andy Bryant, Heidi Cao, Becky Carmona, John Caruthers, Manish Chandhok, Mung Chen, Sunlin Chou, Jerry Cullins, J. Dalin, Giang Dao, Rosanne Der, Mahooya Dinda, Youssef El-Mansy, Toni Fontaine, Dave Fraser, Bob Gasser, Paolo Gargini, Janice Golda, Michael Goldstein, Chuck Gwyn, Jai Hakhu, George Hatzikos, Howard High, Y.C. Huang, Kim Kalune, Chris Krautschik, John Lam, Sang Lee, Ted Liang, Barry Lieberman, Fu-Chang Lo, Andy Ma, Jerry Marcyk, Robert Meagley, Genaro Mempo, Angela McIntyre, Gordon Moore, Tony Martinez, Patrick Nash, Naomi Obinata, Maciek Orczyk, Eric Panning, Gerry Parker, Michael Penn, Chris Philippi, Graham Pugh, Venna Rao, Bryan Rice, Jeanette Roberts, Jack Salvador. Charles Scott, Melissa Shell, Peter Silverman, Kari Skoog, Chris Smith, Dorothy Snow, Alan Stivers, Brigitte Stoehr, Edita Tejnil, Pat Terranova, Pat Trocollo, Kenny Toh, Neil Wester, Rob Willoner, Manny Vara, Sandy Wilson, Pei Yang Yan, and Guojing Zhang.

Micron: Mark Durcan, Tony Krauth, and Bill Rericha.

Motorola: Nathan Bergman, Lester Casoose, Jonathan Cobb, D. Convey, Tony Cuellar, Anne Dinsmore, Eric Fanucchi, Fritz Fielding, Sang-In Han, Scott Hector, A. Hooper, Kevin Kemp, Bing Lu, Pawitter Mangat, Zorian Masnyj, Joe Mogab, Enrique Orci, Richie Peters, Victor Pol, Sergei Postnikov, Bernie Roman, Ken Smith, A. Talin, James Wasson, and Eric Weisbrod.

Lawrence Berkeley National Laboratory: Erik Anderson, David Attwood, Philip Batson, Raul Beguiristain, Matt Bjork, Jeffrey Bokor, John Bowers, Cynthia Bresloff, Patricia Butler, Daniel Chemla, Chang Cho, Jim Comins, Shannon Cristobal, Greg Denbeaux, Paul Denham, Kathleen Fuller, Kevin Geary, Kenneth Goldberg, Eric Gullikson, Tsuneyuki Haga, Kookye Harrison-Williams, Mary Holloway, Keith Jackson, Seongtae Jeong, Lewis Johnson, Benjamin Kaufmann, Ulf Kleiberg, Jim Knight, Mark Legros, Laura Luo, Wayne Mitchell, Stan Mrowka, Patrick Naulleau, Senajith Rekawa, Ron Sabaroff, Hank Sartorio, Farhad Salmassi, Ulrich Schlegel, Gerd Schnieder, Frank Scholz, Charles Shank, Michael Shumway, Ron Tackaberry, James Underwood, Jeff Wiener, Viviana Wolinsky, Moonsuk Yi, and Erik Ziegler.

Lawrence Livermore National Laboratory: Jennifer Alameda, Jay Ayers, Saša Bajt, Sherry Baker, Troy Barbee, Anton Barty, Kenneth Blaedel, Joel Bowers,

Butch Bradsher, Wayne Brocious, Scott Burkhart, E. Michael Campbell, Gene Campbell, Charles Cass, Nat Ceglio, Charlie Cerjan, Henry Chapman, Carl Chung, Orrin Cilly, Rosemarie Cortez-Kudo, Michael Crosley, Courtney Davidson, Todd Decker, Randy Del Chiaro, Tony DeSousa, Daren Dillon, Al Edge, Bruno La Fontaine, Andre Fernandez, Barbara Fox, Richard Freeman, Jim Folta, David Gaines, Curt Garrett, Jim Glaze, Fred Grabner, Daryl Grzybicki, Layton Hale, Linda Ely, Stefan Hau-Reige, Gary Heaton, Darrel Hogan, Gary Howe, Andy Hawryluk, Russell Hudyma, Randy Hurd, Steve Jensen, Mike Johnson, Don Kania, Patrick Kearney, Marcia Kellam, Brian Kelly, Robert Kent, Jeff Klingmann, Adam Krey, Steve Liapis, Cindy Larson, Colin Lau, Ming Lau, Benjamin Law, Rick Levesque, Walt Lindquist, Gary Loomis, Terry Malsbury, Raylene Miller, Paul Mirkarimi, Claude Montcalm, Craig Moore, Stanley Mrowka, Dave Mueller, Nhan Nguyen, Kenneth Olsen, Gary Otani, Jane Parish, Steven Patterson, Don Phillion, Shon Prisbrey, Christina Quin, Susan Ratti, Ton Reason, Ricke Behymer, Jeff Robinson, Ted Saito, Mark Schmidt, Lynn Seppala, David Shafer, Frank Snell, Gary Sommargren, Regina Soufli, James Spallas, Victor Sperry, Eberhard Spiller, Dan Stearns, Johanna Swan, Terry Swan, Don Sweeney, Hooman Tajbakhsh, John Taylor, Will Tong, Peter Thelin, Richard Thigpen, Karma Thomas, Alan Thompson, Shelia Vaidya, Lisa Vasco, Steve Vernon, Rodney Victorine, Shannon Ward, Chris Walton, Abbie Warrick, Marco Wedowski, Jeff Williams, Karl Wilhelmsen, and Gordon Yano.

Sandia National Laboratory: Omar Akkawi, Michael Eric Alford, Richard Anderson, Linda Armegio, Karelyn Baker, Leticia Baker, William P. Ballard, Patrick Barney, Pamela K. Barr, Vernon C. Barr, Walter Bauer, Kurt Berger, Al Ver Berkmoes, Luis J. Bernardez, Mark J. Bernstein, Terry Bersie, Eric Beyer, Kelly Bickford, Stephen Bosson, Freddie Bowie, Dan Bozman, Robert Brandt, Nathan Brough, Dean Buchenauer, Jennifer Burton, Richard Campiotti, Greg Cardinale, Troy Carter, Larry Carrillo, Judith Case, Jennifer Chan, Avijit Ray-Chaudhuri, Jim Chang, Michael Chang, Daniel Chavez, David Chin, Larry Clark, Mark Claudnic, Miles W. Clift, Garrett Close, Mats Cooper, Marcus Craig, Shirley Darymple, Joel Darnold, Daniel Dedrick, Paul Dentinger, Antonio J. DeSousa, Diane Diemer, Bobby Dillon, Sharon Dillon, Jason Dimkoff, Vincent DoSepis, Ed Dutra, Steve Eisenbies, Paul Epp, Bernice Espinoza, Devon Feaster, Michael Firreno, Aron Fisher, Don Fleming, Roger Flynn, Daniel Folk, Julieta Foster, Jerry Friesen, Dennis Fritts, Clay Fulcher, Ford Garberson, Steve Gianoulakis, Charles Edward Giebel, David Goldsmith, John Goldsmith, Samuel Graham, Jeffrey Greving, Phillip Grunow, Scott Gunn, Sarah Guske, Wanda Guthrie, Jim Hachman, Doug Hahn, Gary A. Hall, Jeffery Hall, Steven Haney, Jerry Hargiss, Ann Harper, Ed Hathaway, Arthur Hayes, Charles Healer, Kristopher Hearream, Linda Helmick, Craig Henderson, Stephen Henry, Donald Herron, Barry Hess, Jenni Hidalgo, Todd Hinnerichs, Jeromy Hollenshead, Stephen Horstemeyer, Luke Hunter, Tom Hunter, Richard Isler, Karen Jefferson, Mim John, Terry Johnson, Jay Jordan, Jeff Jortner, Michael Kahn, Steven Kan, Michael Kanouff, Steve Karim, Steve Kenitzer,

Mickey Kennedy, Mark Kiney, Leonard Klebanoff, Dan Knight, John Krafcik, Kevin Krenz, Glenn Kubiak, Cynthia Kuffner, Scott Kuszmaul, Davina Kwon, Robert Lafon, David Lau, Ming K. Lau, Jim Lautter, Arlen Lee, Brian Lee, Michael Lee, Alvin Leung, Matthew Lloyd, Bruce Long, Mariana Loya, Kelvin Lum, Mike Malinowski, Scott Marouka, Kevin McDonald, Sam McFadden, Nathan McGoldrick, Elward McKelrey, Don Meeker, Jerry Merrill, Jill Micheau, Chris Moen, Rick Moehrle, Robert Monson, Shrihari Namperumal, Thanh Nguyen, Spencer Nielsen, Ralil Nieves, Donald A. Nissen, Rodney Nissen, James Pate, Joel Philliber, Tom Probst, Donna O'Connell, Charles Oien, Kurt Olsen, Kathy Gilbert-Oneil, Catherine Otto, Carmen Palya, Jason Anderson Payne, Yon Perras, Eldon Porter, Therese Porter, Dan Rader, Valerie Randall, Erica Rapp, Bill Replogle, Rhoda Rhoades, Paul Rockett, Fran Rupley, Harold Sakowski, Charles Schmitz, George Schubert, Jill Schwegel, Steve Schwegel, Jerry Selfridge, Harry Shields, William Silfvast, Kelby Simison, Todd Simmermacher, Martin Skidmore, Jeffery Spooner, James Stamps, Rick Stulen, Beverly Sturgis, Duane Sunnaborg, Daniel Tichenor, Roger Vecta, Daniel Vickers, Andrew Wessels, Lisa Welcher, Christopher Welcher, John Wheeler, William Wilcox, Aaron Wong, and Michael Thomas Wong.

References

1. M. Hawryluk and L. G. Seppala, "Soft x-ray projection lithography using an x-ray reduction camera," *J. Vac. Sci. Technol. B* **6**, 2162–2166? (1988).
2. W. T. Silfvast and O. R. Wood II, "Tenth micron lithography with a 10 Hz 37.2 nm sodium laser," *Microelec. Eng.* **8**, 3–11 (1988).
3. H. Kinoshita, et al., "Soft x-ray reduction lithography using multilayer mirrors," *J. Vac. Sci. Tech. B* **7**, 1648–1651 (1989).
4. Lawrence Livermore National Laboratory (LLNL), USA, <http://www.llnl.gov>.
5. Lawrence Berkeley National Laboratory (LLNL), USA, <http://www.lbl.gov>.
6. Sandia National Laboratory (SNL), USA, <http://www.sandia.gov>.
7. *International Technology Roadmap for Semiconductors* (ITRS), <http://public.itrs.net>.
8. United States Department of Defense (DOD), <http://www.defenselink.mil>.
9. United States Defense Advanced Research Projects Agency (DARPA), <http://www.darpa.mil>.
10. United States Director of Defense Research & Engineering (DDR&E), <http://www.dod.gov/ddre>.
11. United States Department of Commerce (DOC), <http://www.commerce.gov>.
12. National Institute for Standards and Technology (NIST), USA, <http://www.nist.gov>.
13. SEMATECH, <http://www.sematech.org>.
14. Semiconductor Industry Association (SIA), USA, <http://www.sia-online.org>.
15. Semiconductor Research Corporation (SRC), USA, <http://www.src.org>.

16. Association of Super-Advanced Electronics Technologies (ASET), Japan, <http://www.aset.or.jp>.
17. All EUV Workshop material can be found at <http://www.sematech.org/meetings/archives.htm>.
18. S. Wurm and C.W. Gwyn, "EUV Lithography," Chapter 8 in *Microlithography: Science and Technology, 2nd Edition*, K. Suzuki, Ed., CRC Press/Taylor & Francis Information Group, Boca Raton, Florida, USA (2007).
19. Ma, et al., "Progress towards the development of a commercial tool and process for EUVL mask blanks," *Proc. SPIE* **5751**, 168–177 (2005).
20. K. Lowack, et al., "The EUV resist test center at SEMATECH-North," *Proc. SPIE* **6151**, 61512U (2006).
21. P. Naulleau, et al., "Investigation of the current resolution limits of advanced extreme ultraviolet (EUV) resists," *Proc. SPIE* **6151**, 61510Y (2006).
22. K. A. Goldberg, et al., "Actinic Inspection of EUV Programmed Multilayer Defects and Cross-Correlation Measurements," presented at the 50th International Conference on Electron, Ion, and Photon Beams and Nanolithography (EIPBN), Baltimore, Maryland, May 31–June 2, 2006.
23. Hand, "Infrastructure steps closer to EUV lithography," *Semiconductor International*, 38–42 (Sept. 2005).
24. F. Letzkus, et al., "EUVL mask manufacturing: technologies and results," *Proc. SPIE* **5992**, 59922A (2005).
25. Massachusetts Institute of Technology (MIT), USA, <http://web.mit.edu>.
26. United States Naval Research Laboratory (NRL), <http://www.nrl.navy.mil>.
27. Interuniversity MicroElectronics Center (IMEC), Belgium, <http://www.imec.be>.
28. Commissariat à l'Energie Atomique (CEA)/Laboratoire d'Electronique de Technologie de l'Information (LETI), France, <http://www-leti.cea.fr>.
29. Microelectronics Development for European Applications+ (MEDEA+), France, <http://www.medeaplus.org>.
30. PProgramme Extrême UV (PREUVE) is the French national EUVL program. Its participants include national research laboratories, universities, and leading companies in optics, precision engineering, and semiconductor manufacturing.
31. Extreme UltraViolet Lithography System Development Association (EUVA), Japan, <http://www.euva.or.jp>.
32. National Institute of Advanced Industrial Science and Technology (AIST), Japan, <http://www.aist.go.jp>.
33. 2006 SEMATECH Litho Forum, Vancouver, May 23–24 (2006).



Charles (Chuck) Gwyn joined Intel Corporation in 1997 to manage the Extreme UltraViolet Lithography (EUVL) Program where he was General Manager for the EUV LLC (a consortium of IC manufacturers, including AMD, IBM, Infineon, Intel, Micron, and Motorola). He was responsible for managing the technical development of EUV lithography tools in partnership with the DOE laboratories and commercial suppliers.

His industrial experience includes research in radiation effects in semiconductor devices, application of computer techniques to data processing, computer-aided instruction, computer-aided design, data acquisition systems, and management of the Integrated Circuit Design Department at Sandia National Laboratories in Albuquerque, New Mexico. At the United Technologies Microelectronics Center in Colorado Springs, Colorado, he was responsible for IC design, computer-aided design, management information systems, program management, and government R&D marketing departments.

His educational background includes a BS in electrical engineering from the University of Kansas and MS and PhD degrees in electrical engineering from the University of New Mexico. He is also an IEEE Fellow.



Stefan Wurm has held several positions in technology development—from development engineer to senior staff engineer—at Siemens Semiconductors, Infineon, and Qimonda. Since 2004, he has led the EUVL Strategy Program at SEMATECH. His industrial experience includes CMOS process technology, advanced equipment and process controls, magnetic random access memory development, and next-generation lithography. He has been on assignments to the International 300 mm Initiative (I300I), International SEMATECH, EUVLLC, and SEMATECH. He came to his current position after serving as the Infineon EUVL project manager at the EUV Limited Liability Company in Livermore, California.

He received his undergraduate and doctorate degrees in physics from the Technische Universität München, Germany. His doctoral thesis research contributed to the fundamental understanding of electron-stimulated desorption dynamics.

Chapter 4A

Optics and Multilayer Coatings for EUVL Systems

Regina Soufli, Saša Bajt, Russell M. Hudyma, and John S. Taylor

Contents

4A.1 Introduction	133
4A.2 Properties of EUVL Systems	133
References	134

4A.1 Introduction

EUV lithography (EUVL) employs illumination wavelengths around 13.5 nm, and in many aspects it is considered an extension of optical lithography, which is used for the high-volume manufacturing (HVM) of today's microprocessors. The EUV wavelength of illumination dictates the use of reflective optical elements (mirrors) as opposed to the refractive lenses used in conventional lithographic systems. Thus, EUVL tools are based on all-reflective concepts: they use multilayer (ML) coated optics for their illumination and projection systems, and they have a ML-coated reflective mask.

4A.2 Properties of EUVL Systems

To achieve production-quality lithographic imaging, EUVL systems must be very well-corrected for aberrations. The overall wavefront error budget for an optical system scales with the wavelength of illumination. Compared to optical systems that operate at visible or near-visible wavelengths, EUVL error budgets translate into very tight wavefront (figure) specifications for the mirror substrates and coatings that comprise the EUVL system. The mirror surface roughness in the mid- and high-spatial frequency ranges (commonly referred to as "finish") is also a crucial property because it affects the imaging contrast and throughput of the lithographic system. As a result, the figure and finish of mirror substrates and coatings in a production-scale EUVL system must be controlled to the order of subatomic dimensions. During the EUVL technology development that has been taking place

in the past two decades, the aforementioned requirements imposed on the system wavefront error, on the mirror figure and finish, and on the reflective properties and lateral thickness control of EUV ML thin films have led to enormous advancements in optical substrate manufacturing, optics mounting and alignment techniques, and ML coating technology. Large-area ML optics with figure and finish of 0.1- to 0.2-nm rms have been fabricated and integrated in EUV optical systems with sub-diffraction-limited performance. Furthermore, ML coatings with normal-incidence experimental reflectivities of 70% have been demonstrated in the 11- to 14-nm wavelength range. Scientific areas such as solar physics, astronomy, x-ray microscopy, and plasma diagnostics that need similar instrumentation technology have greatly benefited by the improvements in EUV/x-ray optics motivated by EUVL.

Chapters 4B, 4C, and 4D summarize the basic principles of the optical design, substrate specification/manufacturing, and ML deposition of EUVL optics. In each case, the main challenges are emphasized, and experimental results from state-of-the-art EUVL systems are presented as examples. For further details on the principles and theory behind several of the topics discussed in this chapter, especially those relevant to Chapter 4D (ML interference coatings and interactions of EUV radiation with matter), the reader is referred to books by D. Attwood¹ and E. Spiller.²

References

1. D. T. Attwood, *Soft X-rays and Extreme Ultraviolet Radiation, Principles and Applications*, Cambridge University Press (1999).
2. E. Spiller, *Soft X-ray Optics*, SPIE Press, Bellingham, WA (1994).

Chapter 4B

Projection Systems for Extreme Ultraviolet Lithography

Russell M. Hudyma and Regina Soufli

Contents

4B.1 General EUVL Optical Design Considerations	135
4B.2 EUV Microsteppers	138
4B.2.1 “10×” microstepper	138
4B.2.2 Microexposure tool (MET)	140
4B.3 Engineering Test Stand (ETS)	147
4B.4 Six-Mirror EUVL Projection Systems	149
4B.4.1 Feasibility	149
4B.4.2 Concepts with concave primary mirrors	150
4B.4.3 Concepts with convex primary mirrors	154
4B.4.4 Conclusions	156
Acknowledgments	156
References	157

4B.1 General EUVL Optical Design Considerations

All projection optics in an EUV lithography (EUVL) system must be reflective and are coated with thin films consisting of alternating layers of materials termed “multilayers (MLs),” at a total thickness of about 280 nm. These coatings act as Bragg reflectors and are designed to operate at the EUVL wavelengths of illumination (centered at ~ 13.4 to 13.5 nm) at near-normal-incidence angles. The ability to deposit such highly reflective ML coatings with extremely precise thickness control across the optic surface (in order to preserve the optic figure) has been the enabling technology for EUVL. Since ML coatings are essential, every EUVL projection system must be ML-compatible. The theoretical reflectance properties of a normal-incidence molybdenum-silicon (Mo/Si) ML suited for EUVL are shown in Fig. 4B.1.

In a poorly designed EUV projection system, MLs can induce appreciable amplitude and phase errors at the exit pupil of the image system. In an uncompensated design, the ML-induced phase error can easily exceed 4 to 5 times the residual

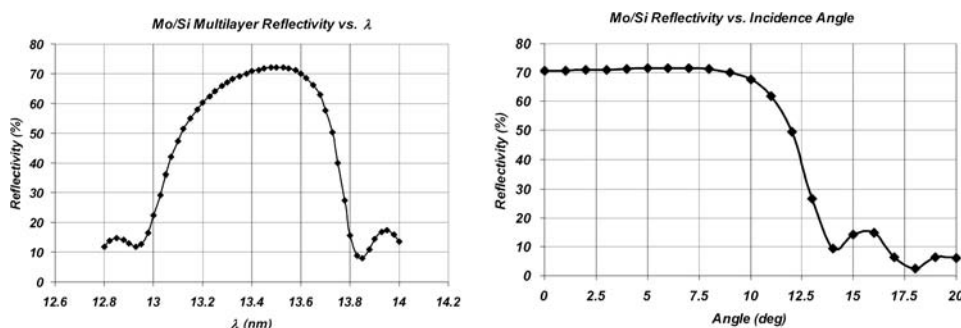


Figure 4B.1 Normal-incidence reflectivity vs wavelength and reflectivity vs angle for an ideal Mo/Si ML with 40 bilayer pairs. The period of a single bilayer is 7.0 nm and the thickness of individual Mo and Si layers is 2.76 nm and 4.14 nm, respectively.

wavefront error of the uncoated system. Amplitude effects are equally important; a poorly designed system will have appreciable apodization across the exit pupil, leading to poor critical dimension (CD) uniformity across the field and telecentricity errors at the wafer for any single field point. There are no rigorous rules to ensure ML compatibility. But a guiding principle is that stringent controls on both the mean incidence angle on each mirror, as well as the range of incidence angles as seen from any point on the mirror, must be enforced.^{1–5}

As with other lithographic technologies, EUVL strives to achieve continuous improvements in resolution, thus enabling smaller device geometries.⁵ This is accomplished fundamentally by increasing the numerical aperture (NA) of the projection optics, which creates an interesting coupled set of technology problems to solve: (1) the synthesis of EUVL projection optics forms with large NAs ($NA > 0.25$) and beyond, and (2) the development of a ML coating design set capable of supporting basic imaging at this increased NA. Recent work has demonstrated that EUVL designs with NAs in excess of 0.40 can be synthesized using relatively deep aspheric mirrors with large aspheric gradients. It has also been demonstrated that these systems will support ML imaging at $4\times$ or even $5\times$ reduction.⁷

The synthesis of these high-NA systems follows five basic steps:

1. The synthesis of all-reflective or catoptric projection system concepts capable of correcting imaging aberrations at NAs in excess of 0.25 over meaningful slit widths with an even number of reflections.
2. The characterization and correction of ML-induced amplitude errors at high NA.
3. The characterization and correction of ML-induced phase errors at high NA.
4. The simultaneous refinement of the complete projection systems (optics and ML coatings) via damped least squared (DLS) optimization using specialized user-defined error functions.

5. A validation, via an analysis of the partial coherent imagery, that the canonical projection systems can meet lithographic imaging standards.

This process flow is illustrated in Fig. 4B.2.

Since EUVL projection systems are all-reflective, there are several additional subtleties beyond simple ML compatibility and the dual-track optimization process to achieve a manufacturable solution. The aspheric mirrors used in an EUVL projection system must have both the peak departures and aspheric gradients carefully controlled to ensure *both* the fabrication and metrology process. First, the absolute aspheric departure from the best-fit sphere sets the maximum number of fringes that the interferometer must accommodate. As the maximum number of fringes increases, the complexity of the compensation optics used to “null” the test wavefront generally increases. Second, the peak aspheric departure is a measure of the material that must be removed during the fabrication process. Since this removal process is performed with sub-aperture tools, excessive departures lead to excessive process times, which add to the risk of introducing mid-spatial-frequency errors due to process fluctuations.

Perhaps even more important than the maximum aspheric departure is the aspheric gradient, or the change in aspheric sag as a function of lateral coordinates across the mirror surface. This sets the local fringe density that the

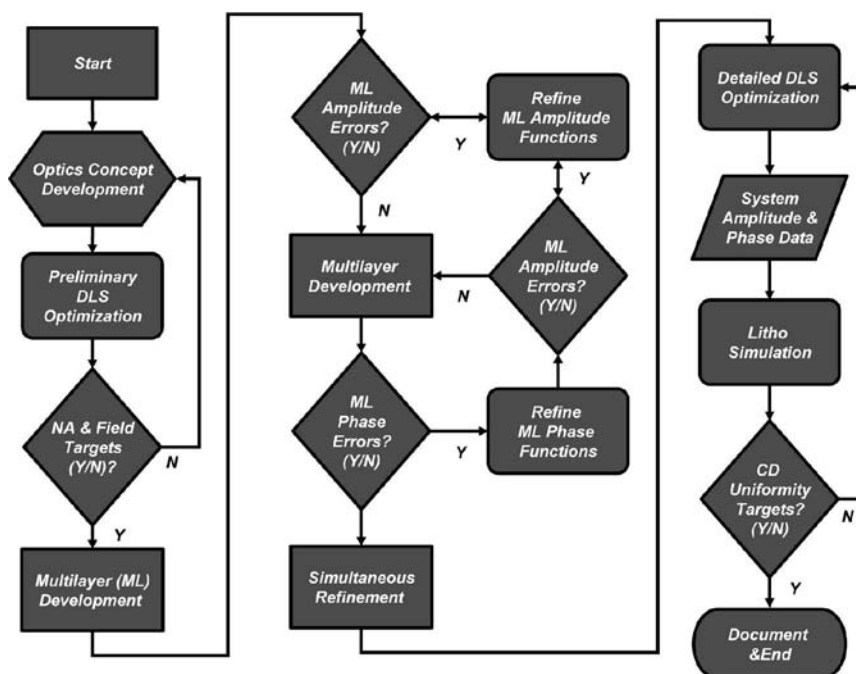


Figure 4B.2 Necessary process flow to determine the extensibility of EUVL. The process starts by conceptualizing canonical EUV projection systems targeted at process nodes down to 15 nm. The remaining tasks determine if these conceptual systems are (1) compatible with EUV MLs and (2) support lithographic-quality imaging.

interferometer's sensor must resolve. At an empirical limit of approximately four pixels per fringe, the interferometry simply no longer has the accuracy with which to test the EUV surfaces. And to generate steeper gradients, higher-frequency tool functions in the polishing process are required. These higher-frequency tool functions have the tendency to increase the mid-spatial-frequency roughness (MSFR). To compound the problem, mid-spatial-frequency smoothing techniques do not work as well in regions of increased mirror slope.

In addition to ML compatibility and the challenges of essentially tailoring aspheric mirrors that need to be figured to atomic dimensions, EUVL systems have the usual challenges related to the development of multimirror systems, including ray clearance, back working distance, volume claims for mounting interface, etc. Working distances and clearances are also driving issues, since mirror substrates need adequate thickness to overcome mount-induced deformations.

Despite these challenges, EUV projection systems are a reality today, and several high-profile systems are enabling EUV researchers to continue to unlock the promise of EUV technology.

4B.2 EUV Microsteppers

The semiconductor industry uses a reduced field image size at a similar optical resolution to that eventually intended to be adopted in production, and microsteppers to gain early learning on new technology nodes four to five years ahead of their introduction. Microsteppers allow manufacturers and researchers alike to develop and qualify new photoresists well before they are required for high-volume integrated circuit (IC) manufacturing. Microsteppers also allow researchers to investigate defect printability, test new reticle designs, and fabricate prototype ICs at the node of interest as well as provide early learning on tool-related technology challenges associated with sources, optics, lens aberrations, imaging effects, materials, metrology, reticles, photoresists, contamination, cost of ownership, reliability, and lifetime. In the field of EUV, both the “10×” microstepper and microexposure tool (MET) have played pivotal roles in the development of EUV technology and infrastructure.

4B.2.1 “10×” microstepper

Between 1997 and 2002, EUVL was given a tremendous technology push with developments made by the Virtual National Laboratory (VNL), which consists of Lawrence Livermore, Sandia, and Lawrence Berkeley National Laboratories (LLNL, SNL, and LBNL, respectively). Funding was supplied by the EUV Limited Liability Company (LLC)—a consortium formed by IC manufacturers Intel, AMD, IBM, Infineon, Micron, and Motorola. Much of the initial technology development work was performed using what was called the “10×” microstepper.⁸

The $10\times$ projection optics consist of a two-mirror objective arranged in a Schwarzschild form with a convex primary mirror and a concave secondary mirror, as light travels left to right from the patterned mask to the wafer. This objective is of the reverse telephoto type so that the back working distance is greater than the focal length of the objective. The projection optics were designed with a maximum centered NA of 0.30, but the aperture stop is decentered to produce a system with an unobscured circular aperture (Fig. 4B.3). The geometry constraints imposed by reasonable opto-mechanical considerations limit the NA of the off-axis bundle to 0.088 by design.

For an object at infinity, the Schwarzschild objective is formed by two concentric spherical mirrors. The design is free from spherical aberration, coma, and astigmatism, provided that the ratio of concave radius to the convex radius (R_2/R_1) is equal to $(\sqrt{5} + 1)/(\sqrt{5} - 1)$ or 2.618034. When the system is used in a microstepper at a reduction ratio, the object distance must be given some finite value. This means that the concave secondary mirror must be weakened to correct the spherical aberration and coma while maintaining the concentricity of the mirrors M1 and M2. For this $10\times$ objective, the new R_2/R_1 ratio is 3.083498, which is in close agreement to an example provided by Kingslake.⁹ The resulting objective is free from spherical aberration, coma, and astigmatism at 0.088 NA, with the field curvature limiting the imaging performance. The residual root mean square (rms) composite wavefront error within a $280\text{-}\mu\text{m}$ square field of view as-designed is 0.055λ ($\lambda = 13.4\text{ nm}$), or 0.75 nm. The inward field curvature is approximately $0.80\text{ }\mu\text{m}$ when analyzed across the $400\text{-}\mu\text{m}$ -diameter field. These parameters are summarized in Table 4B.1.

The $10\times$ microstepper received an upgraded optics package in late 1998, with the figure error of both primary and secondary mirrors approaching 0.4-nm rms. By clocking the mirrors relative to each other, the subaperture wavefront was optimized to achieve a residual rms wavefront error of 0.045λ (0.6 nm). This rms value was derived from a 37-term Zernike expansion to the measured interferogram, representing an as-built wavefront error value that was actually *lower* than the design residual. In addition to the excellent mirror figure, the MSFR (mid-spatial frequency roughness corresponding to spatial periods of 1 mm^{-1} to $1\text{ }\mu\text{m}^{-1}$) achieved

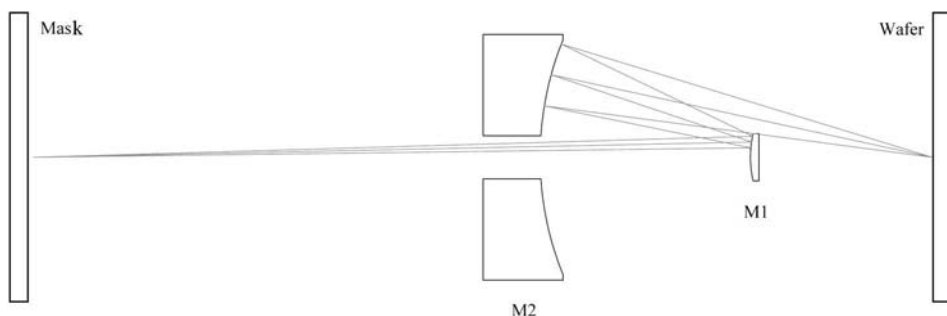


Figure 4B.3 $10\times$ microstepper projection optics illustrating the decentered aperture stop on the primary mirror M1.

Table 4B.1 10× microstepper design parameters.

Parameter	Value
Wavelength	13.4 nm
Numerical aperture (NA)	0.088 (circular stop) 0.088 × 0.10 (rectangular stop)
Reduction ratio	10×
Field format	283 × 283 μm square (400-μm diagonal)
Residual rms wavefront error	0.055λ
Total track	315.2 mm
Demonstrated resolution	70 nm 1:1 L/S

on both the primary and secondary mirrors was 0.13-nm rms and 0.20-nm rms, respectively. These MSFR values enabled low-flare imaging with measured flare levels on the order of 4%. Subsequent printing experiments in 1999 at the VNL demonstrated high-fidelity iso-dense elbows at both 90 nm and 80 nm using the circular 0.088-NA aperture set. Using the 0.10 × 0.088 NA rectangular aperture, a 70-nm L/S (lines and spaces) at a 1:2 pitch and a 1:1 pitch were patterned in a customized thin layer (80 to 100 nm) deep ultraviolet (DUV) resist.⁸ These results were significant at the time because they established a k_1 factor of 0.52 for this process, which foreshadowed the potential for sub-30-nm resolution for a projection system designed with a NA of 0.30, which is going to be discussed in Sec. 4B.2.2.

Yet another upgraded set of 10× microstepper optics was manufactured in 2002 to support a set of frequency-doubling experiments at LBNL's Advanced Light Source (ALS). The spatial frequency-doubling technique utilized a 40 μm × 40 μm silicon nitride (Si₃N₄) transmission grating with an aperture stop that was designed to block or “filter” the zero diffraction order from this grating. Essentially, the technique works by allowing the +1 and −1 diffraction orders to propagate through the optical system, interfering at the image plane. In this manner, a high-contrast spatial frequency doubled image of the grating pitch is produced. The researchers at LBNL were able to print high-quality 50-nm line/space patterns in Shipley's “EUV-2D” resist and quantify the line edge roughness (LER) of these printed images.¹⁰

4B.2.2 Microexposure tool (MET)

It became clear at the VNL that an upgraded micro-exposure capability was needed to demonstrate the full potential of EUVL to a 30-nm half-pitch. Based on some simple work with the lithographic scaling laws, it was decided that this new MET would have a NA of about 0.3, similar to the NA for a commercial alpha-tool, but substantially larger than both the 0.10 NA for the Engineering Test Stand (ETS) and 0.088 NA for the existing 10× microstepper.

The idea of employing a two-mirror aspheric imaging system has been proposed in earlier reports.^{11,12} To achieve the largest possible field of view, the MET

projection optics utilize a primary and a secondary mirror whose radii are nearly the same (within 10% of each other). This enables the field curvature to be corrected to a value approaching that of more sophisticated multi-mirror EUVL projection systems. Compared to the $10\times$ imaging system that uses the same field size at the wafer, this “equal radii” concept reduces the longitudinal field curvature from $1.8\text{ }\mu\text{m}$ to $0.05\text{ }\mu\text{m}$. This 36-fold reduction in field curvature enables a 50% increase in printed field area per exposure relative to the $10\times$ microstepper (Fig. 4B.4). The MET projection optics are designed to accommodate either a transmission mask (TM) or reflection mask (RM), with a depth of focus that can accommodate subtle tilts of the wafer up to ~ 1 deg. With a RM, imaging is controlled by the Scheimpflug condition, which states that the imaging properties of a centered optical system with a tilted object are preserved on a tilted image plane (ignoring distortion). For a system used at finite conjugates, the image plane tilt is the object plane tilt scaled by the reduction ratio. A reflective mask can be tilted up to ~ 5 deg in the MET.

Layouts of the final optical design with reflection and transmission masks are shown in Figs. 4B.5 and 4B.6, respectively. Table 4B.2 summarizes the performance of the optical design relative to parameter goals. A large NA of 0.30 is attained by the use of a centered design, where the imaging bundles are centered on the optical axis. The centered design necessitates that the image passes through a hole in the primary mirror. Eccentric or off-axis pupil design forms are not feasible

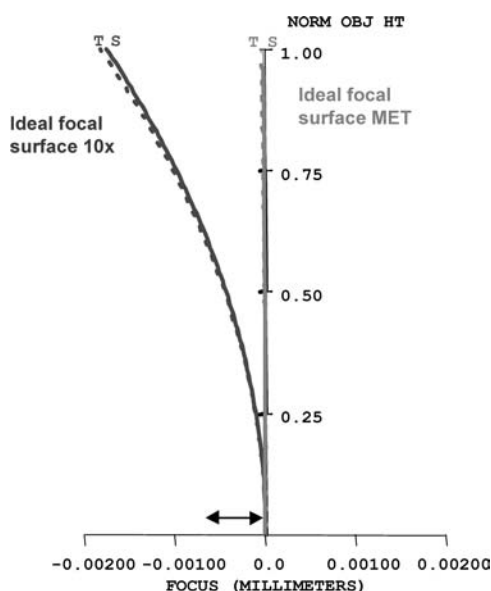


Figure 4B.4 The principal feature of the MET design is the reduction in field curvature, which allows focus to be maintained across the entire tilted wafer plane. The image formed at the wafer with the $10\times$ camera would be outside the depth of focus due to the curvature of field. The y -axis is normalized to the field height of the MET (3 mm), which represents the field of view at the reticle that is projected at $5\times$ reduction at the wafer. Both tangential (T, dashed line) and sagittal (S, solid line) field curvatures are shown.

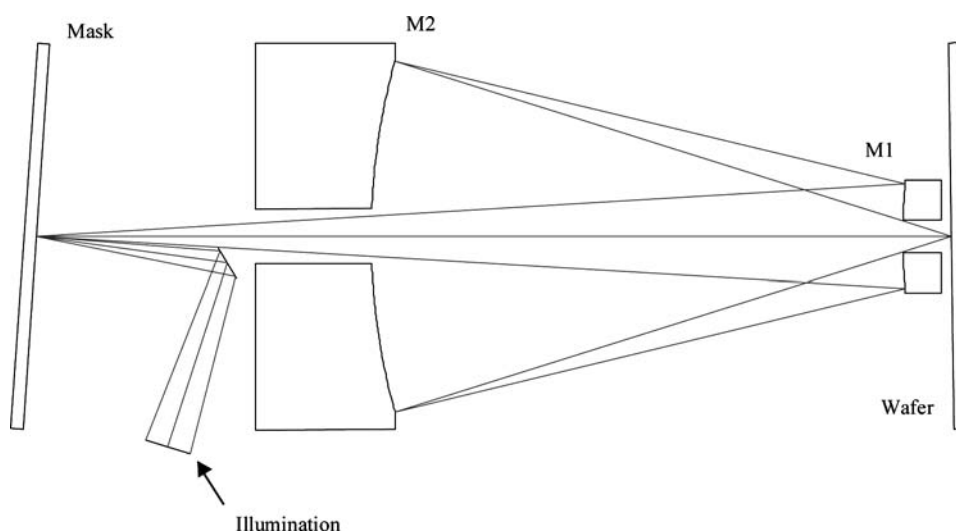


Figure 4B.5 Tilting the mask and wafer planes enables use of a reflection mask. In this embodiment, the mask is tipped by 4.0 deg, with a corresponding wafer tilt of 0.8 deg. The imagery is diffraction-limited on the tilted wafer plane.

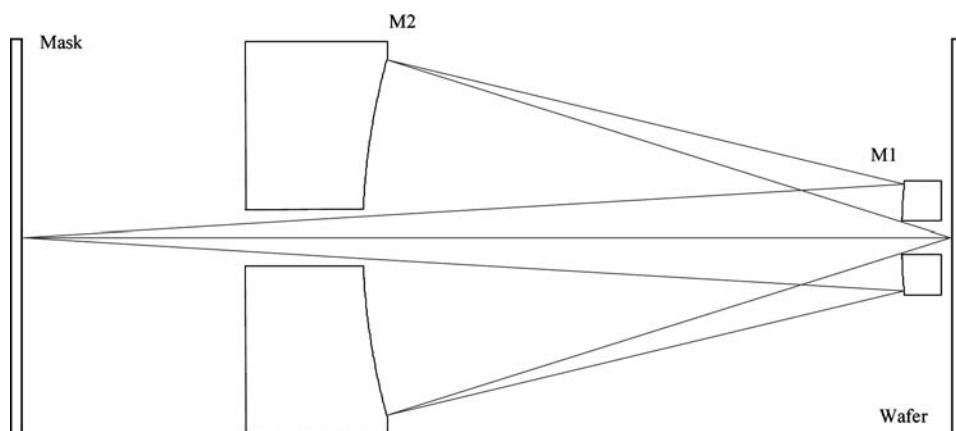


Figure 4B.6 "Equal radii" microstepper concept for use with a transmission mask. The design has a NA of 0.30 at a reduction of 5 $\times$ as measured at the plane of the wafer. Mirror radii R1 and R2 are nearly the same, acting to minimize field curvature across the projected format.

because the individual mirrors work at very fast conjugates. The residual aberrations simply grow too quickly to correct as the pupil moves off the optical axis. This fact forces the central obscuration on the exit pupil of the imaging system. To minimize the obscured pupil area (<10%), the image plane must be kept close to the primary mirror. This reduces the clearance between the back of the primary mirror and the wafer. The vertex thickness of the primary mirror was set to 20 mm to provide ample substrate stiffness, leaving only 5 mm of clearance between the

Table 4B.2 MET projection optics performance summary (RM = reflection mask, TM = transmission mask).

Parameter	Predicted performance
Wavelength	13.4 nm
Numerical aperture	0.30
Focal length	102.5 mm
Field format	
Type	Rectangular
Length $\times$ width	600 $\mu\text{m} \times$ 200 μm
Mask compatibility	RM & TM
Reduction ratio (nominal)	5:1
Residual rms wavefront error (waves @ $\lambda = 13.4$ nm)	
Field point maximum	0.054 λ (RM) 0.027 λ (TM)
Composite	0.031 λ (RM) 0.021 λ (TM)
Resolution	30 nm
Distortion (peak-to-valley static, nm)	
Chief ray	497.6 nm (RM) 2.24 nm (TM)
Depth of focus	200 nm
Telecentricity error	
Δy (nm) image / Δz (nm) focus	0.0148 nm/nm
Package	
Total track (mask/wafer)	474.16 mm
Overall length (vertex/vertex)	275.60 mm
Working distances	
M1/wafer	~ 5.0 mm
M2/mask	~ 113.56 mm
Aperture stop	Accessible on M1
Peak aspheric departure	
M1 (primary)	3.82 μm
M2 (secondary)	5.61 μm
Maximum aspheric slope	
M1 (primary)	-1.18 $\mu\text{m}/\text{mm}$
M2 (secondary)	-0.47 $\mu\text{m}/\text{mm}$
Angles of incidence, from normal	
M1 (max/min)	8.67°/2.54°
M2 (max/min)	1.98°/0.67°

back of the primary mirror and the wafer. This makes mechanical packaging of the primary mirror difficult and precludes the use of a grazing-incidence focus system.

While the limited clearance makes the mechanical design more complicated, this issue is manageable. The working distance is, in fact, about the same as for contemporary DUV steppers. The final design shown in Fig. 4B.5 includes a proposed mirror substrate thickness to help visualize clearance at the wafer and depict how the illumination is brought onto the mask. The design is optimized to work at a $5\times$ reduction across a rectangular field of view of 600×200 μm^2 at the wafer. While the field could be extended in the long dimension, the aspect ratio of 3:1 will

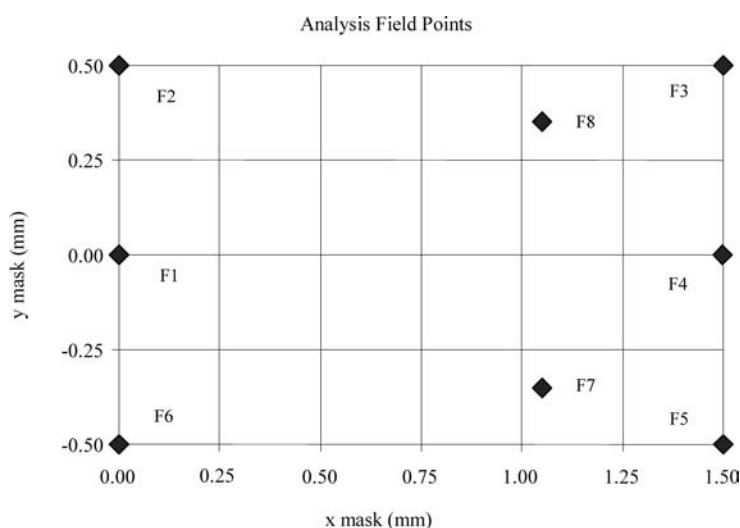


Figure 4B.7 Analysis field points for the computation of rms wavefront error, incoherent square wave modulation transfer function (MTF), and 2D/3D partially coherent imagery, for the MET tool. With a reflection mask, the printed field has bilateral symmetry, so only field points across the half-format need to be analyzed.

help to simplify the design of the illumination system. The mask is tilted clockwise at 4.0 deg; the wafer has a corresponding counterclockwise tilt of 0.8 deg. This is the minimum tilt required to avoid interference between the incoming illumination and imaging bundle.

With a RM, the composite rms wavefront error across a $600 \times 200 \mu\text{m}^2$ rectangular field is 0.42 nm (0.031 λ). This compares favorably to the composite rms wavefront of 0.28 nm (0.021 λ) with a TM. The difference between the two imaging conditions is that the wavefront error varies more across the tilted conjugate planes. With a RM, the wavefront error varies from 0.24 nm (0.018 λ) to 0.74 nm (0.055 λ). The wavefront error variation with a TM is 0.15 nm (0.011 λ) to 0.36 nm (0.027 λ). While this variation across a tilted wafer would be troublesome in a production tool, causing field-dependent CD variations across the field, it is not a significant issue for this R&D tool.

Since the MET projection optics are compatible with either a RM or a TM, the wavefront error and distortion analysis is performed in both modes of operation. The rms wavefront error was analyzed at nine distinct field points across the half-format as shown in Fig. 4B.7. This sampling is sufficient since the design has bilateral symmetry. The field size is set in RM mode because the maximum rms wavefront error at all field points must be less than 0.050 λ . The rms wavefront error, less tilt, for each field point is listed in Table 4B.3. Using a TM, the field composite rms wavefront error is 0.28 nm (0.021 λ). Residual field curvature and astigmatism present in the design cause a slight variation in the residual wavefront error across the field. With a RM, the field composite rms wavefront is 0.42 nm (0.031 λ). There is more variation in the wavefront error in this case, due

Table 4B.3 Rms wavefront error (WFE) for the MET projection system, with tilt removed.

Field	<i>x</i> (mm)	<i>y</i> (mm)	rms WFE (TM)	rms WFE (RM)
F1	0.00	0.00	0.022λ	0.022λ
F2	0.00	0.50	0.018λ	0.046λ
F3	1.50	0.50	0.027λ	0.020λ
F4	1.50	0.00	0.022λ	0.024λ
F5	1.50	−0.50	0.027λ	0.054λ
F6	0.00	−0.50	0.018λ	0.018λ
F7	1.05	−0.35	0.011λ	0.024λ
F8	1.05	0.35	0.011λ	0.023λ
Composite			0.021λ	0.031λ

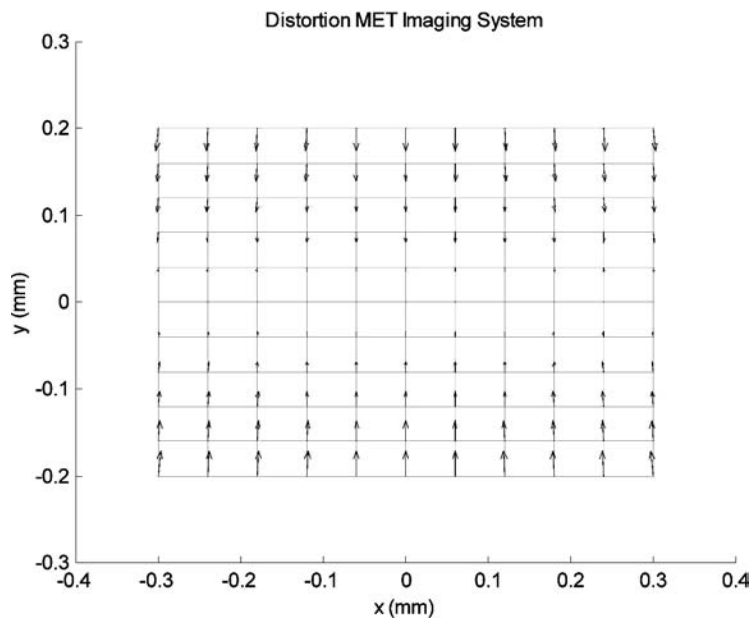


Figure 4B.8 Vector visualization of MET distortion using a TM over a $600 \times 200 \mu\text{m}^2$ imaging field at the wafer. The maximum radial distortion is only 2.24 nm. Since the system is rotationally symmetric in this mode of operation, the distortion field has rotational symmetry about the optical axis.

primarily to a variation in spherical aberration (fringe Zernike term Z9) across the field. This is a subtle effect that can be understood in the following way: with a tilted mask plane, the distance from the object surface to the first principal plane varies across the field, creating a field-dependent conjugate shift. Since the spherical aberration varies with conjugate distance, the spherical aberration will have field dependence.

Figures 4B.8 and 4B.9 graphically depict the distortion at the wafer with a TM and RM, respectively. The distortion vector field is superimposed on top of the ideal image grid. Even though this research tool requires an overlay, users must still understand the distortion fields in both imaging modes to address such issues

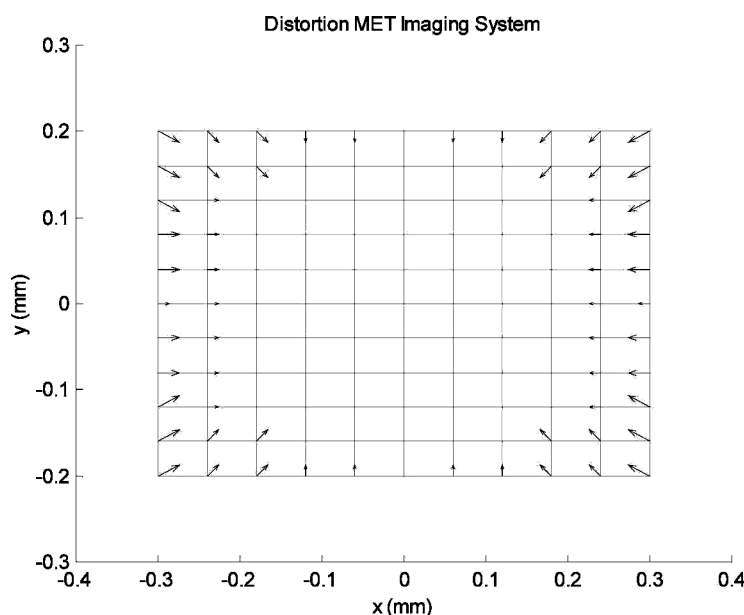


Figure 4B.9 Vector visualization of MET distortion using a RM over a $600 \times 200 \mu\text{m}^2$ imaging field at the wafer. In this case, the maximum radial distortion is $\sim 244 \text{ nm}$. The printed image suffers primarily from anamorphic distortion, which can be viewed simply as a foreshortening of the vertical dimension. Keystone distortion can also be seen in the vector field plot. Both forms of distortion are artifacts of imaging under the Scheimpflug condition.

as horizontal/vertical bias with tilted-plane imaging, and the potential to use this design in a scanning configuration.

With the TM situated perpendicular to the optical axis, the distortion field exhibits simple barrel distortion with rotational symmetry about this axis (Fig. 4B.8). The length of the largest distortion vector (and hence the maximum radial distortion) is 2.24 nm , with maxima being located in the corners of the format. There are no degrees of freedom in the optical design to correct distortion effectively; the distortion is minimized only because the projected field of view is small. An analysis of the scanned imagery shows an image placement error of $\sim 2 \text{ nm}$ in the cross-scan dimension. The residual distortion is small enough to consider the possibility of using this design with a TM in a scanning configuration.

The behavior of the distortion field is much more complex with a RM (Fig. 4B.10). The printed image suffers primarily from anamorphic distortion ($\sim 200 \text{ nm}$), which can be viewed as a foreshortening of the vertical dimension due to the tilted plane. Keystone distortion ($\sim 30 \text{ nm}$) can also be seen in the vector field plot, which relates to the variation in magnification with conjugate distance from the mask to the first principal plane. Both forms of distortion are artifacts of imaging using tilted conjugate planes, and they combine to make a rectangular object imaged into an isosceles trapezoid. The longest distortion vector in the field plot is $\sim 240 \text{ nm}$ in length. Barrel distortion is also present, but it is overwhelmed

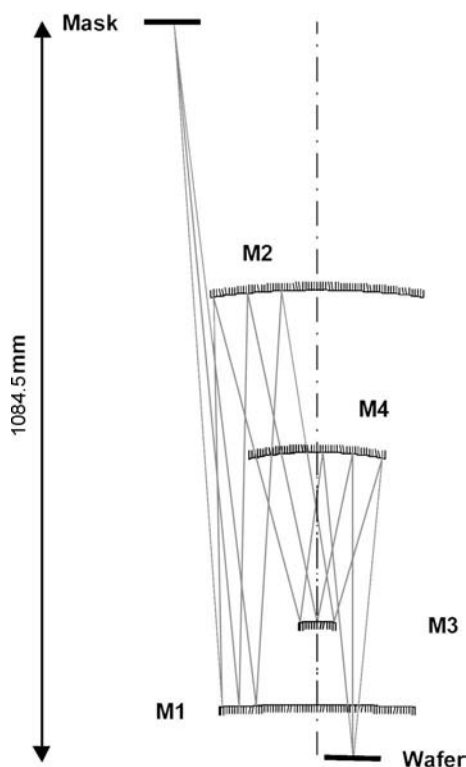


Figure 4B.10 Layout of the ETS projection optics (with full parents) that shows the imaging bundle from the mask (top) to the wafer (bottom). In practice, only off-axis sections of the mirrors are used, making the mirrors much smaller than shown in the figure. The aperture stop is fully accessible and located on mirror M3. Mirror M4 makes the imaging bundle perpendicular to the wafer plane, producing the telecentric design at this location.

by the other distortion forms. The conclusion of this analysis is that the MET camera is not suited for use in a scanning tool using a RM.

The optical design analysis and ML coating results from the first two MET cameras (set 1 and set 2) constructed at the VNL are described in Ref. 13. The set 2 MET camera is currently installed at the ALS synchrotron at LBNL and remains the most accurate micro-field, high-NA EUVL camera to date.^{14–16}

4B.3 Engineering Test Stand (ETS)

The imaging performance specifications for the EUVL projection optics parallel those of other optical lithographies. The principal difference is that the specifications are scaled to reflect the 100-nm CD for the first-generation EUVL systems. The first prototype 0.1-NA, scanning EUVL system was constructed by the VNL. The top-level imaging specifications for the ETS system were:

1. 100-nm CD (70 nm for isolated features) based on $NA = 0.1$, $k_1 = 0.77$, and coherence factor $\sigma = 0.7$;

Table 4B.4 Projection optics performance summary for the ETS.

Parameter	Predicted performance
Wavelength (λ)	13.4 nm
Numerical aperture (NA)	0.10
Ring field format	
Radius to center	52.75 mm
Width	1.50 mm
Chord	26.00 mm
Reduction ratio (nominal)	4:1
Composite rms wavefront error (waves @ $\lambda = 13.4$ nm)	0.014 λ
Resolution	100 nm
Centroid distortion (PTV static, nm)	15.4 nm
Depth of focus	> 1 μ m
Telecentricity (nanometer change in image height defined by centroid location per micron defocus)	0.01 nm/ μ m (ring bottom) −0.08 nm/ μ m (ring top)
Total track (mask/wafer)	1084.5 mm
Aperture stop	Accessible on M3
Maximum aspheric departure	
M1	6.2 μ m
M2	9.6 μ m
M4	2.7 μ m
Angles of incidence, from normal	
M1 (mean/max/min)	3.48/5.19/1.37 deg
M2 (mean/max/min)	6.56/6.95/6.15 deg
M3 (mean/max/min)	12.0/12.6/11.01 deg
M4 (mean/max/min)	6.0/6.67/5.3 deg

2. Ring-field imaging with a ring-field cord length of 26 mm at the wafer;
3. Depth of focus of ± 0.5 μ m with 10% CD control;
4. Reduction factor of 4:1 with residual magnification control of ± 20 ppm and magnification control of 0.1 ppm;¹⁷
5. Telecentric imaging at the wafer;
6. Total dynamic distortion of less than 5 nm over the full field.

The specifications above do not refer directly to lithographic process latitude. As expected, the models of lithographic process latitude indicate that the nominally aligned and focused optical system must produce a design Strehl ratio of about 0.98.

A four-mirror design was selected for the ETS.^{18–21} The optical system design for the ETS camera is shown in Fig. 4B.10. The performance summary for the optical design is presented in Table 4B.4. This novel design form embodies performance improvements when compared to other designs that at the time of construction of the ETS system represented the state of the art.²² This particular design was selected because it has low centroid distortion (~ 15 nm) across a wide (1.5-mm) ring field and a small residual rms wavefront error (0.014 λ or 0.19 nm). Judged by lithographic standards, the low residual wavefront error and balance of

aberrations across the ring field lead to excellent performance. For example, an analysis of the scanned imagery (assuming perfect Köhler illumination) demonstrates that the image placement error (IPE) due to the design is less than 1 nm for both dense, 100-nm, and isolated 70-nm features. The system is relatively compact, having a total track distance from the mask to wafer of ~ 1100 mm, while providing ample clearance at both the mask and wafer.

The design utilizes three aspheric mirrors, and in each case the aspheric departure is less than 10 μm . This small departure reduces the risk associated with the optical fabrication and metrology. Equally important, the use of a negative or convex primary mirror reduces the incident ray angles on the subsequent surfaces. The incidence angles were minimized on each mirror and could be made low enough to allow uniform ML coatings. This substantially reduces the risk in the ML coating process, where spectrally matched, uniform coatings are required. The low angles allow the design to be coated with either Mo/Si or molybdenum/beryllium (Mo/Be) MLs. In addition, the low-incidence angles ensure that visible alignment is the same as EUV alignment. Special at-wavelength interferometers are not required to align and characterize the ETS projection optics performance.

Although the mask illumination is not telecentric, it does allow for easy magnification adjustment by simple translation of the mask and wafer; no adjustment of the individual optics is required. For example, in the current design, movement of the mask by 1.0 mm changes the magnification by 2 ppm.

During optimization of this design, the static distortion was constrained in a unique way so that the dynamic (or scanned) distortion was essentially eliminated. The static centroid distortion of the design is approximately 15 nm, while the dynamic distortion is less than 1 nm. The shape of the static distortion map across the ring field is much more important than the actual distortion values. The relaxation of the static distortion constraints effectively introduces an additional degree of freedom in the optical design.

Two ETS cameras were constructed at the VNL, set 1 and set 2, the latter with improved optics figure that resulted in improved system resolution. The experimental results from the ETS optics fabrication and ML coatings are described in Refs. 23 and 24.

4B.4 Six-Mirror EUVL Projection Systems

4B.4.1 Feasibility

Mo/Si MLs have an experimental reflectivity of about 70% at 13.4 nm, meaning that the transmission of a six-mirror system is reduced by $\sim 50\%$ when compared to that of a four-mirror system. For this reason alone, the feasibility of a six-mirror system has been questioned. However, feasibility arguments based solely on transmission are flawed because transmission does not adequately describe the light-gathering potential of the projection system. The proper metric is the product of the illuminated area and the solid angle of the imaging cone. This area $\times$ (solid

angle) product is called the *étendue*; when it is multiplied by the transmittance, it is a measure of the theoretical throughput of a projection system.

The *étendue* can be considered a 2D generalization of the optical invariant. Like its optical cousin, the *étendue* is the invariant between image and object points for a well-corrected imaging system and is conveniently derived at either the object or image plane. At the wafer, the *étendue* (E_w) is simply $E_w = \pi(A_w)(\text{NA}_w)^2$, where A_w denotes the area of the wafer that is exposed. The throughput is simply the product of the transmittance (T) and the *étendue* (E_w).

As an example of a four-mirror system, the ETS discussed in Sec. 4B.3 has a 1.5-mm-wide ring field at the wafer, spanning a 30-deg angle with a NA of 0.10. The area solid angle product or *étendue* at the wafer E_f is found to be $0.40\pi \text{ mm}^2 \times \text{sr}$. A typical six-mirror projection system described herein has a 2-mm ring field spanning a 60-deg angle with a NA of 0.25, which equates to an *étendue* E_s of $3.50\pi \text{ mm}^2 \times \text{sr}$. When the transmission is factored in and relative throughputs compared $[(0.70^6/0.70^4)(E_s/E_f)]$, the six-mirror system offers a 4.3-fold increase in overall throughput. Thus, the increase in projected area and solid angle easily overcomes the loss of transmission.

By pushing the limits of the optical design and considering larger ring fields, the advantage becomes even more compelling. The throughput advantage for a six-mirror system with 3-mm-wide and 4-mm-wide ring fields is ~ 6.3 -fold and ~ 9.0 -fold, respectively.

Unfortunately, this theoretical advantage is not realized in practice due to the characteristics of real EUV sources. EUV sources are typically isotropic in both the spatial and angular domains, but the ring field format requires that the *étendue* be highly anamorphic in the spatial domain at the reticle or object plane. Fundamentally, this means that the throughput is limited by the mismatch between the characteristics of the EUV source and of the EUV projection system. For this reason, it is often better to consider the *useable étendue* of the system. Nonetheless, a six-mirror EUV projection system is better matched to an EUV source and affords a larger useable *étendue* than its four-mirror counterpart.

4B.4.2 Concepts with concave primary mirrors

PNPPNP configuration

One of the first projection systems tailored for EUVL was developed by Williamson.²⁵ Regardless of the wavelength region, testing convex aspheric mirrors is more difficult than testing concave aspheric mirrors, so it makes sense to minimize the number of convex surfaces in an optical design. A modified version of the Williamson PNPPNP design is shown in Fig. 4B.11. This example was reconstituted from the patent reference with some minor re-optimization in order to restore performance to lithographic levels. In this section, the letter “P” denotes concave (or “positive”) mirrors and the letter “N” is used for convex (or “negative”) mirrors.

Aspheric surfaces are used to correct the design to lithographic quality. The Petzval sum is corrected via the separation of positive and negative powers. If this

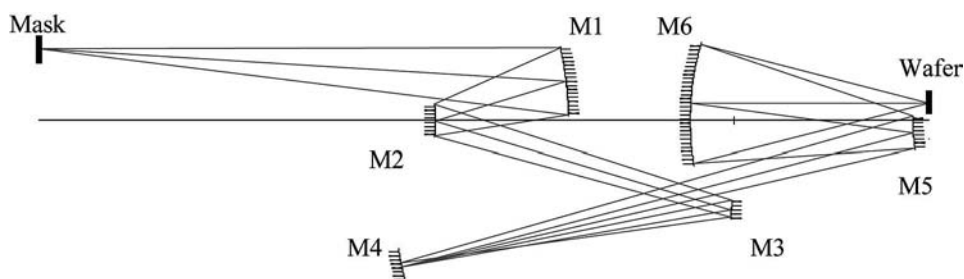


Figure 4B.11 Modified six-mirror PNPPNP EUVL projection optics described by Williamson.²⁵ The basic design was modified to reduce the incidence angles on each of the surfaces. The chief ray incidence angles (central field point) are as follows: mask, 4.0 deg; M1, 10.1 deg; M2, 16.7 deg; M3, 13.3 deg; M4, 2.4 deg; M5, 11.1 deg; and M6, 3.8 deg.

reflective system was “unfolded,” the design would be reminiscent of a dioptric projection lens with a series of “waists” and “bulges.” All the mirrors are aspheric, and the aperture stop is fully accessible on mirror M2, thus ensuring that the partially coherent imagery is stationary across the field. The composite rms wavefront error of this reconstituted example across a 2.0-mm ring field is 0.020λ (0.27 nm); the static distortion can easily be corrected to less than 1.0 nm at $4\times$ reduction. An intermediate image in the design is located between mirrors M3 and M4. This location minimizes the size of mirrors M3 and M4, especially in the sagittal plane. The low-incidence angle of the chief rays at the mask (~ 4 to 5 deg) is also advantageous by minimizing image placement errors due to non-telecentricity and “shadowing” at the mask. (The reflective EUV mask has a nonplanar topology, so the non-telecentric illumination creates “shadows” that have a small performance impact.)

The strong primary mirror coupled with the relative compactness of the design as measured by the total track length (about 1280 mm from mask to wafer) forces some relatively high-incidence angles (defined from the direction normal to the surface) on mirrors M1, M2, and M3. Incidence angles in some parts of the imaging bundles exceed 20 deg at points on various mirrors. Also, the chief ray angles from the central field point are relatively high on mirrors M1, M2, and M3. These factors would conspire to add complications during the ML re-optimization effort.

The design suffers a bit from large peak aspheric departures and relatively large aspheric gradients. In particular, mirrors M2 and M5 will be more difficult to test than the other mirrors in the system. The distance from the vertex of mirror M5 to the wafer is only 26 mm, which means that the back working distance of this particular embodiment is a bit strained.

But not to lose sight of the basic idea, several improvements can be made. Using this basic PNPPNP formulation, ML compatibility is improved by increasing the total track to 1500 mm, while keeping the ring field radius fixed. This effectively stretches the optical design and reduces the apparent offset of the field at the mask. The ray angles at each surface are reduced $\sim 10\%$ using this technique.

Improvements of several millimeters also can be made to the back working distance with additional detailed design effort.

PPNPNP configuration

Assuming that the first mirror will take positive optical power, let us imagine a new projection system. By distributing the positive power between the primary and secondary mirrors, low-incidence angles can be achieved to promote ML compatibility. With the stop at M2, the distortion contribution from this surface is nulled. Now the position of the entrance pupil can be adjusted to null the tangential astigmatism contribution from the base sphere of M1. The relatively low power of M1 and the low chief ray height also reduce the distortion contribution from this surface. Now the strong convex tertiary M3 can be used to compensate for the low-order astigmatism and distortion. The negative convex mirrors are also used in such a way to minimize and nearly correct the Petzval sum independently in each half of the design. The result of this thought process is the PPNPNP design shown in Fig. 4B.12.²⁶

The fundamental layout enables a low mean incidence angle at each mirror, giving the design a high degree of ML compatibility. The intermediate image is located between mirrors M4 and M5 to maximize ray clearance in the aft end of the system. At the wafer, the NA is 0.25 and the ring field width is 2.0 mm (centered on a radius of 30 mm). The composite rms wavefront error is 0.018λ (0.24 nm, $\lambda = 13.4$ nm), and the static distortion is corrected to better than 0.20 nm. This design has the potential to be scaled in either NA or field. For example, the rms wavefront error is only 0.027λ (0.36 nm, $\lambda = 13.4$ nm) when the NA is scaled to 0.28. This represents the rms error *without* re-optimization at the higher NA. Alternatively, the ring field width can be scaled to widths larger than 2 mm with reasonable scan-averaged performance.

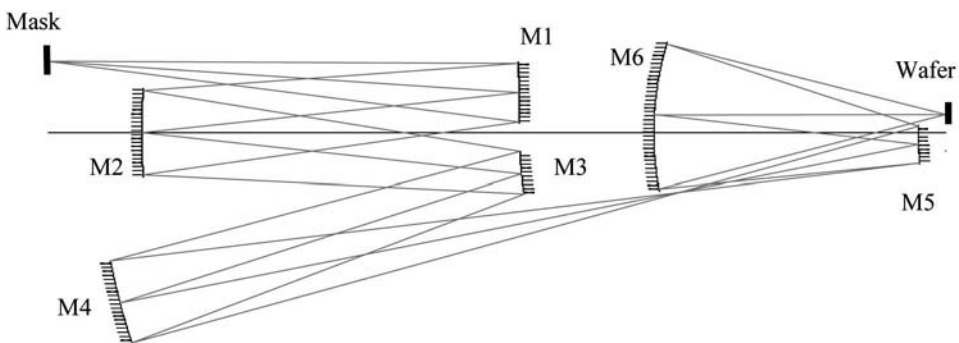


Figure 4B.12 Six-mirror PPNPNP design with low-incidence angles. The positive optical power in mirrors M1 through M4 is split between M1, M2, and M4 to lower the aberration contributions and incidence angles on these surfaces. The chief ray incidence angles (central field point) are as follows: mask, 4.0 deg; M1, 5.0 deg; M2, 6.0 deg; M3, 12.0 deg; M4, 3.3 deg; M5, 8.8 deg; and M6, 3.3 deg.

The total track from mask to wafer is 1500 mm. Of all the high-NA designs, this design has the lowest mean chief ray incidence angles, ranging from 3.3 to 12.0 deg. These chief ray angles are similar to the incidence angles present in the ETS design. The caveat is that the variation in ray angles across mirrors M3, M5, and M6 will require graded ML coatings. Nonetheless, this design is encouraging from a ML standpoint. And like the design shown in Fig. 4B.11, this design uses a low-incidence angle at the mask to minimize image placement errors.

The distance from the vertex of mirror M5 to the wafer is 46.75 mm, thus allowing a mirror substrate with sufficient aspect ratio. The peak aspheric departures are well-controlled; the maximum peak departure, contained on mirror M6, is 14.8 μm . The other mirrors have low-risk aspheres with departures that range from 1.7 μm to 10 μm , consistent with the ETS experience, allowing sophisticated visible light metrology without the need for a complex Computer Generated Holograms (CGHs) or null lenses.²⁷ The drawback of this design is the ± 190.5 mm ($\pm 7.5''$) dimension of mirror M4 in the sagittal or cross-scan plane. This is a direct consequence of the first-order layout used to minimize incidence angles. Such a large mirror size pushes the limits of currently available EUVL mirror and coating fabrication technology.

PNNPNP configuration

Figure 4B.13 illustrates yet another novel arrangement of optical power using a concave primary mirror.²⁶ The design uses a PNNPNP first-order layout to affect the highest level of low-order aberration correction using the base spheres. Like the design shown in Fig. 4B.11, this system uses a relatively strong aspheric primary mirror that adds induced aberrations in such a way to enable low residual wavefront errors. The aberration correction dynamics are quite different than the design of Fig. 4B.12. Here the pairing of positive and negative power is used to “continuously” balance aberrations; the results are clearly seen in a Zernike decomposition of the residual wavefront errors. At a NA of 0.25, the design has a composite rms

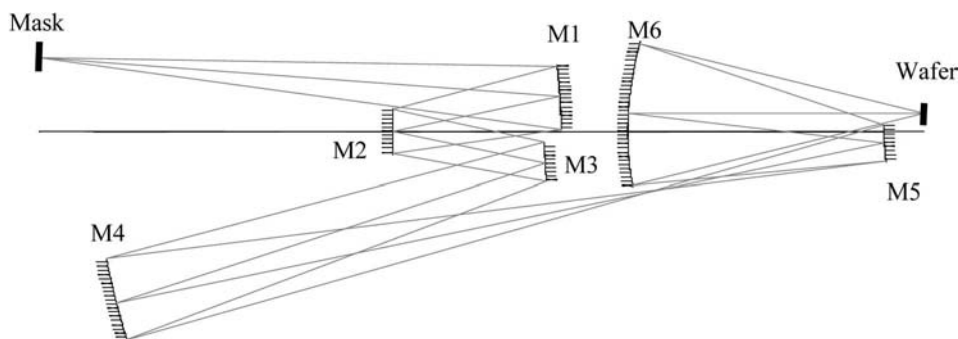


Figure 4B.13 Six-mirror EUVL projection system with a PNNPNP power distribution. The chief ray incidence angles (central field point) are as follows: mask, 4.3 deg; M1, 7.9 deg; M2, 11.5 deg; M3, 14.7 deg; M4, 3.2 deg; M5, 9.2 deg; and M6, 3.3 deg.

wavefront error of 0.012λ (0.16 nm) and less than 0.25 nm of distortion across its 2-mm ring field.

Based on the distribution of aberrations in the Zernike decomposition of the wavefront, it is immediately apparent that this design will have the most robust lithographic performance. Asymmetric aberrations to all orders are virtually eliminated, and the impact of residual even-order aberrations will be nullified via the scan average. This design form is itself robust, with the possibility for increasing either the NA or ring field width. NA aperture scaling and field scaling are possible with this configuration. For example, the field composite rms wavefront error is only 0.028λ (0.36 nm, $\lambda = 13.4$ nm) at 0.28 NA *without* re-optimization at this NA.

The design has a total track length of ~ 1450 mm and 65 mm of “clearance” from the vertex of mirror M5 to the wafer. The peak aspheric departure is 15 μm on mirror M1, while the other mirrors have peak departures that range from 0.5 to 11.0 μm . Again, the incidence angles are well controlled and similar to those in the other candidate designs. With more design effort, the chief ray incidence angles on mirrors M2 and M3 can be reduced by 1 to 2 deg.

Like the PPNPNP design, the location of mirror M4 in relation to the intermediate image makes mirror M4 quite large in the cross-scan dimension (± 186 mm in the sagittal plane). Although this off-axis section could be accommodated in currently existing ML deposition chambers, the mirror fabrication, mounting, and ML-coating thickness control would need to be carefully evaluated.

4B.4.3 Concepts with convex primary mirrors

NPNPNP configurations

Despite the difficulty in measuring a convex surface, there are certain advantages to developing an EUVL projection system using a convex primary mirror. A convex primary mirror can be used to reduce the field angle in the subsequent positive focusing group of mirrors. Also, this construction can be used to effectively minimize both ray angles and the diameter of the aspheric mirror parents.

Examples using a convex primary mirror are shown in Figs. 4B.14 and 4B.15.²⁸ What is immediately apparent is that the parent diameters of mirrors M1 through M4 can be reduced substantially, and this has favorable impacts on tolerance sensitivity and mirror fabrication. The design of Fig. 4B.14 uses a NPNPNP configuration and achieves a high level of aberration correction, in large part by the concentricity of mirrors M2, M3, and M4. Taken as a group, these mirrors relay the virtual image formed by mirror M1 at a $1\times$ magnification to the intermediate image, effectively acting like a $1\times$ Offner relay. At the wafer, this $4\times$ reduction system has a NA of 0.25 and a ring field width of 2.0 mm (centered on a radius of 30 mm) at the wafer. The composite rms wavefront error is 0.023λ (0.31 nm, $\lambda = 13.4$ nm), and the static distortion is corrected to better than 2 nm. The composite rms wavefront error does not tell the complete story; this concept has a unique and distinct

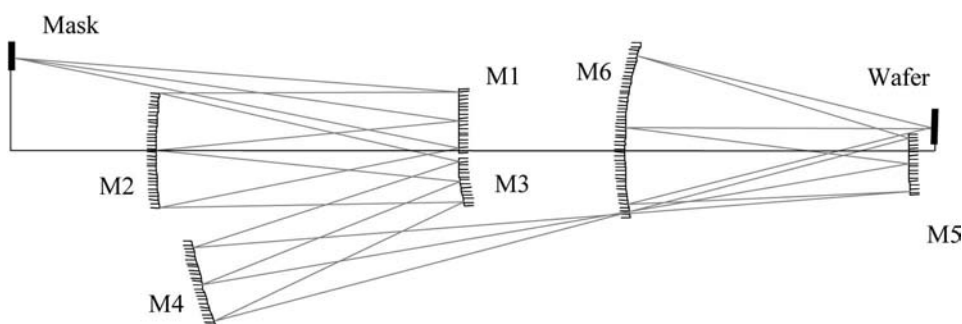


Figure 4B.14 Six-mirror NPNPNP design for EUVL. The design achieves lithographic correction in large part by using the concentricity of mirrors M2, M3, and M4. The chief ray incidence angles (central field point) are as follows: mask, 8.0 deg; M1, 6.9 deg; M2, 5.8 deg; M3, 13.8 deg; M4, 6.0 deg; M5, 8.8 deg; and M6, 3.3 deg.

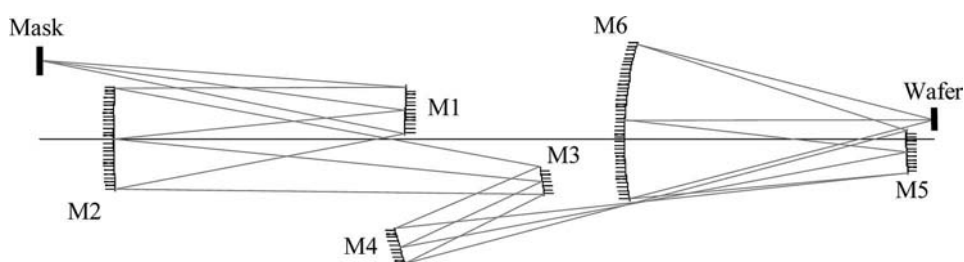


Figure 4B.15 Six-mirror NPNPNP design using mirrors M3 and M4 in closer proximity to the intermediate image. This promotes distortion correction without the need for deep aspheres. The chief ray incidence angles are as follows: mask, 7.6 deg; M1, 6.6 deg; M2, 5.6 deg; M3, 15.0 deg; M4, 7.0 deg; M5, 8.5 deg; and M6, 3.2 deg.

set of residual aberrations, as seen in the Zernike decompositions of the wavefront, reflecting the aberration correction dynamics present in the design.

This design has the potential to be scaled in either NA or field. For example, the rms wavefront error is only 0.036λ (0.48 nm) when the NA is scaled to 0.28, again representing the rms error *without* reoptimization at the higher NA. Alternatively, the ring field width can be scaled to large values.

The total track of the system is compact at a length of 1180 mm, and the ray angles on each of the mirror surfaces are well controlled. However, the 8-deg incidence angle at the mask and the 30-mm distance from the vertex of mirror M5 to the wafer need to be improved.

In addition to the low-incidence angles, the system utilizes low peak aspheric departure. The maximum peak departure, contained on mirror M5, is $17\ \mu\text{m}$. The other mirrors have low-risk aspheres with departures that range from 1.1 to $14.0\ \mu\text{m}$, consistent with the current mirror fabrication process experience. The low aspheric departures of the mirror surfaces facilitate visible light metrology without a null lens or CGH, resulting in a high degree of absolute accuracy.

Figure 4B.15 illustrates a different, but related, approach to the NPNPNP configuration. The idea here is to better use the convex primary to reduce the apparent

field angle to mirrors M2 through M5. Additionally, the extra convex surface in the fore mirror group (M1 through M4) is used to independently correct the Petzval sum at the intermediate image. This decoupling of the Petzval correction allows a bit more freedom to expand the back working distance. Since mirrors M3 and M4 are now closer to the intermediate image, the aspheres generate a better distortion balance, enhancing the overall distortion correction at the wafer.

At a NA of 0.25, this $4\times$ reduction design has a composite rms wavefront error of 0.023λ (0.31 nm, $\lambda = 13.4$ nm) across a 2.0-mm ring field centered on a 30-mm radius at the wafer. Again, all six mirrors are aspheric, and distortion is corrected to less than 0.5 nm. A hidden benefit of the distortion balance created by the quasi-field group (mirrors M3 and M4) is that the distortion remains well corrected as the ring field is expanded. The ring field width of this design can probably be increased in excess of 2 mm. The total track is ~ 1400 mm, and the back working distance as measured from the vertex of mirror M5 is ~ 44 mm.

The incidence angles are well controlled on each of the mirrors. The incidence angle at the mask is 7.6 deg and would need to be reduced in a real system. The peak aspheric departure is $15.2\ \mu\text{m}$ on mirror M5; the other peak departures range from 1.0 to $11.0\ \mu\text{m}$, again reducing fabrication and metrology risk. The proximity of mirrors M3 and M4 to the intermediate image has the effect of minimizing mirror dimensions in both meridians.

4B.4.4 Conclusions

The systems described in Sections 4B.4.2, 4B.4.3 look very similar in that they all have six mirrors and similar geometries. However, the reality is the residual aberrations in the various orders are quite distinct and when coupled with the effects of the multilayers, lithographic simulation will demonstrate performance differences that warrant further study. The commonality, which is good for EUVL as a technology, is that several potential optical systems exist to support the general technology at the 30 nm device node and beyond. Based on high optical performance, scalability, low incidence angles, low metrology risk, and back working distance, three concepts do stand out. The PPNNPP design is probably the best overall candidate due to high level of aberration correction, the low incidence angles, and low peak departure. The second NNPPNP design is a close second, being designed with exceeding low coma and low aspheric departures. The PNNPPNP design is compelling since its residual wavefront error is extremely well corrected across the field with very low higher-order aberration components.

Due to the high level of correction at 0.25 NA, the potential exists to scale concepts further in either numerical aperture or field.²⁹

Acknowledgments

The authors gratefully acknowledge the EUV LLC and SEMATECH for their support of EUVL programs at Lawrence Berkeley, Lawrence Livermore, and Sandia National Laboratories.

References

1. T. E. Jewell and J. M. Rodgers, "Apparatus for Semiconductor Lithography," U.S. Patent No. 5,063,586 (Nov. 5, 1991).
2. M. Suzuki, et al., "X-Ray Reduction Projection Exposure System of Reflection Type," U.S. Patent No. 5,153,898 (Oct. 6, 1992).
3. J. H. Bruning, A. R. Phillips, D. R. Shafer, and A. D. White, "Lens System for X-Ray Projection Lithography Camera," U.S. Patent No. 5,353,322 (Oct. 4, 1994).
4. R. M. Hudyma, "High Numerical Aperture Projection System for Extreme Ultraviolet Projection Lithography," U.S. Patent No. 6,072,852 (June 6, 2000).
5. Y. Ichihara and A. Higuchi, "Reflecting Optical Imaging Apparatus Using Spherical Reflectors and Producing an Intermediate Image," U.S. Patent No. 5,071,240 (Dec. 10, 1991).
6. R. H. Stulen and D. W. Sweeney, "Extreme ultraviolet lithography," *IEEE J. Quantum Elec.* **35**, 694–699 (1999).
7. R. Hudyma, M. Chandhok, and M. Shell, "Resolution limits of EUV projection technology", in 2006 SEMATECH Litho Forum, Vancouver, May 23, 2006. The SEMATECH Litho Forum materials can be found at <http://www.sematech.org/meetings/archives.htm>
8. J. E. M. Goldsmith, K. W. Berger, D. R. Bozman, et al., "Sub-100-nm imaging with an EUV 10 $\times$ microstepper," *Proc. SPIE* **3676**, 264–271 (1999).
9. R. Kingslake, *Lens Design Fundamentals*, Academic Press, New York (1978).
10. S. Lee, M. Shumway, L. Marchetti, et al., "Fabrication and alignment of 10x Schwarzschild optics for F2X experiments," SEMATECH 2003 EUVL Symposium, <http://www.sematech.org/meetings/archives/litho/euvl/20030930/posters/Poster117.pdf>.
11. R. Hudyma, "Projection Concepts for Advanced Microstepper," *AMP Technical Memorandum* M9801124 (Aug. 31, 1998).
12. J. Bokor and D. Shafer, "Design study for a high NA (>0.25) microstepper objective," *LBL Technical Memorandum* (Sept. 18, 1998).
13. R. Soufli, R. M. Hudyma, E. Spiller, et al., "Sub-diffraction-limited multilayer coatings for the 0.3 numerical aperture micro-exposure tool for extreme ultraviolet lithography," *Appl. Opt.* **46**, 3736–3746 (2007).
14. K. A. Goldberg, P. P. Naulleau, P. E. Denham, S. B. Rekawa, K. Jackson, E. H. Anderson, and J. A. Liddle, "At-wavelength alignment and testing of the 0.3-NA MET optic", *J. Vac. Sci. Technol.* **B 22**(6), 2956–2961 (2005).
15. P. P. Naulleau, K. A. Goldberg, J. P. Cain, E. H. Anderson, P. Denham, B. Hoef, K. Jackson, A.-S. Morlens, S. Rekawa, and K. Dean, "EUV microexposures at the ALS using the 0.3-NA MET projection optics," *Proc. SPIE* **5751**, 56–63 (2005).
16. P. P. Naulleau, C. N. Anderson, K. Dean, P. Denham, K. A. Goldberg, B. Hoef, B. La Fontaine, and T. Wallow, "Recent results from the Berkeley 0.3-NA EUV microfield exposure tool," *Proc. SPIE* **6517**, 65170V-6 (2007).

17. H. N. Chapman, R. M. Hudyma, D. R. Shafer, and D. W. Sweeney, "Reflective Optical Imaging System with Balanced Distortion," U.S. Patent No. 5,973,826 (Oct. 26, 1999).
18. D. R. Shafer, "Projection Lithography System and Method Using All-Reflective Optical Elements," U.S. Patent No. 5,686,728 (Nov. 11, 1997).
19. D. W. Sweeney, R. M. Hudyma, H. N. Chapman, and D. R. Shafer, "EUV Optical Design for a 100 nm CD Imaging System," *Proc. SPIE* **3331**, 2–10 (1997).
20. D. M. Williamson, "Four Mirror EUV Projection Optics," U.S. Patent No. 5,956,192 (Sept. 21, 1999).
21. R. M. Hudyma, "Reflective Optical Imaging System with Balanced Distortion," U.S. Patent No. 6,226,346 (May 1, 2001).
22. T. E. Jewell and K. P. Thompson, "Ringfield Lithography," U.S. Patent No. 5,315,629 (May 24, 1994).
23. R. Soufli, E. Spiller, M. A. Schmidt, J. C. Davidson, R. F. Grabner, E. M. Gulikson, B. B. Kaufmann, S. L. Baker, H. N. Chapman, R. M. Hudyma, J. S. Taylor, C. C. Walton, C. Montcalm, and J. A. Folta, "Multilayer optics for an extreme ultraviolet lithography tool with 70 nm resolution," *Proc. SPIE* **4343**, 51–59 (2001).
24. D. A. Tichenor, A. K. Ray-Chaudhuri, W. C. Replogle, et al., "System integration and performance of the EUV Engineering Test Stand," *Proc. SPIE* **4343**, 19–37 (2001).
25. D. M. Williamson, "High Numerical Aperture Ring Field Optical Reduction System," U.S. Patent No. 5,815,310 (Sept. 29, 1998).
26. R. M. Hudyma, "High Numerical Aperture Ring Field Projection System for Extreme Ultraviolet Projection Lithography," U.S. Patent No. 6,033,079 (Mar. 7, 2000); R. M. Hudyma, "High Numerical Aperture Ring Field Projection System for Extreme Ultraviolet Projection Lithography," U.S. Patent No. 6,183,095 (Feb. 6, 2001); R. M. Hudyma, "High Numerical Aperture Ring Field Projection System for Extreme Ultraviolet Projection Lithography," U.S. Patent No. 6,318,869 (Nov. 20, 2001).
27. G. E. Sommargren, "Phase shifting diffraction interferometry for measuring extreme ultraviolet optics," in *OSA Trends in Optics and Photonics, Vol. 4, Extreme Ultraviolet Lithography*, G. D. Kubiak and D. R. Kania, Eds., Optical Society of America, Washington, D.C., pp. 108–112 (1996).
28. R. M. Hudyma and D. R. Shafer, "High Numerical Aperture Ring Field Projection System for Extreme Ultraviolet Projection Lithography," U.S. Patent No. 6,188,513 (Feb. 13, 2001); R. M. Hudyma and D. R. Shafer, "High Numerical Aperture Ring Field Projection System for Extreme Ultraviolet Projection Lithography," U.S. Patent No. 6,262,836 (July 17, 2001).
29. R. M. Hudyma, "An overview of optical systems for 30 nm resolution lithography at EUV wavelengths", *Proc. SPIE* **4832**, 137–148 (2002).



Russell M. Hudyma received his BS and MS degrees in Optics from the University of Rochester. He specializes in the field of optical design, analysis, and simulation for a wide range of applications, including remote sensing, surveillance and defense systems, microlithography and semiconductor process. Over 100 of his designs have been built and implemented into commercial systems. He holds 83 U.S. and international patents, most of which are related to optical systems for semiconductor applications. He is the co-founder and managing partner of Hyperion Development, LLC.



Regina Soufli received her PhD in Electrical Engineering from the University of California, Berkeley, in 1997, and was staff scientist at the Harvard-Smithsonian Center for Astrophysics in 1997–99, studying the optical properties of iridium-coated mirrors for NASA’s Chandra X-ray Observatory. She joined LLNL in 1999 and has been the principal investigator on EUV/x-ray optics programs for semiconductor lithography, solar physics, synchrotron and free-electron lasers, and high-energy physics. Her interests are in EUV/x-ray interactions with matter, surface science, thin films, roughness and scattering. She has received several LLNL awards and two “R&D 100” awards while at LLNL.

Chapter 4C

Specification, Fabrication, Testing, and Mounting of EUVL Optical Substrates

John S. Taylor and Regina Soufli

Contents

4C.1 Introduction	161
4C.2 Specification	162
4C.3 Projection Optics	163
4C.4 Effect of Substrate Errors on Imaging Performance	164
4C.5 Low-Frequency (Figure) Errors	165
4C.6 Mid-Spatial-Frequency Errors	169
4C.7 High-Spatial-Frequency Errors	170
4C.8 Influence of Coatings on Roughness Specification	171
4C.9 Calculation of Surface Errors	171
4C.10 Uniformity	173
4C.11 Substrate Materials	173
4C.12 Fabrication	174
4C.13 Metrology	176
4C.14 Mounting and Assembly	177
4C.15 Alignment	179
4C.16 Condenser Optics	179
Acknowledgments	181
References	181

4C.1 Introduction

The specification, fabrication, testing, and mounting requirements of optical system substrates are intimately related. This statement may seem self-evident, but the delivery of coated, characterized, and mounted optics that meet functional specifications is often the long straw when it comes to delivering a leading-edge lithographic tool. Even this collection of four tasks is an abbreviated list, because many other aspects of designing and manufacturing a lithographic optical system are

also interrelated, including the optical design (e.g., avoiding designs where an optical surface is close to the edge of the substrate), multilayer (ML) coating (e.g., maximizing the amount of smoothing from the deposition process to potentially relax the polishing requirements and minimize coating-added figure errors), and alignment (e.g., offering sufficient degrees of freedom so some aberrations that are constant over the field, such as astigmatism or defocus, can be mitigated by the repositioning of elements).

Some aspects of this chapter may be familiar to people with knowledge of delivering an optical system to leading-edge specifications. It is hoped that this chapter has not omitted too many of the details, nor emphasized concerns that have been rendered as standard operating procedures. The intended audience for this chapter includes new personnel entering the optics area for the first time, team members that interact with the optical fabrication team, and the broader lithographic community that depends on the successful performance of the optical system. Here we are concerned with the substrates in particular, while other aspects of the optical elements, such as the ML coatings, are covered in other chapters.

The key to constructing any optical system is in formulating a system error budget, which includes all of the contributions to the final set of aberrations and scattered light in the installed system. As a preliminary (and simplistic) example, the system performance specification will lead to a required level of pupil aberrations. These aberrations could be partitioned into figure errors (phase errors) for each of the mirrors in the projection system. The error budget for figure on a mirror would need to be shared among fabrication, coating, metrology uncertainty, and mounting. Other system considerations, such as thermal management of the mirrors, should also be considered. The toughest and most important job of the system engineer is to lead the partitioning of errors among the different contributors, so each has goals that have a reasonable chance of success, i.e., an acceptable level of risk. This ensures that the production yield of the completed substrates is acceptably high and predictable.

4C.2 Specification

This chapter on substrate requirements will broadly address the tolerances of manufactured optical surfaces whose errors deviate from the ideal surfaces that are determined from the optical design process.¹ Note that all designs for a wide-field imaging system will have “design residuals,” where there are nonzero levels of aberrations even if the substrates are made perfectly true to specifications. Although small, these design residuals are important because their characteristics may determine the system’s sensitivity to alignment errors, fabrication figure errors, and effective depth of focus (DOF). The lithographic optics community has developed detailed metrics for evaluating the quality of imaging systems, a discussion that extends well beyond the introductory nature of this chapter.² Generally, the fabrication errors on the mirrors will greatly outweigh the design residuals.

Once an optical design is committed to fabrication, the designer or system engineer should focus on the system's sensitivity to manufacturing errors. Occasionally, there is a tendency to call the design process complete when the aspheric coefficients and sag table are committed to a drawing and the drawings move off to the fabricator. However, this stage of the design process is a vital link for the fabricator and the means for closure for the system engineer. Instead of focusing on design residuals, the emphasis should now be on establishing a rapid methodology for inserting real fabrication errors into the performance simulation to determine the system's sensitivity to real substrate errors. Although fabricators may perform some sensitivity analyses, such as for classic Zernike terms^{3,4} to complete the drawing package, fabricators have remarkable creativity to generate surface errors that are not well described by just a handful of Zernike terms. For example, small slope errors may result from cyclical structures and isolated holes ("phase bumps") where the material process may leave a localized trough. At this stage, fabrication and design enter an iterative process where anticipated and measured figure errors (phase errors) are reinserted into the design analysis to predict the level of performance degradation for a given set of errors. By considering a wide variety of error formulations, usually with some *a priori* knowledge of what errors could be expected from fabrication, mounting, and assembly processes, a set of tolerances can be formulated for characteristic errors that are observed on the substrates. Although this iterative process may be happening as production proceeds, at least with prototype optics, this process will enable the formulation of an error budget that spans a range of anticipated errors. This error budget will lead to a credible understanding of the relative importance of different errors and their contribution to the risk in meeting performance requirements.

4C.3 Projection Optics

The principal goal of the projection imaging system is to deliver doses of optical energy to the photo-sensitive resist-coated wafer in the correct locations, namely within the critical dimension (CD) of the printed pattern. One means of considering the imaging process is to map a point on the mask (reticle) and determine what happens to the radiant energy reflected from this point as it propagates through the optical system, fills the aperture, and is directed to the wafer. In all optical systems, the energy bundle will broaden due to diffraction at the aperture and to shape errors and roughness on the mirrors. The bundle of energy from a single object point incident on the wafer plane is called the point-spread function (PSF). For an imaging system with a circular aperture and perfect optical elements with an appropriate design, the PSF will be the familiar Airy pattern. Generally speaking, all optical designs of lithographic quality will demonstrate a PSF with near-Airy-pattern width, assuming perfect surfaces; an imaging system whose resolution is largely determined by the width of the Airy pattern is considered diffraction-limited. For pupils with an obscuration, the shape of the ideal PSF will be different than the classic Airy pattern. For lithographic optical systems, simple metrics for

diffraction-limited imaging are generally not sufficient.⁵ The imaging system may exhibit distortion, degraded DOF, and proximity effects from coherence effects in the overlap of the PSFs from neighboring field points.

As errors in the elements of the optical system are incorporated into the analysis, the PSF generally broadens by redistributing energy to a wider area. This area will not typically be circularly symmetric, and the converging wavefront may begin to show intensity variations akin to speckle. All of these effects will degrade resolution, and likely degrade DOF. Generally, if the PSF broadening is sufficiently small compared to the original width, then the system may still be called diffraction-limited. One common metric for defining the concept of diffraction-limited is Marechal's criterion, which suggests that the added rms error to the optical wavefront should not exceed $\lambda/14$ (~ 0.07 waves) of added error for a Strehl ratio of 0.80. Yet, from a lithographic perspective, imaging performance (e.g., DOF), uniformity over the field, the exposure-defocus window, flare, sensitivity to defects and line edge roughness (LER), horizontal-vertical bias, etc., can all be significantly degraded.⁵

With the overall goal of placing the dose of incident energy at the correct locations on the wafer, the centroid of the PSF should be centered at the correct position on the wafer, which is a deviation from some design approaches that focus on the position of the chief ray as it intersects the wafer plane. There is a general goal that the design of an optical system should be telecentric, which means that the chief ray of the system is normal to the wafer plane so that small errors in the flatness or defocus of the wafer plane do not result in the image shifting "through focus." However, even with a telecentric design, some aberrations (especially coma) that are introduced by design residuals or figure errors on the optics will cause the PSF centroid to laterally shift for different image planes, leading to through-focus image placement errors.⁶ Astigmatism will also vary in horizontal-to-vertical resolution characteristics as a function of defocus. Thus, when the robustness of an optical design or corresponding fabrication specifications to maintain diffraction-limited performance is evaluated, both the wafer-plane and through-focus behavior of the PSF, including lateral shifts, should be considered.

This chapter will discuss the first-order effects of substrate errors on imaging performance, the formulation of specifications, and the characterization of the errors. It is outside the scope of this chapter to develop a rigorous specification procedure that embodies the 3D variation of the PSF at the wafer plane.

4C.4 Effect of Substrate Errors on Imaging Performance

As a light ray strikes a mirror with surface errors, it will be deflected off its *as-designed* location. The amount of deflection can be calculated by one of two methods: (1) considering the slope errors on the mirror and then applying geometrical ray tracing, or (2) considering the surface to be a grating that comprises a spectrum of frequencies and applying diffraction theory, where the deflection is a function of the spatial frequency and amplitude. Large slope errors, high frequencies,

and large sinusoidal amplitudes correspond to large angular deflections. Similarly, small slope errors, lower spatial frequencies, and lower amplitude errors correspond to smaller angular deflections.

To specify the figure on a substrate, one must consider the difference between specifying the figure to meet a given aberration requirement at a single field point and the need to meet the aberration requirements over the entire field. This is best discussed by considering the rays incident on a mirror from a single field point versus the collection of rays incident on the mirror from the entire illuminated field. As light from a single point on the mask passes from mirror to mirror in an EUV imaging system, it will illuminate a footprint on each of the mirrors. From an analysis of the projection optics alone (i.e., without considering the condenser), one can consider the projection of the system's circular aperture stop on each of the mirrors centered on the chief ray from a point on the mask, within the system's field of view. This circular patch on the mirror is referred to as the instantaneous clear aperture (ICA) of the mask point on that mirror. All light radiating from the mask can be considered to be the sum of the circular ICAs of the mask points within the field of view. This area will generally form a region on each mirror called the clear aperture (CA), which is kidney-shaped for a ring-field imaging system, as is shown in Fig. 4C.1. A mirror that serves as an aperture stop will have all of the ICAs overlapping in the same circular pattern. For any mirror, the portion of the surface that needs to be specified for quality control is within the CA. For any specific point on the mask (i.e., field point), the only region on the mirror that must be specified is its respective ICA. This leads to the question of how to specify the CA with respect to the needs of the ICA. Ultimately, a mirror comprises a single physical surface with a requirement for global profile accuracy in the CA that meets the needs of each ICA.

For an extended field of view such as a ring-field imaging system, the image quality requirements must be considered for each point within the field of view. Thus, the quality of the mirror must be considered for each ICA on each mirror. For some of the ICAs, it may be easier to ensure good surface quality during fabrication than for others. This might be the case when some ICAs are close to a physical edge on the mirror, leading to potential difficulties in polishing up to the edge of a piece of glass. In this case, some field points might exhibit diffraction-limited image quality while the points with the more difficult ICAs may exhibit degraded character. The specification of mirror quality generally considers both the full CA of the mirror and the variation that can be accepted among the set of ICAs. Lithographic operating conditions, such as dose control in compensating for flare, will be constrained if there are variations in mirror quality across the field.

4C.5 Low-Frequency (Figure) Errors

When considering the errors on the mirror as a function of spatial frequency, there is essentially a continuum of frequencies, each contributing to angular deviations of the rays. However, it is convenient to divide the spatial frequencies of the errors

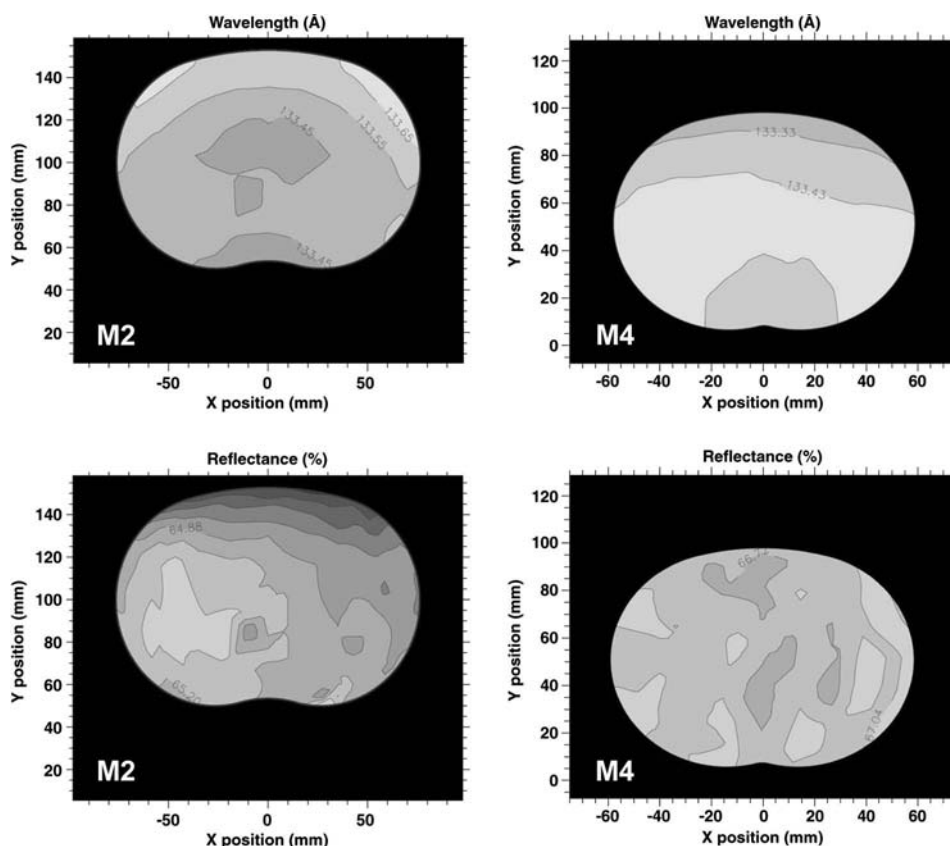


Figure 4C.1 Two-dimensional contour maps of wavelength (top) and reflectance (bottom) in the kidney-shaped clear aperture (CA) area of the M2 (left) and the M4 (right) mirrors of the four-mirror ETS projection system. The wavelength maps confirm the ML thickness uniformity over the entire CA and the rotational symmetry of the coating process around the optical axis, located at $(x, y) = (0, 0)$ mm. There is a 2.5% variation in absolute reflectance across the M2 surface and a 0.6% variation in reflectance across the M4 surface due to substrate finish variations. (Reprinted from Ref. 40.)

into broad categories—low, mid, and high—where each category has a qualitatively different influence on imaging performance. Low-frequency errors are considered to be those that lead to ray deflections lying approximately within the CD of the image. Thus, if the CD is 45 nm, then the delineation of the low-frequency errors on the mirror would be those that deflect the rays within a small neighborhood around the 45-nm feature. These errors determine resolution, horizontal-vertical bias, through-focus errors from coma, etc. The small slope deviations lead to fantastically small allowable height errors on the mirrors. For example, a mirror with a ripple pattern and a spatial wavelength of 1 cm located an effective distance of 0.5 m from the wafer could have a P-V (peak-to-valley) amplitude of only 0.15 nm, such that the ray deviation would be less than 45 nm.

Because the ICA on any particular mirror is circular, it is possible to analyze the low-frequency errors in terms of either spatial frequency or Zernike

polynomials, with essentially equivalent results. Typically, it is the first 16 to 37 Zernike terms that are used for low-frequency analysis. The advantage of using Zernike terms is the familiarity with qualitative imaging metrics, as in a statement such as “figure errors on mirror x lead to a variation in astigmatism over the field.” On the other hand, the spatial periods covered by the Zernike terms are not as neatly delineated, for example, as when low-frequency figure errors are defined as errors with a spatial period below 1 mm. The spatial frequency delineation enables one to account for all of the errors in the mirrors in terms of power spectral density (PSD); if lower-frequency errors are specified in terms of Zernike terms and higher-frequency errors are specified in terms of spatial frequencies, one must be careful to avoid gaps or double-counting some frequencies in the spectrum.

The practical approach to specifying low-frequency errors is to look at three important metrics: (1) the total rms power over the full CA integrated up to the frequency that scatters to the edge of the CD; (2) the total rms power within each ICA integrated to the same frequency limit, along with the variation over the set of ICAs; and (3) an analysis of key Zernike terms for each ICA and their variation over the field. By considering all of these approaches to specification, one gains a connection between the physical characteristics of the mirror, a qualitative sense of the impact on imaging performance, and often a valuable link to the method of fabrication.

Although this chapter does not define acceptance criteria for each type of aberration, it is instructive to consider the relationship between specifications for the ICA and those for the full CA. For illustration, we will consider the variation of tilt over the set of ICAs and how this relates to a specification for the figure within the CA. A variation in ICA tilt aberrations across the field leads to image placement errors, or distortion.

In considering tilt, which comprises Zernike terms 2 and 3 (depending on the naming convention), we have a straightforward requirement: we cannot deflect the centroid of the image of a field point by an amount determined by the distortion and image placement specification. Therefore, the tilt variation among all ICAs will be limited to an amount such that the arithmetic sum of the tilts among the corresponding ICAs on all sequential mirrors is below a maximum value. (Note the distinction between the ICAs on a single mirror and the sequential ICAs on different mirrors corresponding to a single field point.) This upper limit on tilt can be partitioned among each of the mirrors. It is reasonably straightforward to take a figure map of the mirror's CA and statistically sample the average tilt of the ICAs on the mirror to determine if they are all below a given value, then assert that the centroid of the image point will lie within its distortion tolerance. Other aberrations may lead to migration of the centroid, but this is a good first approach to inter-relating ICAs and the overall specification on the CA. Because the surface needs to be continuous, and the tilt implies an average height difference across the ICA, there is an implied height specification at a spatial period of twice the diameter of the ICA or longer (imagine ICAs on opposite sides of the peak of a sine wave). For example, consider a 50-mm ICA located 0.5 m from the wafer, and

a specification of $CD/10 = 4.5$ nm for the image placement error; the allowable tilt from a reflective surface would be a fraction of 0.23 nm across the ICA, depending on the system error budget. This would suggest a specification for 100-mm spatial periods across the CA of 0.23 nm P-V or ~ 0.08 nm rms (or less, depending on the system error budget).

Long-spatial-period errors across the CA also contribute to defocus variations across the field (field flatness) and astigmatism, as when defocus variations that are positive in one direction and negative in another direction. The lowest spatial frequencies (defocus, tilt, and astigmatism) are mostly related to where image points are located, with differences in horizontal and vertical foci associated with astigmatism.

Returning to the Marechal's criterion for a six-mirror system, if the requirement for wavefront error is $\lambda/14$ rms and the contributions from each of the mirrors are assumed to be statistically independent, then each mirror is allocated a maximum wavefront error of $(\lambda/14)/\sqrt{6} = 0.029\lambda$. The height specification is half of the wavefront for a reflective system, or about 0.015λ . For $\lambda = 13.5$ nm, the figure specification (Marechal) is 0.2 nm rms. Similarly, for a four-mirror system, the figure specification per Marechal would be about 0.25 nm rms. In Fig. 4C.2, the height errors for four mirrors of the Engineering Test Stand show that in 2000, 0.25 nm surface figure was achieved for the first demonstration of diffraction-limited performance for a full-field EUVL projection system.^{36–38} Note that the figure on

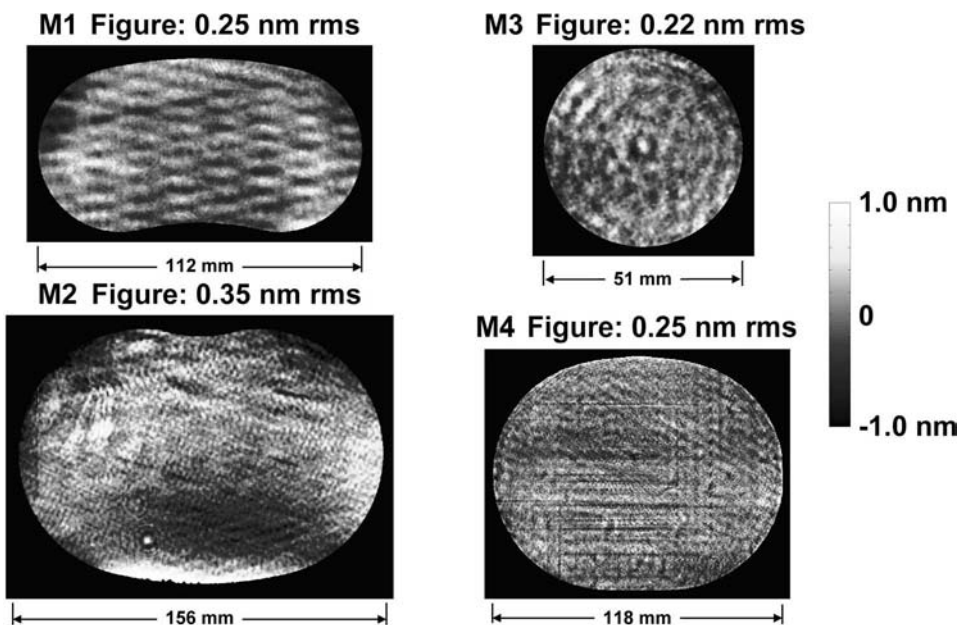


Figure 4C.2 Two-dimensional maps of height error for the four mirrors of the ETS imaging system measured using the Phase-Shifting Diffraction Interferometer at LLNL.³⁶ The clear aperture (CA) of the substrates is indicated for the full ring-field. Substrate fabrication was performed at ASML Optics.³⁷

substrate M2 is 0.35 nm rms instead of 0.25 nm rms. Analysis of imaging performance using the real fabrication errors indicated that this additional error resulted in uniform astigmatism across the field and would be automatically removed during system alignment, and thus did not require further correction during fabrication.

As mentioned above, if other concerns such as the effective DOF of the system are taken into account, Ref. 5 suggests that the system wavefront errors may need to be limited to $\lambda/50$ rms. This is about a factor of 3 smaller than allowed by Marechal, thus suggesting that the figure errors on the mirrors should be less than 0.06-nm rms. The numerical distinction between these two sets of specifications (~ 0.06 versus 0.20 nm rms) is at the state of the art in mirror manufacturing (fabrication *and* testing). Understanding the nuances of each aspect of the specification and what determines acceptable lithographic performance (process window) is the key to the acceptance criterion. Aside from effective DOF, another concern in applying these broad “bucket-type” specifications is the assumption that the figure errors are uncorrelated among the mirrors. Six mirrors is not a large number of surfaces, and the averaging of a localized phase bump of one mirror among the other surfaces is not nearly as effective as blending errors across the dozens of surfaces for an excimer-based transmissive projection system. In fact, a more conservative approach to tolerancing certain low-order errors, such as astigmatism, would be to choose a combinatorial rule that allows some correlation among the low mode errors from different mirrors, such as astigmatic-shaped errors (the egg-shaped phase error has a chance of being co-aligned among the different mirrors). However, simulating performance with the as-fabricated errors is essential, such as in the case mentioned above where the surface errors due to uniform astigmatism across the field could be compensated during alignment.

4C.6 Mid-Spatial-Frequency Errors

When ray deviation angles (or scattering angles) lead to the dose being incident on the wafer outside of the CD, the contrast of the printed features degrades. This condition is commonly referred to as *flare*. This broadly considers scattering angles, where the irradiance on the wafer ranges from the CD width to the edge of the printed field. If the exposure tool has a moving shutter or blades that delineate the region on the wafer exposed to light, then the range of scattering angles that contribute to flare are those that place any unwanted energy within the instantaneous exposed field. Because the distance from each mirror to the wafer is different, the spatial frequencies that contribute to flare will be different for each mirror, thus leading to a different set of specifications on each of the mirrors. In round numbers, the spatial periods that contribute to flare are often of the order of 1 μm to 1 mm. For a ring-field system, the chord length of the field is larger than the width of the ring, perhaps by 12:1, which indicates that the scattering angles that contribute to flare in the cross-field direction can extend a factor of 10 further than in the scan direction (assuming that framing blades are used to delimit the ring-field shape).

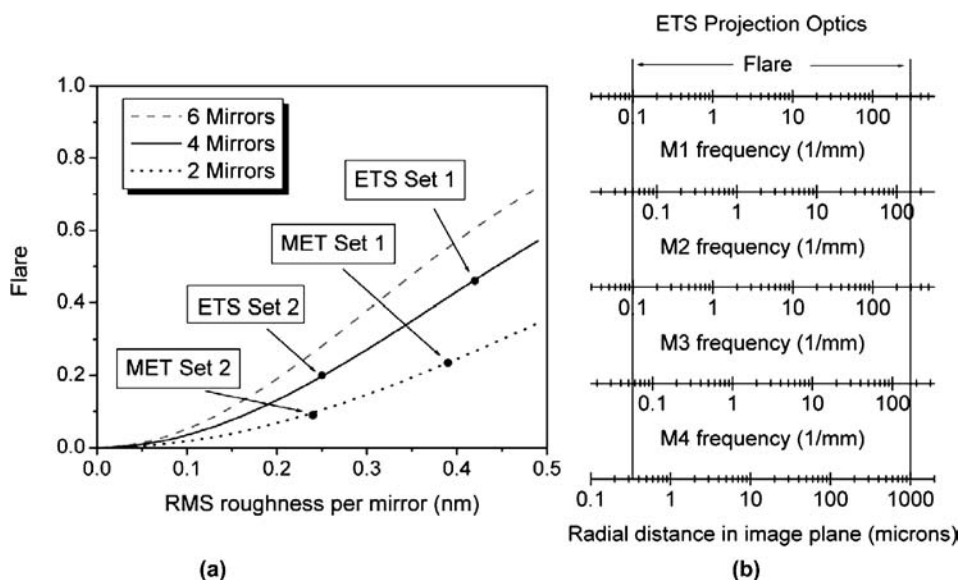


Figure 4C.3 (a) Flare calculations versus substrate roughness are shown for a full-field, 0.1 numerical aperture (NA), four-mirror camera (the Engineering Test Stand, ETS), and for a microfield, 0.3-NA, two-mirror camera (the Micro-Exposure Tool, MET). The solid points are calculations derived from actually fabricated and measured substrate sets. A calculation of the flare for a six-mirror EUVL camera is also shown as a dashed line. (b) Spatial frequencies relevant to flare for each of the four mirrors in the ETS camera. (Reprinted from Ref. 10 courtesy of E. M. Gullikson at LBNL.)

The influence of flare is to lower the contrast between the lines and spaces, leading to a decreased exposure-defocus (E-D) process window. Flare can also be analyzed by PSF broadening, which has been described as the addition of a skirt around the core of the intensity peak.⁷ Essentially, all effects that redistribute energy from the peak of the PSF to the skirt have an influence on flare by decreasing the Strehl ratio. The finite size of the CD distinguishes mid-spatial-frequency errors from figure errors for longer spatial periods, and the finite field of view delimits the effect of mid-spatial-frequency errors from wide-angle scattering for short spatial periods. Gullikson^{8,9} analyzed mid-spatial-frequency errors from developmental EUV mirrors and estimated the level of flare for projection optical systems with differing numbers of mirrors, as is illustrated in Fig. 4C.3 from Ref. 10. It has been shown that the influence of flare on lithographic printing can be approximated as a convolution between a *flare PSF* and the printed image.¹¹

4C.7 High-Spatial-Frequency Errors

When the scattering angle is sufficiently large to direct light outside of the image field, it leads to an energy loss, i.e., low dose. The specific spatial periods of roughness that contribute to wide-angle scattering are unique to each mirror. In general, high-spatial-frequency roughness (HSFR) is most often characterized

using an atomic force microscope (AFM), an example of which is shown in Fig. 4C.4. HSFR might be superficially delimited at spatial periods less than $1\text{ }\mu\text{m}$, although there may be a difference factor of 10 in the spatial period that defines wide-angle scattering among the mirrors. There may be a factor of 12 difference in spatial periods that define the low-spatial-frequency boundary in the scan and cross-scan directions. HSFR variations across a substrate CA will lead to commensurate variations in reflectivity from the ML-coated mirror. If such variation is sufficiently large, it will lead to apodization effects across the system exit pupil and will ultimately result in poor CD uniformity across the printed field, as was discussed in Sec. 4C.2. Figure 4C.1 from Ref. 40 provides an example of reflectance nonuniformity due to substrate finish across actual ML-coated EUVL mirrors.

4C.8 Influence of Coatings on Roughness Specification

All of the mirrors will have a ML coating deposited upon them. Stearns has modeled the film growth and evolution of substrate roughness during the ML deposition process, and how this relates to scattering.¹² Broadly speaking, for the high-quality coatings that have been deposited for EUVL applications, there will be some smoothing due to the deposition process. This is distinctly different from coating processes that lead to “cauliflower” growth, or the intentional deposition of columnar structures for photonics applications.¹³ For the DC-magnetron coatings familiar to the authors, a smoothing effect begins for spatial periods shorter than about 50 nm. This smoothing might be characterized as a transfer function where periods smaller than 50 nm are attenuated and periods longer than 50 nm are replicated throughout the coating. The filtering effect is important in estimating the predicted loss from a surface, and in setting an upper limit on spatial frequency for specifying the HSFR for the substrate fabricator. It has been shown that the smoothing effect of the coating can be extended to longer spatial periods ($>1\text{ }\mu\text{m}$) for ion-beam deposition, particularly if an intermediate ion etching process is incorporated into the process.¹⁴

4C.9 Calculation of Surface Errors

Except for the consideration of specific Zernike terms, the useful metric for describing surface height errors is the 2D PSD. The formalism for calculating the 2D PSD is described by Taylor, where the output is a 2D image in frequency space delineated by spatial frequency in the x and y directions, respectively.¹⁵ The units of the 2D PSD are length to the 4th power. Analysis of these frequency-space plots can be useful, especially in searching for specific directional periodicities. In the case of roughness, it is often useful to calculate the average radial PSD, which is determined by selecting a broad set of traces from the 2D plot beginning at the origin, where each trace is directed in a different direction. The set of radial 2D PSDs are then averaged and plotted as a single curve versus spatial frequency; the units are still length to the 4th power. The value of this representation is that tendencies for

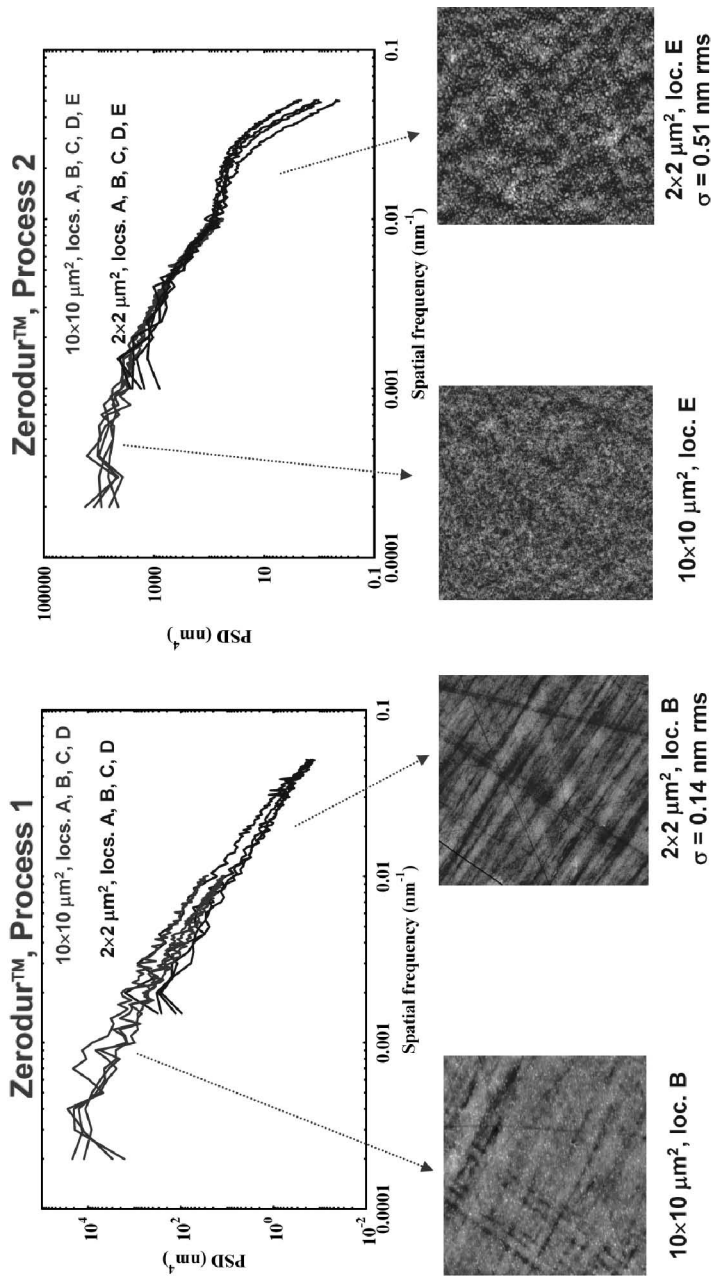


Figure 4C.4 AFM measurements performed at LLNL on two Zerodur substrates designed for imaging at EUV wavelengths. On the left, the two AFM images contain superimposed polishing marks, in preferential and random directions on the surface, and are attributed to a conventional polishing process. On the right, the two AFM images show uniform and isotropic surface topography with granular appearance and a shoulder-like feature in the PSD curve, which are attributed to an ion-beam polishing process. (Reprinted from Ref. 25 with permission of the Optical Society of America.)

periodicities are graphically discernable, and that PSDs may be more readily compared. For example, it is often convenient to compare PSDs from different mirrors or different vendors, or to track a mirror as it progresses through various polishing or coating operations. From the average radial PSD, one can observe whether the coating operation has had a smoothing effect on the higher spatial frequencies. The radial PSD should only be considered if there is a reason to assume that the height errors encompassed by the spatial frequency range of the calculation are isotropic. It is necessary to build up a broad-spectrum PSD from the overlapping PSDs of many measurements, spanning different instruments and instrument bandwidths. The PSD from each instrument will show some evidence of its intrinsic transfer function and will generally have a range that is representative of the surface and not dominated by instrument roll-off. It is often useful to fit a high-order polynomial (e.g., 6th order) to the PSD for a simplified representation of the errors, or to consider a fractal fit. Note that a 1D PSD is not a single trace from a 2D PSD, but is related to the 2D PSD by an integral transform.¹⁶

4C.10 Uniformity

The goals of constructing an optical system include meeting a minimal level of wavefront control and distortion for all points within the ring-field. Variations in optical quality across the ring-field also should be minimized, because they affect the variations in the E-D window across the field. For example, variations in flare across the field tend to change the contrast and the exposure demands to clear the resist across the field. In deep ultraviolet (DUV) systems, some flare variations are predictable and could be considered in the mask design. For EUV systems, flare variations will generally be dominated by variations in polishing quality across the field, which should be minimized. Variations in HSFR lead to nonuniform pupil illumination, resulting in anomalies in spatial coherence and weighting of the pupil aberrations. As an example, some nonuniformity in the effective pupil illumination due to variations in wide-angle scattering could result in a horizontal-vertical printing bias. The flare variation across the field for EUV imaging systems is potentially much less than for DUV imaging systems, with significant roll-off only at the edge of the field.¹⁷

4C.11 Substrate Materials

The basic choices for projection (camera) optics and for reflective masks are glasses and glass-ceramics with low coefficients of thermal expansion (CTE), which are produced by several companies. For EUV applications, it is important to work closely with the material vendor to obtain the properties of near-zero CTE for an application-specific temperature, which may require a different material than what is provided in the catalog. For example, if the thermal modeling of the lithographic tool suggests that the steady-state operating temperature of a mirror will be near 30°C, it may be desirable to choose a material that has a zero CTE at this

temperature. Similarly, it may be important to choose a material that has a uniform CTE throughout its cross section. For example, Zerodur and ULE have been used as substrate materials for projection optics and masks, respectively, in developmental and alpha-class EUVL tools. Having minimal residual stress, and variation in residual stress, is also important to minimize shape deformations that may occur during material removal operations. Condenser optics for EUVL systems are subject to a slightly different set of requirements, because their surface figure specifications are not as stringent and they may be required to survive much harsher environments (elevated temperatures and contamination) than the camera or the mask. For these reasons, silicon (Si), silicon-carbon (SiC), and other novel types of substrates have been implemented in EUVL collector and illuminator systems. Sections 4C.16, 4D.5, and references therein have more details on this topic.

4C.12 Fabrication

The fabrication of optical substrates has advanced during the past decade, motivated by the continued push of excimer-based lithography, particularly in the increasing use of aspheric elements and the need to correct for inhomogeneity. Although the figure and finish requirements for EUV elements are tighter than for laser-based lithography systems, the difference is not as great as the ratio in wavelengths might suggest. This is because current-generation excimer-based lithography scanners have many more surfaces, and their need to control the E-D window is potentially more challenging because the “ k_1 factor” tends to be much lower than for proposed EUV systems.

The sequence of substrate fabrication operations may include many proprietary operations and is not commonly publicized. In general, the fabrication process begins with a shaping operation where the basic shape is prepared by a combination of sawing, grinding, and lapping. Datum surfaces such as the outer periphery will be prepared by a polishing operation and validated with a coordinate measuring machine (CMM). The basic shape of the optical surface is generated by fixed-abrasive and/or loose-abrasive grinding. When all of the grinding is complete (prior to any polishing), there may be an etching operation to relieve grinding-induced surface stresses. Typically, all of the substrate surfaces are polished to control particulate generation and minimize outgassing in the coating chamber and lithographic tool. When the CA is very near the edge of the substrate, special measures are necessary to enable the material-removal tools to approach the edge without altering their performance. In some cases, grinding operations are necessary after final polishing; these operations can pose a risk that the shape of the substrate may deform either due to residual stresses in the material or machining-induced stress from the operation.

The preparation of the optical surface has typically been performed by an iteration of polishing and interferometry. There are many different approaches to the final surface finishing; here we will consider the traditional concept of small-tool polishing.^{18,19} From an interferogram of the surface, a map of the

height errors on the surface is generated within the coordinate system defined by the data. The polishing tool will have a characteristic removal footprint, which might qualitatively be envisioned as Gaussian, although vastly different shapes are possible. The amount of material that is removed is a function of how long the tool dwells in a location, or analogously, how slowly it laterally scans over the optic. The amount of material that is removed from any one point on the surface is due to the sum of the contributions from all positions of the polishing tool. A deconvolution routine determines the appropriate scan speeds or dwell times as the tool traverses over the surface. For a given tool and set of errors, only a fraction of the errors will be removed in one iteration. As the height of the errors decreases to the process control limits and the repeatability level of the interferometry, the convergence will become less deterministic. At this ragged edge of technology, meeting the leading-edge specifications will stress the equipment, data analysis, and procedural discipline of the team. Note that other methods for the finishing of optics include magnetorheological finishing²⁰ and ion-beam figuring.^{21–24} Figure 4C.2 illustrates the residual low-frequency errors on Zerodur EUVL substrates for the ETS^{36,37} and Fig. 4C.4 shows an example of the morphology in the high-spatial-frequency range, as measured by AFM at Lawrence Livermore National Laboratory (LLNL), for two Zerodur EUV optical substrates polished by two different techniques (from Ref. 25).

Often during the final convergence phases on figure and finish specifications, a tradeoff develops between figure correction and polishing to achieve an acceptable surface finish.²⁶ This tradeoff is best exemplified by considering a plot of the average radial PSD. Figuring tools tend to conform to the optical surface and achieve their desired removal by dwelling at a given location for a specified period of time (usually accomplished by a variation in scan speed). Tools for improving finish tend to have a stiff surface, and they remove material by bridging across the roughness and preferentially removing the high spots. The art of designing a polishing process is to have tools that fulfill both of these requirements, or separate tools with characteristics that do not overlap into each other's spatial frequency domain (e.g., a figuring tool that does not address finish, and a smoothing tool that does not affect figure). In reality, this separation between figure and finish does not perfectly occur, and switching between tools tends to degrade the PSD in the zone of overlap. When tracking the convergence of meeting a specification on a PSD plot, one sees the PSD tilt down to the left when improving figure, and tilt up on the right while degrading finish. The converse can be observed when the finish tool is used. The point at which the PSD tilts (i.e., the fulcrum) is often around a spatial period of 1 mm. Successful polishing operations will minimize the amount of degradation that occurs for spatial periods other than the one being purposefully addressed while sequentially lowering the fulcrum point with each iteration.

4C.13 Metrology

As discussed above in terms of specifications, all of the spatial frequencies of the height errors on the substrate affect the performance of the optical system. Therefore, metrology covering the full spectrum of spatial frequencies is necessary to aid in fabrication, validate specifications, and provide substrate data to simulate the performance of the optical system. For figure errors, the most common means of obtaining height data is interferometry (often phase-shifting), where the aperture of the measurement can range from portions of the CA or ICAs, to the full CA. The mirrors are typically aspheric, which usually results in the fringes being very closely spaced in the regions of high aspheric slope. This condition will require either the use of null compensators,²⁷ or high-resolution cameras to resolve high fringe density, or the adoption of stitching methods to link multiple height maps from subregions on the surface.^{28,29} The measurement of aspheric optical surfaces poses numerous challenges in controlling measurement errors, although detailed approaches to understanding measurement errors have been presented.^{30–34} In prototype EUVL systems (see Fig. 4C.2), interferometric measurements have been made using the phase-shifting diffraction interferometer (PSDI)³⁵ that support the determination of figure errors (spatial periods ranging from the full CA to 1 mm) with an accuracy of less than 0.25 nm rms.^{36–38} In the case referred to in Ref. 35, the estimated accuracy for the interferometric measurement was consistent with the measured wavefront error of the aligned optical system. In another case, some small discrepancies were found between independent interferometric measurements of the same mirror, possibly due to systematic errors in one of the systems.³⁹

For MSFR, the relevant spatial frequencies include the high-spatial-frequency portion of the range measured by large-aperture interferometry, the range covered by phase-measuring microscopy (PMM), and often the low-frequency portion of the range covered by an AFM instrument. The specifics of the mid-frequency range depend on the factors mentioned regarding specifications, although this can nominally include periods of 1 mm to 1 μm , which corresponds to the bandwidth typically covered by PMMs. As the mid-frequency roughness of a high-quality lithographic mirror may be about 0.1- to 0.2-nm rms, this may be comparable or better than the roughness of many reference mirrors used in PMMs. Although these reference mirrors can be specially fabricated to a lower roughness (with significant difficulty), the usual procedure is to calibrate the reference mirror by a multiple-measurement averaging process. For aspheric surfaces, care must be taken to repeat the calibration when moving to regions of different curvature or when the fringe pattern is adjusted to ensure that the appropriate region of the reference mirror is used.

AFM is typically required to measure HSMR, because the spatial periods are typically less than 1 μm . Due to the smoothing tendency of ML deposition, the smallest periods normally needed for measurement are 20 to 50 nm. Without this smoothing tendency, characterization to smaller periods would be needed where

the band limit of the measurement was approximately the tip radius of the stylus (~ 5 nm), with some extension using deconvolution techniques. The quality of the AFM measurement is highly dependent on the methodology employed by the microscopist, such as in the selection of styli, the frequency of changing tips to account for wear, control of electrostatic charge, and care in minimizing background vibration. At LLNL, the AFM used to measure EUVL optics has a background signal noise of about 0.03-nm rms.²⁵ Of particular importance in the use of the AFM is the interpretation of the micrographs. Residual contamination of the surface due to solvent residue or polishing compound can be identified, especially when working closely with vendors or technicians, and a familiarity with cleaning capabilities and fabrication methods can develop. Often, significant differences have existed in the measured rms roughness between LLNL AFM results and those of other organizations. At LLNL, the surface finish metrology is often compared with angle-resolved scattering measurements by the Advanced Light Source (ALS) at Lawrence Berkeley National Lab (LBNL) to continually validate the relationship between profile metrology and functional performance.^{40,41}

4C.14 Mounting and Assembly

The support of the optical elements is of extreme importance. The method of support must not induce unexpected changes in the figure, must not be overly sensitive to thermal changes or vibrations, and must provide optical registration with respect to a global coordinate system. Furthermore, the support method must be temporally stable, not outgas, allow for the installation and removal of the optics, and provide for alignment actuation for specified degrees of freedom. The mounting methodology generally follows the principles of *exact constraint design*,^{42,43} and a detailed analysis is performed to estimate what forces and moments may be applied to the optical substrate. The substrate geometry, such as thickness and overall boundary around the CA, are designed in conjunction with the mounts to minimize nonspherical deformation within the CA. It is particularly important to estimate nonrepeatable, nonspherical deformation, such as from “trapped friction” due to the insertion of the optic into a kinematic mount.

The mounting hardware may be epoxied or otherwise attached to the substrate, which typically couples to a flexure mechanism. The flexures provide a combination of stiff and compliant degrees of freedom to precisely locate the optic while minimizing the transmission of unnecessary, unknown, or undesirable forces and moments. The flexure is mounted onto a portable ring, or cell, that in turn can be mounted into the lithographic camera or an interferometer. Generally, the same mounting hardware, including the cell, is used in the interferometer during fabrication as that used in the actual lithographic camera, so the figure metrology records the shape of the mirror in the same orientation and with the same support forces that will be present in the installation of the optic.

A key goal of the assembly and mounting process is to locate the optical surface with respect to the optical axis of the system. The global coordinate system might

be determined from datum features, such as tooling balls, mounted on the housing or superstructure that will support all of the optics and form the foundation for the aligned optical system, which can be installed in alignment interferometers and then into the lithographic tool. When taking interferometry data on the individual mirrors, it is essential to relate the coordinates in the measurement to the datum surfaces on the glass (or mounting hardware). A CMM can be used to relate the datum surfaces on the glass, such as the outer periphery, to tooling balls on the mounting cell. Then, when the mounting cell is installed into the housing, the CMM can be used to relate the tooling balls on the cell to the global coordinate system defined by the datum surfaces on the housing. So the chain of steps in registering the optic to the housing includes: (1) relate the interferogram (height map) to datum features on the edge of the mirror; (2) relate the mirror datums to datums (tooling balls) on the cell; (3) relate the datums on the cell (tooling balls) to datums on the housing. At the completion of this assembly process, the coordinates for each mirror will be known with respect to the global coordinate system. The inter-relationships among the mirrors can then be determined. By rigorously documenting the uncertainty in locating all of the datum surfaces, the uncertainty in locating the optics relative to one another can be estimated. It has been demonstrated that the mechanical assembly of a four-mirror EUVL projection system, without adjustment, could achieve a 5-nm rms wavefront.³⁶ Figure 4C.5 illustrates two examples of the mounting schemes implemented for the Engineering Test Stand (ETS) four-mirror, full-field projection system, and the microexposure tool (MET) two-mirror micro-field system.

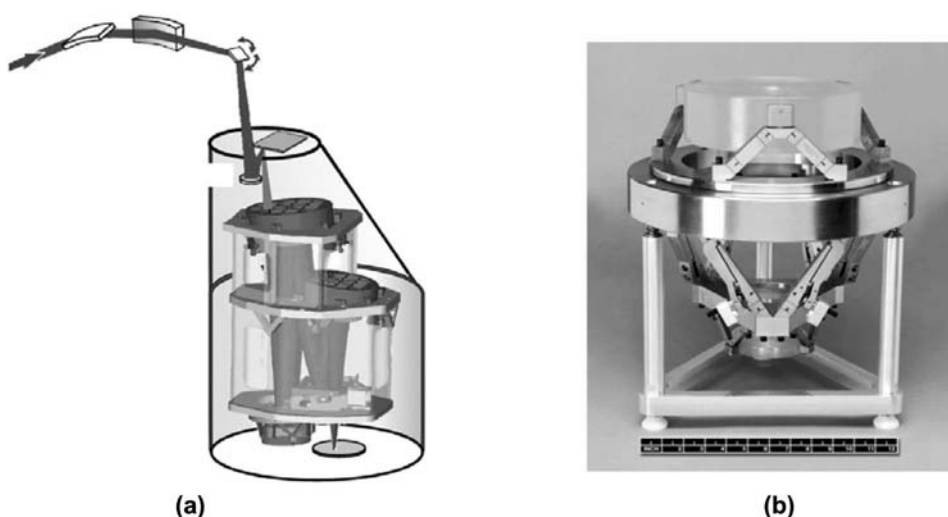


Figure 4C.5 (a) Schematic drawing of the ETS camera installed at the Static Exposure Station at the LBNL's ALS. (b) MET camera shown in its mounting assembly.

4C.15 Alignment

A rigorous procedure for aligning EUVL optical systems has been developed where the influence of rigid body positional errors on the optical system were calculated in terms of Zernike polynomials.⁴⁴ In many cases, similar influences on the system aberrations could be obtained with different choices in optics adjustments. An analysis using singular value decomposition was employed to determine the sensitivities of system performance to the alignment motions and to determine the optimal adjustments for optimizing performance with a given starting set of aberrations. The analysis can be performed initially using the sensitivities determined from the optical design code using the ideal mirror shapes; however, inserting the as-built mirror metrology data into the analysis will account for substrate aberrations. The sensitivities can be measured experimentally by using an alignment interferometer and measuring the change in system aberrations with small actuations of the mirrors. This would be performed for multiple field points within the ring-field.

When performing system alignment, wavefront errors and distortion must be measured at numerous points within the ring-field. A phase-shifting point-diffraction interferometer (PSPDI) has been developed for alignment that has achieved an absolute accuracy of less than 0.20-nm rms.^{45,46} Essentially, a calibrated, nearly-perfect spherical wave (i.e., the “test wave”) is propagated from one of the system’s field points to its conjugate point, where it is combined with a nearly-perfect reference wave. The wave that passes through the optical system becomes aberrated due to design residuals, fabrication errors, and alignment errors. The test wave and the reference wave interfere and are interpreted to determine the system aberrations. The locations of the points where the test and reference waves are launched are varied over the full ring-field to determine the full-field performance. The measured tilt aberrations can be related to distortion. The combination of wavefront error and distortion data over the full set of field points can be used to optimize the mirror alignment. Generally, the average performance over the field will be optimized such that all points meet a minimally acceptable criterion or process window.

4C.16 Condenser Optics

The requirements for condenser optics are significantly different than for projection optics. The condenser’s basic requirement is to direct EUV illumination onto the mask and through the pupil of the camera. For a Köhler condenser, the general goal is to image the source onto the pupil of the projection system. The condenser does not need to be diffraction-limited because its goal is to direct light, not control phase errors. With the goal of controlling the source image location within the camera pupil to a fractional percent of the pupil diameter, one can construct a slope error budget for each of the condenser optics. In general, the slope errors can be

divided into low-frequency slope errors, where a P-V slope specification is formulated based on the gross positioning of the source image in the pupil. For waviness, such as 1- to 10-mm spatial periods, the influence on performance will be smearing of the source image, leaving irregularities around the image, and illumination nonuniformity within the image. It is convenient to formulate an rms slope specification for this mid-spatial-frequency regime. An essential specification is for a low level of HSFR. As with the projection optics, wide-angle scattering appears as energy loss and lower system throughput. A specific flare requirement for the condenser does not exist, so MSFR can generally be much looser for condenser optics than projection optics, with one caveat: the PSD describing the surface must

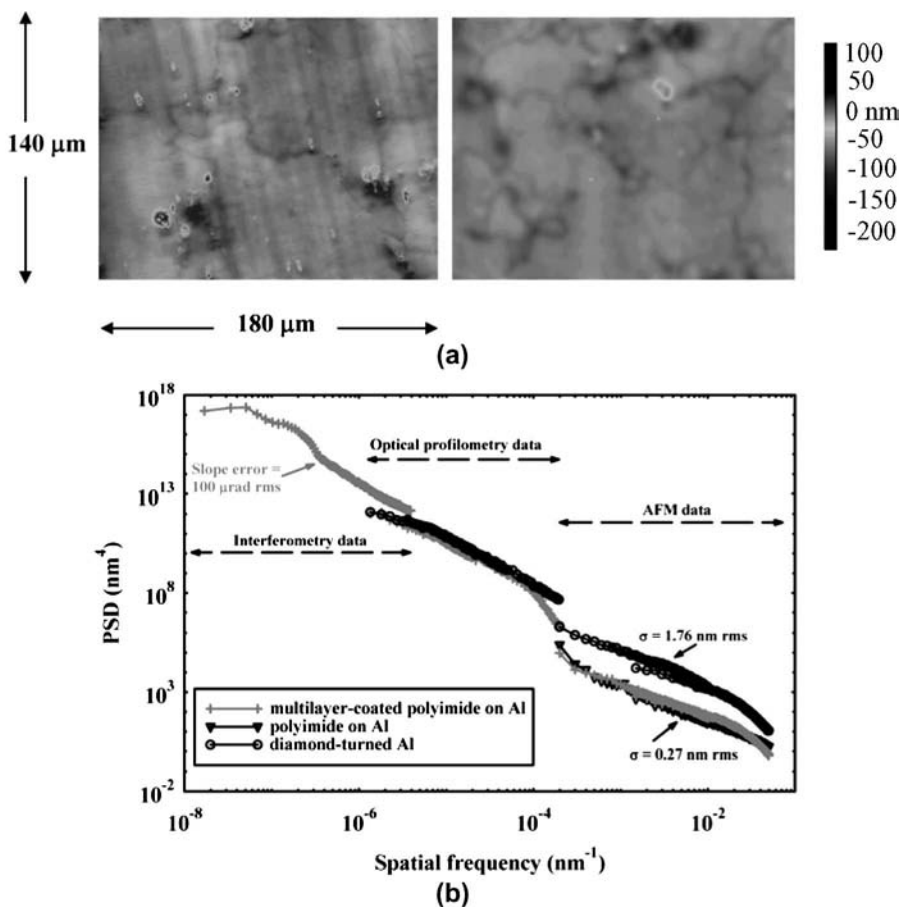


Figure 4C.6 (a) MSFR measurements with a Zygo New View optical profiling microscope operated at 40 $\times$ objective lens magnification shown on a bare, diamond-turned Al condenser substrate (top left) and after polyimide and ML-coating (top right), demonstrating the smoothing of the diamond-turning tool marks due to the polyimide layer. (b) Measured, radially averaged, 2D PSD spectrum of the condenser mirror plotted over a wide spatial-frequency range at all stages of fabrication. Each of the PSD curves obtained from optical profilometry and AFM data is an average over measurements on three radial locations on the surface. (Reprinted from Ref. 47.)

be relatively continuous and consistent with the quality required by the adjoining specifications for mid-spatial-frequency waviness and HSFR.

An important area of development for condenser optics is in lowering the cost of the elements, especially the collector, whose degradation is expected to be faster than that of the projection optics. Novel approaches have been developed to smooth HSFR by applying either a polyimide,^{47,48} as illustrated in Fig. 4C.6, or spin-on glass coatings.⁴⁹ These applied coatings will smooth the HSFR, with the goal to not significantly degrade the slope errors at the longer spatial periods. Promising results have been presented for the polyimide smoothing of diamond-turned aluminum (Al) substrates⁴⁷ and ground SiC substrates,⁴⁸ and the spin-on-glass smoothing of Al and copper (Cu) diamond-turned substrates.⁴⁹ These results show that high reflectance is obtained when a ML coating is applied on top of the smoothing layer, and that the smoothing layer is temporally stable and does not outgas.

Acknowledgments

The authors gratefully acknowledge the EUV LLC and SEMATECH for their support of EUVL programs at the Lawrence Berkeley, Lawrence Livermore, and Sandia National Laboratories.

References

1. R. Hudyma, "An overview of optical systems for 30 nm resolution lithography at EUV wavelengths," *Proc. SPIE* **4832**, 137–148 (2002).
2. For example, see D. G. Flagello, J. de Klerk, G. Davies, et al., "Towards a comprehensive control of full-field image quality in optical photolithography," *Proc. SPIE* **3051**, 672–685 (1997).
3. F. Zernike, "Beugungstheorie des Schneidverfahrens und seiner verbesserten Form, der Phasenkontrastmethode," *Physica* **1**, 689–704 (1934).
4. J. C. Wyant and K. Creath, "Basic wavefront aberration theory for optical metrology," in *Applied Optics and Optical Engineering, Volume XI*, Academic Press, New York, pp. 1–53 (1992).
5. D. M. Williamson, "The elusive diffraction limit," in *Extreme Ultraviolet Lithography*, F. Zernike and D. T. Attwood, Eds., *OSA Proc.* **23**, 68–76 (1994).
6. See Ref. 2 for a discussion of *bananicity*.
7. J. E. Harvey, W. Zmek, and C. Ftaklas, "Imaging capabilities of normal-incidence x-ray telescopes," *Opt. Eng.* **29**(6), 603–608 (1990). The reader is also referred to papers by E. Church, P. Takacs, and J. Bennett.
8. E. M. Gullikson, "Scattering from normal incidence EUV optics," *Proc. SPIE* **3331**, 72–80 (1998).
9. E. M. Gullikson, S. L. Baker, J. E. Bjorkholm, et al., "EUV scattering and flare of 10× projection cameras," *Proc. SPIE* **3676**, 717–723 (1999).

10. E. M. Gullikson, "Development of reflective EUV and soft x-ray optics," presented at the *2nd International Symposium on Technologies and Applications of Photoelectron Micro-Spectroscopy with Laser-Based VUV Sources*, Tsukuba, Japan, Feb. 1–3, 2005.
11. M. Chandhok, S. H. Lee, C. Krautschik, et al., "Comparison of techniques to measure the point spread function due to scatter and flare in EUV lithography systems," *Proc. SPIE* **5374**, 854–860 (2004).
12. D. G. Stearns, "Stochastic model for thin film growth and erosion," *Appl. Phys. Lett.* **62**, 1745–1747 (1993).
13. Lakhtakia and R. Messier, *Sculptured Thin Films: Nanoengineered Morphology and Optics*, SPIE Press, Bellingham, WA (2005).
14. E. Spiller, S. L. Baker, P. B. Mirkarimi, et al., "High-performance Mo-Si multilayer coatings for extreme ultraviolet lithography," *Appl. Opt.* **42**, 4049–4058 (2003).
15. J. S. Taylor, G. E. Sommargren, D. W. Sweeney, and R. M. Hudyma, "The fabrication and testing of optics for EUV projection lithography," *Proc. SPIE* **3331**, 580–590 (1998).
16. E. L. Church and P. Z. Takacs, "Specification of the Figure and Finish of EUV mirrors in terms of performance requirements," in *Extreme Ultraviolet Lithography*, F. Zernike and D. T. Attwood, Eds., *OSA Proc.* **23**, 77–82 (1994).
17. S. H. Lee, M. Chandhok, C. Krautschik, and M. Goldstein, "Anisotropic EUV flare measured in the Engineering Test Stand (ETS)," *Proc. SPIE* **5374**, 818–823 (2004).
18. J. S. Taylor, M. Piscotty, and A. Lindquist, Eds., *Fabrication and Testing of Aspheres*, Trends in Optics and Photonics (TOPS), Vol. XXIV, Optical Society of America, Washington, D.C. (1999).
19. R. A. Jones, Ed., *Selected Papers on Computer Controlled Optical Surfacing*, Vol. MS40, SPIE Press, Bellingham, WA (1991).
20. D. Golini, "Precision optics manufacturing using magnetorheological finishing," *Proc. SPIE* **3739**, 78–85 (1999).
21. F. Frost, R. Fechner, B. Ziberi, D. Flamm, and A. Schindler, "Large area smoothing of optical surfaces by low-energy ion beams," *Thin Solid Films* **459**, 100–105 (2004).
22. L. N. Allen and R. E. Keim, "An ion figuring system for large optics fabrication," *Proc. SPIE* **1168**, 33–50 (1989).
23. R. Geyl and E. Rolland, "Large optics ion figuring," *Proc. SPIE* **3739**, 161–166 (1999).
24. P. Kürz, "Optics for EUV lithography," presented at the 2nd International Workshop on EUV Lithography, Burlingame, CA, Oct. 17–19, 2000, sponsored by SEMATECH.
25. R. Soufli, S. L. Baker, D. L. Windt, et al., "Atomic force microscopy characterization of Zerodur mirror substrates for the extreme ultraviolet telescopes aboard NASA's Solar Dynamics Observatory," *Appl. Opt.* **46**, 3156–3163 (2007).

26. U. Dinger, G. Seitz, S. Schulte, et al., "Fabrication and metrology of diffraction-limited soft x-ray optics for the EUV microlithography," *Proc. SPIE* **5193**, 18–28 (2004).
27. D. Shafer, "Null lens design techniques," *Appl. Opt.* **31**(13), 2184–2187 (1992).
28. M. Bray, "Stitching interferometry: Side effects and PSD," *Proc. SPIE* **3782**, 443–452 (1999).
29. J. Fleig, P. Dumas, P. E. Murphy, and G. W. Forbes, "An automated subaperture stitching interferometer workstation for spherical and aspherical surfaces," *Proc. SPIE* **5188**, 296–307 (2003).
30. G. E. Sommargren, D. W. Phillion, M. A. Johnson, N. Q. Nguyen, A. Barty, F. J. Snell, D. R. Dillon, and L. S. Bradsher, "100-picometer interferometry for EUVL," *Proc. SPIE* **4688**, 316–328 (2002).
31. D. Phillion, "General methods for generating phase shifting interferometry algorithms," *Appl. Opt.* **37**(3), 8098–8115 (1997).
32. S. M. Arnold and R. Kestner, "Verification and certification of CGH aspheric nulls," *Proc. SPIE* **2536**, 117–126 (1995).
33. L. A. Selberg, "Interferometry accuracy and precision," *Proc. SPIE* **1400**, 24–32 (1990).
34. C. J. Evans, "Absolute figure metrology of high precision optical surfaces," PhD thesis, The Univ. of Birmingham, June 1996.
35. G. E. Sommargren, "Phase shifting diffraction interferometry for measuring extreme ultraviolet optics," in *Extreme Ultraviolet Lithography*, G. Kubiak and D. Kania, Eds., OSA Trends in Optics and Photonics (TOPS), Vol. 4, pp. 108–112 (1996).
36. J. S. Taylor, "Construction of the projection optics box for the Engineering Test Stand," presented at the 2nd International Workshop on EUV Lithography, Burlingame, CA, Oct. 17–19, 2000, sponsored by SEMATECH.
37. L. Marchetti, D. Bajuk, J. Kennon, et al., "Fabrication of the ETS Set II optics: Results and future development," presented at the 2nd International Workshop on EUV Lithography, Burlingame, CA, Oct. 17–19, 2000, sponsored by SEMATECH.
38. D. A. Tichenor, et al., "System integration and performance of the EUV Engineering Test Stand," *Proc. SPIE* **4343**, 19–37 (2001).
39. J. S. Taylor, G. Sommargren, R. Soufli, et al., "Fabrication and metrology of the high-NA imaging optics for the micro-exposure tool (MET)," presented at the 3rd International Workshop on EUV Lithography, Matsue, Japan, Oct. 29–31, 2001, sponsored by SEMATECH.
40. R. Soufli, E. Spiller, M. A. Schmidt, et al., "Multilayer optics for an extreme ultraviolet lithography tool with 70 nm resolution," *Proc. SPIE* **4343**, 51–59 (2001).
41. R. Soufli, R. M. Hudyma, E. Spiller, et al., "Sub-diffraction-limited multilayer coatings for the 0.3 numerical aperture micro-exposure tool for extreme ultraviolet lithography," *Appl. Opt.* **46**, 3736–3746 (2007).

42. L. C. Hale, "Principles and techniques for designing precision machines," PhD thesis, Massachusetts Institute of Technology (1999).
43. D. L. Blanding, *Exact Constraint: Machine Design Using Kinematic Processing*, American Society of Mechanical Engineers, New York (1999).
44. H. N. Chapman and D. W. Sweeney, "A rigorous method for compensation selection and alignment of microlithographic optical systems," *Proc. SPIE* **3331**, 102–113 (1998).
45. D. W. Phillion, G. E. Sommargren, M. A. Johnson, et al., "Calibration of symmetric and non-symmetric errors for interferometry of ultra-precise imaging systems," *Proc. SPIE* **5869**, 5869OR (2005).
46. M. A. Johnson, D. W. Phillion, G. E. Sommargren, et al., "Construction and testing of wavefront reference sources for interferometry of ultra-precise imaging systems," *Proc. SPIE* **5869**, 5869OP (2005).
47. R. Soufli, E. Spiller, M. A. Schmidt, et al., "Smoothing of diamond-turned substrates for extreme-ultraviolet illuminators," *Opt. Eng.* **43**(12), 3089–3095 (2004).
48. R. Soufli, S. L. Baker, S. Ratti, et al., "Substrate smoothing for high-temperature condenser operation in EUVL source environments," *Proc. SPIE* **5751**, 140–145 (2005).
49. F. Salmassi, P. P. Naulleau, and E. M. Gullikson, "Spin-on-glass coatings for the generation of superposited substrates for use in the extreme-ultraviolet region," *Appl. Opt.* **45**, 2404–2408 (2004).



John S. Taylor leads the Precision Systems and Manufacturing Groups at LLNL and is the Chief Engineer for fabricating targets for the National Ignition Facility. He previously led LLNL's X-ray Optics Group and EUV Lithography Program, which designed and constructed the first wide-field diffraction-limited EUVL imaging cameras. His experience includes optical manufacturing, diamond turning, and metrology. He received his PhD in Mechanical Engineering from Purdue University in 1984. In his work at LLNL, he was awarded five US patents and three R&D 100 Awards. He is a member of the Optical Society of America, the American Society of Mechanical Engineers, a charter member of the American Society for Precision Engineering, and a Fellow of SPIE.



Regina Soufli received her PhD in Electrical Engineering from the University of California, Berkeley, in 1997, and was staff scientist at the Harvard-Smithsonian Center for Astrophysics in 1997–99, studying the optical properties of iridium-coated mirrors for NASA's Chandra X-ray Observatory. She joined LLNL in 1999 and has been the principal investigator on EUV/x-ray optics programs for semiconductor lithography, solar physics, synchrotron and free-electron lasers, and high-energy physics.

Her interests are in EUV/x-ray interactions with matter, surface science, thin films, roughness and scattering. She has received several LLNL awards and two “R&D 100” awards while at LLNL.

Chapter 4D

Multilayer Coatings for EUVL

Regina Soufli and Saša Bajt

Contents

4D.1 Overview and History of EUV Multilayer Coatings	187
4D.2 Choice of ML Materials and Wavelength Considerations	188
4D.3 Multilayer Deposition Technologies	189
4D.4 Theoretical Design	190
4D.5 High Reflectivity, Low Stress, and Thermal Stability Considerations	191
4D.6 Optical Constants	192
4D.7 Multilayer Thickness Specifications for Imaging and Condenser EUVL Mirrors	193
Acknowledgments	197
References	197

4D.1 Overview and History of EUV Multilayer Coatings

Highly reflective multilayer (ML) coatings deposited on precisely polished mirror substrates have enabled imaging at EUV and x-ray wavelengths at near-normal angles of incidence. These ML films essentially represent synthetic Bragg crystals made of alternating layers of materials, where the constructive interference of light between the layers results in significant reflectivity at normal incidence. Stable interfaces and sufficient contrast in the refractive index between the material layers are the most fundamental requirements for these ML structures to function efficiently. The first attempt in 1940 by DuMond and Youtz¹ to make copper-gold (Cu-Au) MLs resulted in the loss of reflective performance after a few days due to interdiffusion between the layers. However, Dinklage² in 1967 and Spiller³ in 1972 were the first to make successful experimental demonstrations of ML films with stable reflective performance over time, operating at EUV/x-ray wavelengths, followed by T. Barbee⁴ and J. Underwood.⁵ In the following two decades, significant activity occurred in this direction by the groups at Bell Laboratories and at Lawrence Berkeley, Lawrence Livermore, and Sandia National Laboratories (LBNL, LLNL, and SNL, respectively) in the U.S., and NTT Laboratories in Japan. These early efforts were motivated by the need for ML mirrors for EUV/x-ray

solar physics, EUV/x-ray lithography⁶ x-ray microscopy, and x-ray lasers for defense applications. These researchers established the vacuum-deposition techniques and general principles of making such ML structures into practical elements for EUV and x-ray instrumentation. The rapid advancement of laser-produced plasma (LPP) source EUV reflectometers^{7–9} and second- and third-generation synchrotron facilities¹⁰ that occurred at about the same time made possible the accurate and reproducible at-wavelength characterization of ML films, thus further accelerating the development of ML technology.

4D.2 Choice of ML Materials and Wavelength Considerations

The illumination wavelength of 13.5 nm was chosen for EUV lithography (EUVL) based on the early development and good performance of molybdenum-silicon (Mo/Si) MLs in this wavelength region. Mo/Si still remains the most extensively investigated and best understood ML material pair to date, and 13.5 nm is in the wavelength region just longer than the $L_{2,3}$ absorption edge of Si (12.4 nm), where Mo/Si achieves its best reflective performance. In addition, the first available sources for EUVL were LPP sources, with good conversion efficiency in this wavelength region. The earliest optical systems constructed to demonstrate printing capabilities at EUV wavelengths were $10\times$ Schwartzchild cameras (microsteppers) at 13.4 nm, using Mo/Si coated mirrors.¹¹ At around the same time, a new class of beryllium (Be) based MLs was developed, including Mo/Be, Ru/Be, Rh/Be, and Nb/Be.^{12,13} The aim of this development was to explore the potential of the wavelength region just longer than the Be K edge (11.12 nm) for EUVL. Mo/Be MLs with measured reflectivity approaching 70% were demonstrated at 11.3 nm, the highest experimental reflectivity achieved at any EUV wavelength at that time.¹⁴ Adding to the appeal of the 11-nm wavelength was the fact that the potential LPP EUVL sources had spectra with higher output at 10 to 11 nm, and the shorter wavelength allowed for photoresist layers with higher thickness and fewer defects. For these reasons, Mo/Be was seriously considered as a candidate ML pair for EUVL optics, and was later revisited and further optimized.^{15,16} MoRu/Be MLs were also demonstrated¹⁷ at wavelengths around 11 nm and had the additional advantage of MoRu's amorphous layer structure (versus the crystalline structure in both Mo and Be layers in Mo/Be MLs), which are amenable to smoothing for both EUVL optics and masks. Nevertheless, in 1999–2000 the international semiconductor community abandoned Be-based MLs and the 11-nm wavelength region for EUVL, mainly due to health and safety issues associated with the toxicity of Be particles. The focus was shifted to ML optimization for the 13.5-nm region. Even though the output of the LPP source at 13.5 nm was lower than at 11 nm, the natural width of the Bragg peak of a Mo/Si ML at 13.5 nm is broader than the peak width of a Be-based ML at 11 nm. Hence, the overall integrated reflectivity is comparable at both 11- and 13.5-nm wavelengths. The broader peak width at 13.5 nm also relaxes specifications for optic-to-optic wavelength matching, as will be discussed later in this chapter. There are other

benefits associated with operating at 13.5 versus 11 nm. These benefits are related to the amount of mid-spatial-frequency roughness (MSFR) scattering from the mirror substrate (flare, leading to loss of imaging contrast) discussed in Chapter 4C. Flare scales according to $1/\lambda^2$ (where λ = wavelength), so for a mirror with a given surface roughness the flare would be higher (worse) at 11 nm than at 13.5 nm.

4D.3 Multilayer Deposition Technologies

It is well known that the reflectivity of ML mirrors does not depend only on the materials being used but also on the structural quality of the coatings. Coating quality depends on the deposition method (magnetron-beam sputtering, ion-beam sputtering, electron-beam evaporation, pulsed laser deposition) and the overall deposition control. The first ML structures were made by physical vapor deposition (PVD). A nice overview of PVD methods, including thermal and sputter vapor depositions, can be found in Barbee's review paper.¹⁸ Another way to deposit thin films and ML coatings is chemical vapor deposition (CVD),¹⁹ although this technique involves complex chemistry and chemical reactions, often requires a high deposition temperature, and traditionally has not been used to produce EUV MLs. Recent developments and challenges in ML x-ray optics are presented in another review paper by Vinogradov.²⁰

The most commonly used deposition technique for EUVL mirrors is magnetron sputtering. High-quality Mo/Si MLs were already achieved in the mid-1980s.²¹ The advantages of this technique are the ability to coat large optics, great control, the stability of the sources, reproducibility from run to run, and a relatively fast sputtering rate. The first EUVL optics sets for 0.1-NA full-field systems and 0.3-NA microfield systems were fabricated using magnetron deposition.^{22–24} An example of a DC-magnetron sputtering system optimized for the coating of large-area optics is shown in Figs. 4D.1 and 4D.2. Similar mirrors for an EUVL process development tool²⁵ were coated using e-beam evaporation in combination with ion-beam smoothing.²⁶ High-quality EUV ML coatings are also obtained with ion-beam deposition^{27–29} and ion-assisted deposition.³⁰ This technique is primarily used to coat EUVL mask blanks because it is a low-defect process. Because of the high energy of impacting ions, this technique also enhances smoothing by increasing the motion of the atoms on the surface. With additional ion polishing, such a technique can relax the requirement for the surface finish of EUV optics and mask substrates.²⁷ Another technique is pulsed laser deposition.^{31–33} Other modes of film deposition—though not yet demonstrated—may be possible [e.g., atomic layer deposition (ALD), molecular beam epitaxy (MBE), and modified chemical vapor deposition (CVD) arrangements].

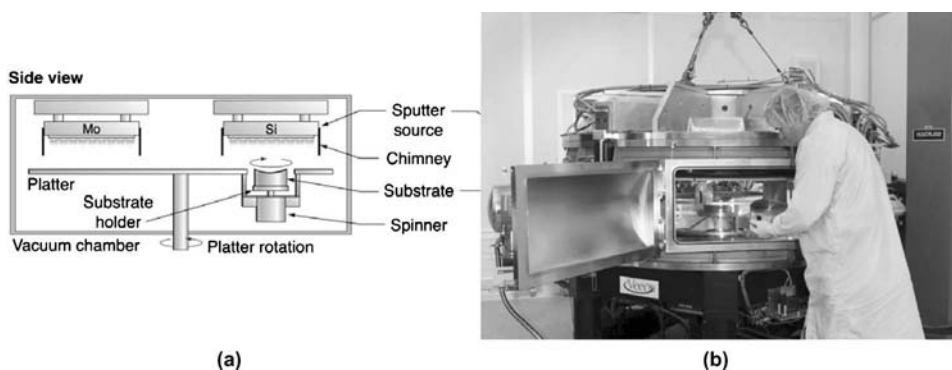


Figure 4D.1 (a) Side view of the LLNL large-optics DC-magnetron sputtering system. (b) An optic introduced into the chamber through a side door. This deposition system was used to ML-coat the EUVL projection optics in Refs. 23 and 24.

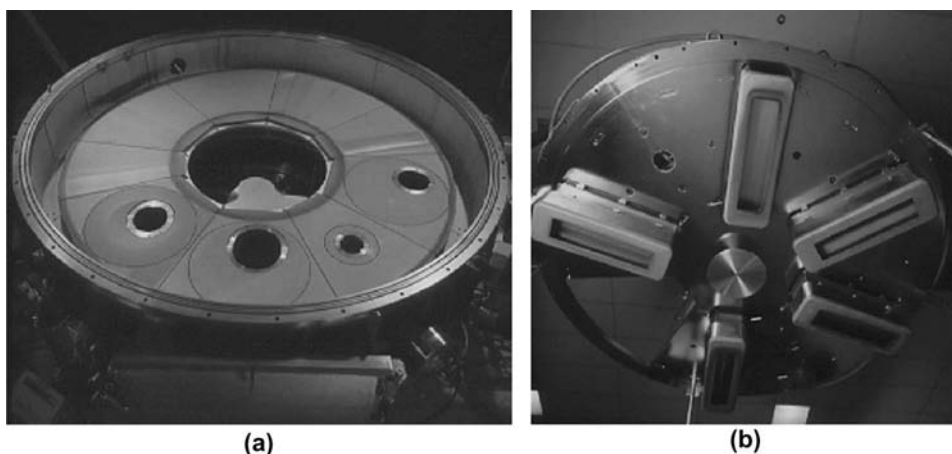


Figure 4D.2 (a) View of the substrate platter of the DC-magnetron sputtering system shown in Fig. 4D.1 with the chamber lid raised. Four Si wafers of various sizes are mounted in on-axis and off-axis positions. (b) View underneath the chamber lid with five sputtering targets.

4D.4 Theoretical Design

In a seminal paper,³ Spiller showed that quarter-wave stacks of absorbing materials can be used effectively as optics in the EUV and soft x-ray regions. In the first approximation, the highest reflectivity is achieved with a material pair that has a minimum absorption and a maximum difference in the refractive indices among the constituent materials. The theory on the design of ML structures is covered by Spiller³⁴ and the references therein. The theory of sub-quarter-wave MLs^{35–37} predicts enhanced EUV reflectivity at 13.5 nm based on the use of thin films of several materials with the largest possible refractive index differences. However, such MLs have often performed better only in theory. Other parameters, such as the roughness, interdiffusion, chemical reactivity, and lifetime stability of the layer interfaces

play the most dominant role in ML film performance. Enhanced reflectivity was demonstrated and studied by different groups in MLs with diffusion barrier layers whose primary function was to suppress interdiffusion.^{33,38–41} Reflectivity can also be optimized by varying the layer thickness ratio of the individual materials. If MLs must be thermal or radiation stable, the design requires the use of refractive materials such as oxides, carbides, silicides, and alloys, or the introduction of barrier layers that are deposited on interfaces to reduce the interdiffusion due to elevated temperatures. High-resolution MLs can be achieved by selecting materials with a certain ratio of optical constants, by optimization of layer thickness and of the number of bilayers,^{42–45} and by using higher-reflectance orders from ML structures.⁴⁶ A wide spectral bandwidth requires aperiodic ML design.^{47,48}

4D.5 High Reflectivity, Low Stress, and Thermal Stability Considerations

Recent advances in ML technology have enabled normal-incidence Mo/Si MLs at 13.5 nm with over 68% experimental reflectivity. The optical throughput in an EUVL tool is proportional to the reflectivity to the n -th power, where n is the number of reflective elements in the system. Therefore, rather small increases in reflectivity per mirror can be significant for the overall increase in the optical throughput. This was the primary motivation to achieve the highest possible reflectivity on Mo-Si MLs. The highest reflectivity, 70% at 13.5 nm, was achieved using interface-engineered MLs, such as the Mo/B₄C/Si/B₄C³⁸ made by magnetron sputtering (shown in Fig. 4D.3), and Mo/C/Si/C, Mo/B₄C/Si/B₄C, and other combinations made by pulsed laser deposition.³³ Similar results were also reported for Mo/Si MLs deposited with e-beam evaporation where the width of each interface was reduced and sharpened with ion-beam polishing.^{26,49}

Numerous studies investigated the thermal stability of Mo/Si MLs that operate in the EUV region.^{38,50–59} The MLs were exposed to high temperatures either to study the kinetics of silicide formation,^{51,60,61} to control the growth and optimize ML fabrication,^{52,54,61,62} or to reduce stress in the MLs.^{55,56,63,64} Structural changes in Mo/Si MLs due to increased temperature are of great importance for lithography applications due to the stringent requirements for reflectance and wavelength stability and figure errors due to stress changes in the MLs. For example, it has been shown that the period thickness of Mo/Si MLs shrinks considerably after annealing at 300°C, but measurable change in EUV reflectivity already occurs at or above 100°C.^{55,56,59,65} Thermal stability can be substantially improved by introducing diffusion barriers such as carbon (C) and boron carbide (B₄C) as discussed above, other carbide-based diffusion layers,⁴¹ SiO₂,⁶⁶ or by using a different ML material pair such as Mo₂C/Si, MoSi₂/Si,^{54,56,57,67} or Mo/SiC.^{67,68} Thermally stable MLs have recently been demonstrated on actual EUVL collector optics.^{69,70} Multilayers can also be optimized for minimum stress⁷¹ by either varying the composition,^{72–75} base pressure, or deposition condition,⁷⁶ annealing during deposition; post-deposition annealing;⁷⁷ or stress compensation with a buffer layer.

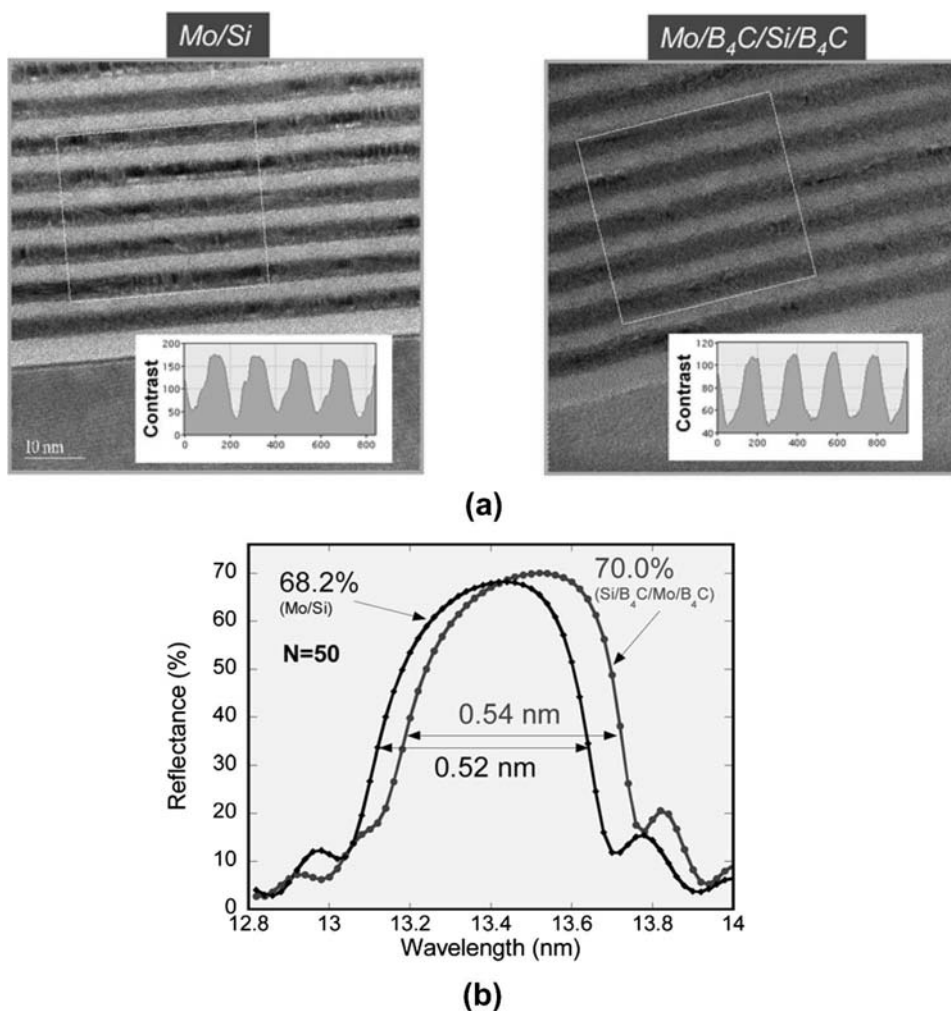


Figure 4D.3 (a) Cross-sectional transmission electron microscopy (TEM) images of a Mo/Si ML (top left) and a Mo/B₄C/Si/B₄C ML with improved interface contrast due to the B₄C barrier layers (top right). (b) EUV reflectance curves of the two MLs shown in the TEM images, illustrating the improvement in reflectance due to the B₄C barrier layers. See also Ref. 38.

Often a combination of these techniques is required to achieve the desired results.⁷⁸ The lifetime stability of EUVL MLs, and in particular, contamination issues due to exposure in the EUVL environment, is covered in Chapter 6A.

4D.6 Optical Constants

To successfully model and predict the performance of ML coatings for EUVL, precise knowledge of the optical properties of a system's constituent materials is required. The absorptive and dispersive behavior of each material can be obtained from the real and imaginary part of the wavelength-dependent refractive index,

also known as optical constants. In the EUV/x-ray region, where the wavelength of radiation is comparable to the binding energies of the inner electrons in the material, measurements of the refractive index can be particularly challenging due to sensitivity to surface oxides, contamination, and roughness of the material samples under study. Although sophisticated models have been developed to determine the refractive index of materials using first-principles calculations, experimental measurements are always recommended as the best method to accurately determine the refractive index of vapor-deposited thin films. This is especially true for energy regions in the vicinity of electronic absorption edges, where the optical properties can strongly depend on experimental conditions such as the method and environment of deposition. The optical constants of important EUVL materials for ML coatings such as Si,⁷⁹ Mo,^{80,81} Be,⁸² and Ru⁸³ have been updated in recent years with more accurate experimental results. A comprehensive compilation of the optical constants for all elements in the periodic table, including recently obtained data, are maintained in the Center for X-Ray Optics (CXRO) database⁸⁴ (and presented in the Appendix of this book) and in the IMD software package.⁸⁵ Other databases for the optical properties of materials in the EUV/x-ray region are maintained by the National Institute of Standards and Technology (NIST)⁸⁶ and LLNL.⁸⁷

4D.7 Multilayer Thickness Specifications for Imaging and Condenser EUVL Mirrors

Several criteria must be considered when specifying thickness tolerances for reflective, ML-coated optics for EUVL.⁸⁸ The specifications discussed below apply to the clear aperture of each mirror surface within the EUVL imaging system. As case examples, experimental results from the ML coatings of a four-mirror, 0.1 numerical aperture (NA), full-field system²³ (the Engineering Test Stand or ETS) and a two-mirror, 0.3-NA microfield system²⁴ (the microexposure tool or MET) are presented. The applicability of the requirements discussed below on EUVL condenser mirrors is addressed at the end of this section.

Throughput

An EUVL scanner consists of an all-reflective optical system with ML coatings on the projection (imaging) elements, on the condenser/illuminator assembly, and on the mask. All of these elements should be tuned to reflect at or near the same wavelength to obtain a substantial output from the system. Any spectral mismatch between the mirrors would translate to throughput reduction. If a goal is set to match the reflectance peak position of all EUVL optics to within $\Delta\lambda = \pm 0.050$ nm, then in a system with six reflections, for example, this level of wavelength matching would ensure at least 97.4% of the ideal throughput. Meeting this goal requires atomic-level repeatability of the coating process from one deposition run to another. In addition to optic-to-optic wavelength matching, another throughput constraint is the tolerance on wavelength variation across the surface of any individual

optic in the system. For maximum throughput, the ML should have its reflectivity peak at the same wavelength for all surface points on any given mirror. If an arbitrary goal is set to stay within 99% of the reflectivity peak for all points on the optic surface, then a Mo/Si ML operating at $\lambda = 13.4$ nm is allowed to have its wavelength vary to within $\Delta\lambda = \pm 0.050$ nm, which is equivalent to having the wavelength (or the thickness) vary from its prescribed value to within $\pm 0.37\%$ peak-to-valley (P-V) across the surface.

Intensity variations

In addition to the throughput constraints discussed above, a reflectivity mismatch—or other causes such as variations in substrate roughness—across any individual mirror surface in the projection system results in intensity variations (apodization) of the reflected wavefront at the system exit pupil. These variations can lead to a narrowing of the NA or a nonuniformity across the pupil. In lithography terms, these effects cause loss of aerial image contrast, and variations in key aberrations and in the critical dimension (CD) of printed images across the field. For example, the tolerance for these effects was determined to be $\pm 0.2\%$ P-V for the wavelength (or thickness) variation across each of the MET and ETS camera optics shown in Figs. 4D.4 and 4D.5.

Multilayer-added figure errors

In the spatial frequency range corresponding to surface figure, wavefront errors due to ML thickness variations on the imaging mirrors introduce aberrations that can be detrimental to the overall performance of the imaging system. Such ML-induced errors can be decomposed into a compensable and a noncompensable part, the latter being the added figure error that the ML is contributing to the system. The ML-added figure error is determined from the as-measured ML thickness results after subtracting the portion of thickness variation that can be compensated during alignment of the system. The compensable portion is represented by a best-fit spherical term, which can be aligned out through tilt and focus shifts after the mirrors are installed in the camera. For this reason, when ML thickness profile results are evaluated for an EUVL projection optic, the most desirable thickness profiles should be the most highly compensable, i.e., the families of profile curves with spherical-like shapes. The remainder of the subtraction (the noncompensable portion of the ML thickness variation) is the ML-added figure error, with its value weighted according to illuminated area, and is plotted at the lower part of the graphs in Figs. 4D.4 and 4D.5. To avoid the ML coatings from adversely affecting the imaging system performance, their added figure errors should be negligible compared to the substrate figure error. For the ETS and MET Set 2 camera mirrors shown in Figs. 4D.4 and 4D.5, the substrate figure error specification was 0.25-nm rms. Given that the substrate and ML coating errors are uncorrelated and therefore add in a quadratic fashion, the maximum allowable added figure error for the ETS and MET Set 2 ML coatings was set at 0.1-nm rms. For a typical 280-nm-thick Mo/Si film, this corresponds to 0.04% rms ($\sim 0.1\%$ P-V). This ML-added figure error specification

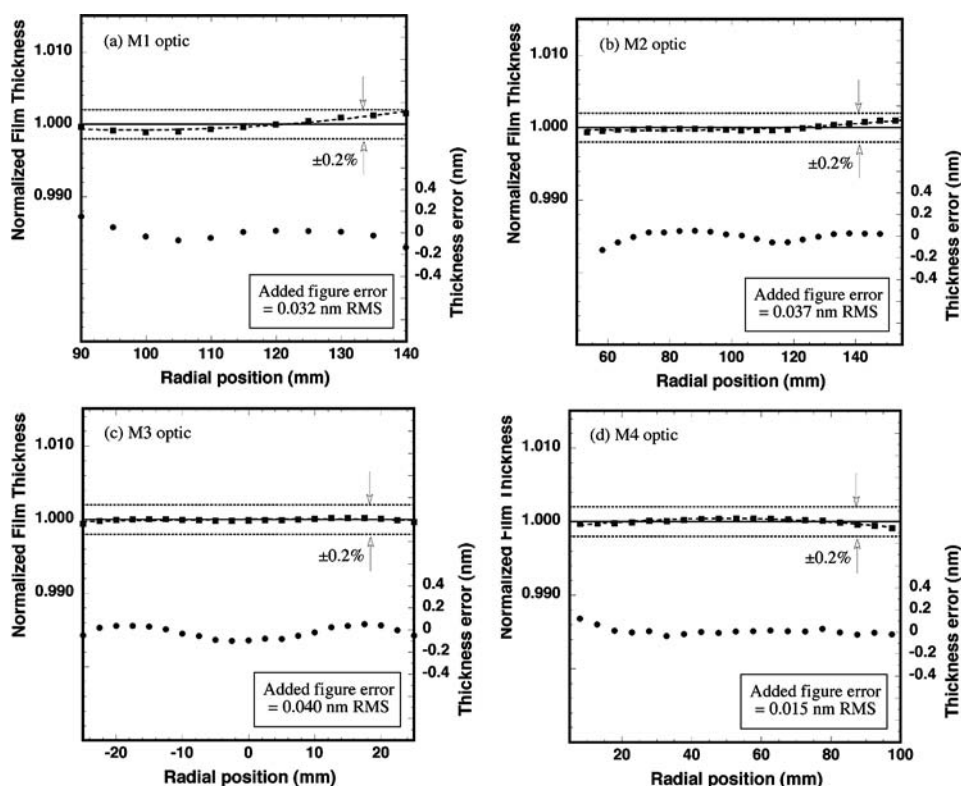


Figure 4D.4 Measured thickness profile results are plotted versus radial distance from the optical axis for the four mirrors of a 0.1-NA, full-field EUVL system (the ETS Set 2 camera). The clear aperture area of each optic is shown. In each plot, the top curve (left y axis) is the normalized film thickness. Each data point is derived from the wavelength at the center of the full-width-at-half-maximum of the measured EUV reflectance Bragg peak. Data have been normalized to the wavelength at an arbitrary location on the surface. The bottom curve (right y axis, in nm) represents the noncompensable figure error that the Mo/Si ML coating adds to the system. All four ML coatings are contributing added figure errors below 0.05-nm rms, which is well within the 0.1-nm rms specification. (Reprinted from Ref. 23.)

is consistent with sub-diffraction-limited system performance, as is discussed in Ref. 24.

The tightest among the constraints discussed above for ML thickness variations on EUVL imaging optics are the P-V thickness uniformity and the rms added figure error requirements. Both of these specifications have to be met independently for a given ML coating: the P-V thickness uniformity criterion is applied to the as-measured ML thickness profile, while the added figure error is determined from the noncompensable portion of the as-measured profile (as discussed above). Satisfying the rms added figure error constraint depends to a large degree on the “shape” of the thickness profile, i.e., profile shapes approaching a second-order polynomial are largely compensable during system alignment. During process development of the ETS and MET ML coatings shown in Figs. 4D.4 and 4D.5, it was concluded that the added figure error tolerance requires the tightest control on the

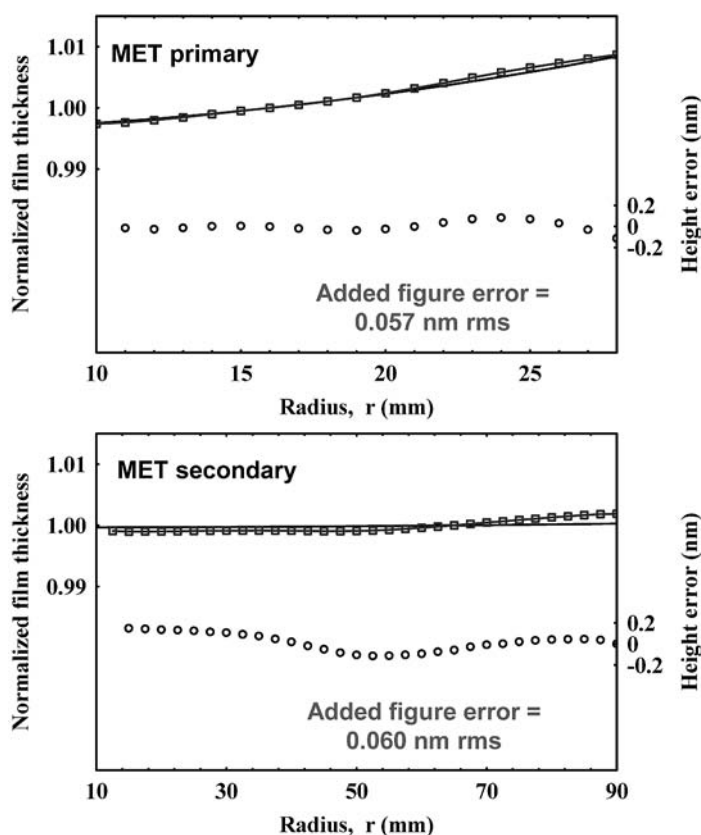


Figure 4D.5 Measured ML thickness results are plotted versus radial distance from the optical axis for the primary and secondary mirrors of a 0.3-NA, microfield EUVL system (the MET Set 2 camera). The clear aperture area of each optic is shown. In each plot, the top two curves (left y axis) are the measured thickness profile (square data points) and the designed thickness profile (solid line). Each data point is derived from the wavelength at the center of the full-width-at-half-maximum of the measured EUV reflectance Bragg peak. Data have been normalized to the wavelength at an arbitrary location on the surface. The bottom curve (circle data points plotted on the right y axis) represents the noncompensable figure error that the Mo/Si ML film adds to the optic surface. Both primary and secondary ML coatings contribute added figure errors well within the 0.1-nm rms specification. (Reprinted from Ref. 24 with permission of the Optical Society of America.)

coating thickness. For this reason, the thickness profiles presented in Figs. 4D.4 and 4D.5 were optimized primarily for the lowest added figure error rather than P-V uniformity. The next generation of EUVL projection optics is currently being implemented in beta and production tools. Substrate figure requirements have been set at about 0.1-nm rms for these systems. Consequently, ML-added figure errors of less than 0.05-nm rms should be achieved—a factor of 2 more stringent than the ETS and MET camera requirements. Commercial EUVL scanner designs include six-mirror cameras, with the clear aperture extending up to 200 mm from the optical axis, for some of the mirrors. To meet all the additional constraints imposed on EUVL beta and production ML coatings, extremely sophisticated control

of the ML film thickness is required. The results presented in Figs. 4D.4 and 4D.5 illustrate the feasibility of meeting such specifications.

In the case of EUVL condenser mirrors, the specifications for ML thickness control are more relaxed compared to the projection mirrors because condenser optics are not required to satisfy the stringent figure error (wavefront) requirements discussed above, as explained in Chapter 4C. Slope error specifications are most commonly attached to the figure and mid-spatial frequencies of EUVL condenser optics, driven by displacement considerations of the illumination beam spot. Nevertheless, the throughput requirements discussed above do apply to the ML coatings for condenser elements, and they impose the restrictions on P-V variations of the ML thickness across the optic surface.

Acknowledgments

The authors gratefully acknowledge the EUV LLC and SEMATECH for their support of the EUVL program at the Lawrence Berkeley, Lawrence Livermore, and Sandia National Laboratories. We also thank Eberhard Spiller for many enlightening discussions.

References

1. J. DuMond and J. P. Youtz, "An x-ray method for determining rates of diffusion in the solid state," *J. Appl. Phys.* **11**, 357–365 (1940).
2. J. Dinklage, "X-ray diffraction by multilayered thin film structures and their diffusion," *J. Appl. Phys.* **38**, 3781–3785 (1967).
3. E. Spiller, "Low-loss reflection coatings using absorbing materials," *App. Phys. Lett.* **20**, 365–367 (1972).
4. T. W. Barbee and D. C. Keith, "Synthetic structures layered on the atomic scale," in *Workshop on Instrumentation for Synchrotron Radiation Research*, H. Winick and G. Brown, Eds., Stanford Synchrotron Radiation Laboratory Report 78/04, p. III-36 (1978).
5. J. H. Underwood and T. W. Barbee, "Layered synthetic microstructures as Bragg diffractors for X rays and extreme ultraviolet: theory and predicted performance," *Appl. Opt.* **20**, 3027–3034 (1981).
6. For a comprehensive list of the early efforts on ML coatings for EUV/x-ray lithography, see, for instance, the manuscripts and references in *Extreme Ultraviolet Lithography*, F. Zernike and D. T. Attwood, Eds., *OSA Proc.* **23** (1994).
7. M. C. Hettrick and J. H. Underwood, "Stigmatic high throughput monochromator for soft X-rays," *Appl. Opt.* **25**, 4228–4231 (1986).
8. D. L. Windt and W. K. Waskiewicz, "Soft X-ray reflectometry of multilayer coatings using a laser-plasma source," *Proc. SPIE* **1547**, 144–158 (1991).
9. E. M. Gullikson, J. H. Underwood, P. C. Batson, and V. Nikitin, "A soft x-ray/EUV reflectometer based on a laser produced plasma source," *J. X-ray Sci. Tech.* **3**, 283–299 (1992).

10. D. Attwood, "New opportunities at soft x-ray wavelengths," *Physics Today*, 24–31 (August 1992).
11. D. A. Tichenor, et al., "10× reduction imaging at 13.4 nm," in *Extreme Ultraviolet Lithography*, F. Zernike and D. T. Attwood, Eds., *OSA Proc.* **23**, 89–97 (1994).
12. K. M. Skulina, C. S. Alford, R. M. Bionta, et al., "Beryllium-based multilayers for normal incidence EUV reflectance," in *Extreme Ultraviolet Lithography*, F. Zernike and D. T. Attwood, Eds., *OSA Proc.* **23**, 52–55 (1994).
13. D. G. Stearns, K. M. Skulina, M. Wall, et al., "Beryllium-based multilayer structures," in *Structure and Properties of Multilayered Thin Films*, T. D. Nguyen, B. M. Lairson, B. M. Clemens S.-C. Shin, and K. Sato, Eds., *MRS Proc.* **382**, 329–337 (1995).
14. K. M. Skulina, C. S. Alford, R. M. Bionta, et al., "Molybdenum/beryllium multilayer mirrors for normal incidence in the extreme ultraviolet," *Appl. Opt.* **34**, 3727–3730 (1995).
15. C. Montcalm, S. Bajt, P. B. Mirkarimi, et al., "Multilayer reflective coatings for extreme ultraviolet lithography," *Proc. SPIE* **3331**, 42–51 (1998).
16. S. Bajt, R. D. Behymer, P. B. Mirkarimi, et al., "Experimental investigation of beryllium-based multilayer coatings for extreme ultraviolet lithography," *Proc. SPIE* **3767**, 259–270 (1999).
17. S. Bajt, "Molybdenum-ruthenium/beryllium multilayer coatings," *J. Vac. Sci. Technol. A* **18**, 557–559 (2000).
18. T. W. Barbee Jr., "Multilayers for x-ray optics," *Opt. Eng.* **25**, 898–915 (1986).
19. K. L. Choy, "Chemical vapour deposition of coatings," *Prog. in Mater. Sci.* **48**, 57–170 (2003).
20. V. Vinogradov, "Multilayer x-ray optics," *Quantum Electron.* **32**, 1113–1121 (2002).
21. T. W. Barbee Jr., S. Mrowka, and M. C. Hettrick, "Molybdenum-silicon multilayer mirrors for the extreme ultraviolet," *Appl. Opt.* **24**, 883–886 (1985).
22. C. Montcalm, R. F. Grabner, R. M. Hudyma, et al., "Atomic-precision multilayer coating of the first set of optics for an extreme-ultraviolet lithography prototype system," *Appl. Opt.* **41**, 3262–3269 (2002).
23. R. Soufli, E. Spiller, M. A. Schmidt, et al., "Multilayer optics for an extreme ultraviolet lithography tool with 70 nm resolution," *Proc. SPIE* **434**, 51–59 (2001).
24. R. Soufli, R. M. Hudyma, E. Spiller, et al., "Sub-diffraction-limited multilayer coatings for the 0.3 numerical aperture, micro-exposure tool for extreme ultraviolet lithography," *Appl. Opt.* **46**, 3736–3746 (2007).
25. E. Louis, E. Zoethout, R. W. E. van de Kruijs, et al., "Multilayer coatings for the EUVL process development tool," *Proc. SPIE* **5751**, 1170–1177 (2005).
26. E. Louis, A. E. Yakshin, P. C. Görts, et al., "Mo/Si multilayer coating technology for EUVL, coating uniformity and time stability," *Proc. SPIE* **4146**, 60–63 (2000).

27. E. Spiller, S. L. Baker, P. B. Mirkarimi, et al., "High-performance Mo-Si multilayer coatings for extreme-ultraviolet lithography by ion-beam deposition," *Appl. Opt.* **42**, 4049–4058 (2003).
28. P. A. Kearney, C. E. Moore, S. I. Tan, S. P. Vernon, and R. A. Levesque, "Mask blanks for extreme ultraviolet lithography: ion beam sputter deposition of low defect density Mo/Si multilayers," *J. Vac. Sci., Technol. B* **15**, 2452–2454 (1997).
29. T. Chassé, H. Neumann, B. Ocker, et al., "Mo/Si multilayers for EUV lithography by ion beam sputter deposition," *Vacuum* **71**, 407–415 (2003).
30. T. Chassé, H. Neumann, and B. Rauschenbach, "Ion beam assisted deposition of multi-layer x-ray mirrors for the extreme ultraviolet lithography," *NIM B* **206**, 377–381 (2003).
31. D.-E. Kim, S.-M. Lee, I.-J. Jeon, and M. Yanagihara, "Characterization of a multilayer soft x-ray reflector fabricated by pulsed laser deposition," *Appl. Surf. Sci.* **127–129**, 531–535 (1998).
32. S. Braun, R. Dietsch, M. Haidl, et al., "Mo/Si multilayers for EUV application prepared by pulsed laser deposition (PLD)," *Microelectron. Eng.* **57–58**, 9–15 (2001).
33. S. Braun, H. Mai, M. Moss, R. Scholz, and A. Leson, "Mo/Si multilayers with different barrier layers for applications at extreme ultraviolet mirrors," *Jap. J. Appl. Phys.* **41**, 4074–4081 (2002).
34. E. Spiller, *Soft X-Ray Optics*, SPIE Press, Bellingham, WA (1994).
35. J. I. Larruquert, "Sub-quarterwave multilayers with enhanced reflectance at 13.4 and 11.3 nm," *Opt. Comm.* **206**, 259–273 (2002).
36. J. I. Larruquert, "Reflectance enhancement in the extreme ultraviolet and soft x-rays by means of multilayers with more than two materials," *J. Opt. Soc. Am. A* **19**, 391–397 (2002).
37. M. Singh and J. M. Braat, "Design of multilayer extreme ultraviolet mirrors for enhanced reflectivity," *Appl. Opt.* **39**, 2189–2197 (2000).
38. S. Bajt, J. B. Alameda, T. W. Barbee Jr., et al., "Improved reflectance and stability of Mo-Si multilayers," *Opt. Eng.* **41**, 1797–1804 (2002).
39. S. Yulin, N. Benoit, T. Faigl, and N. Kaiser, "Interface-engineered EUV multilayer mirrors," *Microelect. Eng.* **83**, 692–694 (2006).
40. H. Maury, P. Jonnard, J.-M. André, et al., "Non-destructive X-ray study of the interphases in Mo/Si and Mo/B₄C/Si/B₄C multilayers," *Thin Solid Films* **514**, 278–286 (2006).
41. L. G. A. M. Alink, R. W. E. van de Kruijs, E. Louis, F. Bijkerk, and J. Verhoeven, "Improved temperature stability of Mo/Si multilayers by carbide based diffusion barriers through implantation of low energy CH_x⁺ ions," *Thin Solid Films* **510**, 26–31 (2006).
42. V. Arkadiev, A. Baranov, A. Erko, et al., "Carbon/carbon multilayers for synchrotron radiation," *Proc. SPIE* **3773**, 122–127 (1999).
43. C. Morawe, J.-C. Peffen, E. Ziegler, and A. K. Freund, "High resolution multilayer x-ray optics," *Proc. SPIE* **4145**, 61–71 (2001).

44. R. Dietsch, T. Holz, H. Mai, et al., "X-ray optical properties of C/C multilayers prepared by pulsed laser deposition (PLD)," *Proc. MRS* **382**, 345–350 (1995).
45. Y. C. Lim, T. Westerwalbesloh, A. Aschentrup, et al., "Fabrication and characterization of EUV multilayer mirrors optimized for small spectra reflection bandwidth," *Appl. Phys. A* **72**, 121–124 (2001).
46. S. Yulin, T. Kuhlmann, T. Feigl, and N. Kaiser, "Spectral reflectance tuning of EUV mirrors for metrology applications," *Proc. SPIE* **5037**, 286–293 (2003).
47. L. Beigman, A. P. Pirozhkov, and E. N. Ragozin, "Reflection of a few cycle x-ray pulses by aperiodic multilayer structures," *J. Opt. A, Pure Appl. Opt.* **4**, 433–439 (2002).
48. A. Wonisch, Th. Westerwalbesloh, W. Hachmann, et al., "Aperiodic nanometer multilayer systems as optical key components for attosecond electron spectroscopy," *Thin Solid Films* **464–465**, 473–477 (2004).
49. A. E. Yakshin, R. W. E. van de Kruijs, I. Nedelcu, et al., "Enhanced reflectance of interface engineered Mo/Si multilayers produced by thermal particle deposition," *Proc. SPIE* **6517**, 65170I (2007).
50. H. Takenaka and T. Lawamura, "Thermal stability of Mo/C/Si/C multilayer soft x-ray mirrors," *J. of Elec. Spec. and Rel. Phenom.* **80**, 381384 (1996).
51. Z. Jiang, X. Jiang, W. Liu, and Z. Wu, "Thermal stability of multilayer films Pt/Si, W/Si, Mo/Si, and W/Si," *J. Appl. Phys.* **65**, 196–200 (1989).
52. Klodt, K. Nolting, U. Kleineberg, et al., "Enhancement of the reflectivity of Mo/Si multilayer mirrors by thermal treatment," *Appl. Phys.* **58**, 2601–2603 (1991).
53. R. S. Rosen, D. G. Stearns, M. A. Villiardos, et al., "Silicide layer growth rates in Mo/Si multilayers," *Appl. Opt.* **32**, 6975–6980 (1993).
54. V. V. Kondratenko, Yu. P. Pershin, O. V. Poltseva, et al., "Thermal stability of soft x-ray Mo-Si and MoSi₂-Si multilayer mirrors," *Appl. Opt.* **32**, 18111816 (1993).
55. D. L. Windt, "Stress, microstructure, and stability of Mo/Si, W/Si, and Mo/C multilayer films," *J. Vac. Sci. Technol. A* **18**, 980–991 (2000).
56. T. Feigl, H. Lauth, S. Yulin, and N. Kaiser, "Heat resistance of EUV multilayer mirrors for long-time applications," *Microelectr. Eng.* **57–58**, 3–8 (2001).
57. T. Feigl, S. Yulin, T. Kuhlmann, and N. Kaiser, "Damage resistant and low stress EUV multilayer mirrors," *Jpn. J. Appl. Phys.* **41**, 4082–4085 (2002).
58. T. Böttger, D. C. Meyer, P. Paufler, et al., "Thermal stability of Mo/Si multilayers with boron carbide interlayers," *Thin Solid Films* **444**, 165–173 (2003).
59. H. Takenaka, H. Io, T. Haga, and T. Kawamura, "Design and fabrication of highly heat-resistant Mo/Si multilayer soft x-ray mirrors with interleaved barrier layers," *J. Synchrotron Rad.* **5**, 708–710 (1998).
60. Y. Ijdiyaou, M. Azizan, E. L. Ameziane, M. Brunel, and T. A. N. Tan, "On the formation of molybdenum silicides in Mo-Si multilayers: the effect of Mo thickness and annealing temperature," *Appl. Surf. Sci.* **55**, 165–171 (1992).
61. H.-J. Voorma, E. Louis, N. B. Koster, and F. Bijkerk, "Temperature induced diffusion in Mo/Si multilayer mirrors," *J. Appl. Phys.* **83**, 4700–4708 (1998).

62. J. M. Liang and L. J. Chen, "Interfacial reactions and thermal stability of ultrahigh vacuum deposited multilayered Mo/Si structures," *J. Appl. Phys.* **79**, 4072–4077 (1996).
63. R. R. Kola, D. L. Windt, W. K. Waskiewicz, et al., "Stress relaxation in Mo/Si multilayer structures," *Appl. Phys. Lett.* **60**, 3120–3122 (1992).
64. T. Leisegang, D. C. Meyer, A. A. Levin, S. Braun, and P. Paufler, "On the interplay of internal/external stress and thermal stability of Mo/Si multilayers," *Appl. Phys. A* **77**, 965–972 (2003).
65. H. Azuma, A. Takeichi, I. Konomi, Y. Watanabe, and S. Noda, "Thermally induces structural modification of nanometer-order Mo/Si multilayers by the spectral reflectance of laser-plasma soft x-rays," *Jpn. J. Appl. Phys.* **43**, 2078–2082 (1993).
66. M. Ishino, O. Yoda, H. Takenaka, K. Sano, and M. Koike, "Heat stability of Mo/Si multilayers inserted with compound layers," *Surf. Coat. Technol.* **169–170**, 628–631 (2003).
67. H. Takenaka, T. Kawamura, Y. Ishii, T. Haga, and H. Kinoshita, "Evaluation of Mo-based multilayer EUV mirrors," in *Extreme Ultraviolet Lithography*, F. Zernike and D. T. Attwood, Eds., *OSA Proc.* **23**, 26–32 (1994).
68. S. Bajt and D. G. Stearns, "High-temperature stability multilayers for extreme ultraviolet condenser optics," *Appl. Opt.* **44**, 7735–7743 (2005).
69. S. Yulin, N. Benoit, T. Feigl, and N. Kaiser, "High-temperature multilayers," *Proc. SPIE* **5751**, 1155–1161 (2005).
70. T. Feigl, S. Yulin, N. Benoit, et al., "High-temperature LPP collector mirror," *Proc. SPIE* **6151**, 61514A (2006).
71. P. B. Mirkarimi, "Stress, reflectance, and temporal stability of sputter-deposited Mo/Si and Mo/Be multilayer films for extreme ultraviolet lithography," *Opt. Eng.* **38**, 1246–1259 (1999).
72. T. D. Nguyen, X. Lu, and J. H. Underwood, "Stress characterization in periodic multilayer structures for x-ray optics," in *Physics of X-ray Multilayer Structures*, Vol. 6, pp. 103–105, Optical Society of America, Washington, D.C. (1994).
73. T. D. Nguyen, C. Khan-Malek, and J. H. Underwood, "Achievement of low stress in Mo/Si multilayer mirrors," in *OSA Proc. on Extreme Ultraviolet Lithography*, F. Zernike and D. T. Atwood, Eds., Vol. 23, pp. 56–59, Optical Society of America, Washington, D.C. (1994).
74. D. L. Windt, W. L. Brown, and C. A. Volkert, "Variation in stress with background pressure in sputtered Mo/Si multilayer films," *J. Appl. Phys.* **78**, 2423–2430 (1995).
75. M. C. K. Tinone, T. Haga, and H. Kinoshita, "Multilayer sputter deposition stress control," *J. Electron. Spectrosc. Relat. Phenom.* **80**, 461–464 (1996).
76. S. P. Vernon, D. G. Stearns, and R. S. Rosen, "Ion-assisted sputter deposition of molybdenum-silicon multilayers," *Appl. Opt.* **32**, 6969–6974 (1993).
77. C. Montcalm, "Reduction of residual stress in extreme ultraviolet Mo/Si multilayer mirrors with postdeposition thermal treatments," *Opt. Eng.* **40**, 469–477 (2001).

78. M. Moss, T. Böttger, S. Braun, T. Foltyn, and A. Leson, “Stress compensation of a Mo/Si/C highly reflective multilayer by means of an optimized buffer layer and heat treatment,” *Thin Solid Films* **468**, 322–331 (2004).
79. R. Soufli and E. M. Gullikson, “Reflectance measurements on clean surfaces for the determination of optical constants of silicon in the extreme ultraviolet-soft-x-ray region,” *Appl. Opt.* **36**, 5499–5507 (1997).
80. R. Soufli and E. M. Gullikson, “Absolute photoabsorption measurements of molybdenum in the range 60 to 930 eV for optical constant determination,” *Appl. Opt.* **37**, 1713–1719 (1998).
81. C. Tarrio, R. N. Watts, T. B. Lucatorto, J. M. Slaughter, and C. M. Falco, “Optical constants of in situ-deposited films of important extreme-ultraviolet multilayer mirror materials,” *Appl. Opt.* **37**, 4100–4104 (1998).
82. R. Soufli, S. Bajt, and E. M. Gullikson, “Optical constants of beryllium from photoabsorption measurements for x-ray optics applications,” *Proc. SPIE* **3767**, 251–256 (1999).
83. U. Schlegel, “Determination of the optical constants of Ruthenium in the EUV and soft x-ray region using synchrotron radiation,” Diploma thesis, Technische Fachhochschule Berlin, May 2000.
84. B. L. Henke, E. M. Gullikson, and J. C. Davis, “X-ray interactions: photoabsorption, scattering, transmission, and reflection at $E = 50\text{--}30,000$ eV, $Z = 1\text{--}92$,” *At. Data Nucl. Data Tables* **54**, 181–342 (1993). The updated version of these data is available at http://henke.lbl.gov/optical_constants/asf.html.
85. D. L. Windt, “IMD-software for modeling the optical properties of multilayer films,” *Computers in Physics* **12**, 360–370 (1998). IMD software is available at <http://www.rxollc.com/idl>.
86. X-Ray and Gamma-Ray Data, <http://physics.nist.gov/PhysRefData/contents-xray.html>.
87. Elastic Photon-Atom Scattering, <http://physci.llnl.gov/Research/scattering/>
88. D. W. Sweeney, R. M. Hudyma, H. N. Chapman, and D. Shafer, “EUV optical design for a 100 nm CD imaging system,” *Proc. SPIE* **3331**, 2–10 (1998).



Regina Soufli received her PhD in Electrical Engineering from the University of California, Berkeley, in 1997, and was staff scientist at the Harvard-Smithsonian Center for Astrophysics in 1997–99, studying the optical properties of iridium-coated mirrors for NASA’s Chandra X-ray Observatory. She joined LLNL in 1999 and has been the principal investigator on EUV/x-ray optics programs for semiconductor lithography, solar physics, synchrotron and free-electron lasers, and high-energy physics.

Her interests are in EUV/x-ray interactions with matter, surface science, thin films, roughness and scattering. She has received several LLNL awards and two “R&D 100” awards while at LLNL.



Saša Bajt received her PhD in Physics at the University of Heidelberg in Germany. She worked for The University of Chicago at the National Synchrotron Light Source (NSLS) developing x-ray fluorescence microprobe and micro x-ray spectroscopy. She joined Lawrence Livermore National Laboratory in 1996 where she was a principal investigator of a multilayer development team. As of 2008, she leads a Novel X-ray Optics group at DESY (Hamburg, Germany). She was a recipient of the Haw-

ley medal in 1999, given by The Mineralogical Association of Canada, for the innovation and application of microbeam XAFS to mineralogical research, and she has also received several LLNL awards. She holds several US and international patents on novel multilayer structures. Her protective capping layer design to extend the lifetime of the EUV multilayers was accepted as a benchmark by the semiconductor industry. Her research interests include multilayer optics for EUV and x-ray regions, optics damage and lifetime, physics of surfaces and interfaces, and x-ray microscopy and spectroscopy. She is currently developing optics for short pulsed Free Electron Lasers (FELs) and is studying the damage of the coatings exposed to extreme conditions.

Chapter 5

EUV Optical Testing

Kenneth A. Goldberg

Contents

5.1 Introduction	205
5.2 Target Accuracy	207
5.3 Techniques for Angstrom-scale EUV Wavefront Measurement Accuracy	208
5.3.1 Spherical-wave illumination	209
5.3.2 Basic testing requirements	209
5.3.3 Knife-edge test	210
5.3.4 Point-diffraction interferometer	210
5.3.5 Phase-shifting point-diffraction interferometer	211
5.3.6 Shearing interferometry	213
5.3.7 Hartmann wavefront sensor	215
5.3.8 EUV interferometry examples	216
5.3.9 Aerial image monitors	217
5.3.10 Calibration techniques	218
5.4 Intercomparison	218
5.4.1 Visible-light and EUV interferometry	219
5.5 Future Directions	219
5.5.1 At-wavelength optical testing in commercial lithography applications	220
5.5.2 EUV optical testing in other areas	221
References	222

5.1 Introduction

The goal of creating lithographic-quality EUV imaging systems has pushed researchers to develop the most accurate wavefront aberration measurement techniques ever created. During the development of EUV lithography (EUVL) technology, at-wavelength optical testing has proven valuable as a tool for understanding chromatic aberrations and multilayer (ML) influences on performance, and also as a highly deterministic independent measurement for comparison with visible-light interferometry. Because of the perceived trade-offs among complexity, cost, and necessity, no universal conclusion has yet been reached on the role at-wavelength

testing will play as EUVL transitions to production. EUV interferometric measurements have achieved accuracy levels of 0.4–1.0 Å rms for primary aberration terms (verified by lithographic imaging), with state-of-the-art visible-light testing methods only slightly behind. Measurement precision levels have been higher still, with researchers claiming uncertainty levels on the order of 0.05 Å rms or below. But precision and accuracy are separate concerns: precision relies only on the measurement stability, while accuracy requires that the measurements be correct. Despite the substantial effort needed to achieve these levels, these techniques are not widely practiced, and it is generally acknowledged that some progress is still needed to meet the demands of commercial lithography tools.

Over the past several decades, interferometry has become the cornerstone measurement method in the development of high-accuracy, diffraction-limited optical systems. With countless varieties and variations in its implementation, *interferometry* refers to the class of wavefront measurement techniques that rely on the ability of coherent light to interfere and produce measurable intensity fluctuations. When well-controlled coherent light is passed through a test lens, it can be made to interfere with delayed, displaced, or filtered versions of the same wave packet in such a manner that an optical system's wavefront aberrations or wavefront slope errors can be revealed through an interference pattern, or *interferogram*. In this way, the light wavelength becomes the fundamental unit of measurement. In modern interferometers, the interferograms are recorded digitally on a light-sensitive charge-coupled device (CCD) camera, and many individual interferograms can be combined to form a single measurement.

For interferometry, nowhere is the difficulty higher than in the alignment and testing of EUV optical systems and the testing of the corresponding individual aspheric mirrors, which require subnanometer rms wavefront quality specifications to meet lithographic performance goals. This chapter focuses on the testing of assembled EUV optical imaging systems. With EUV-specific, resonant-reflective ML coatings, the performance of EUV optics is highly wavelength dependent. Performing the final alignment and testing using the operational wavelength is one way to guarantee that the total optical system performance is accurately known. However, as the demonstrated accuracy of visible-light interferometric testing methods has improved, the necessity of EUV interferometry remains a subject of open debate. Our experience has shown that the highest-quality EUVL imaging has repeatedly followed careful alignment with EUV interferometry.

A number of successful techniques have been developed specifically to meet the challenges presented by EUV source limitations and the required measurement accuracy. These testing methods have their origins in published work dating to the 1900s and 1930s,^{1–3} but for the challenges at hand, the methods have recently been greatly expanded to capitalize on the development of nanofabricated diffractive optical elements, modern data recording and analysis methods, and precision actuation and metrology tools. In nearly all cases, these methods have been so-called *common-path* interferometers that use spherical reference wavefronts to measure assembled lenses prealigned with visible-light interferometry. Other

techniques, including noninterferometric methods, also have been applied successfully in certain circumstances.

Until recently, EUV interferometry has been performed almost exclusively at synchrotron sources.^{4–7} However, high-power incoherent EUV sources based on laser-produced plasma (LPP) or discharge-produced plasma (DPP),⁸ and coherent EUV sources based on high-harmonic generation⁹ and laser amplification in discharge-created plasmas,¹⁰ are all promising nonsynchrotron candidate sources for EUV interferometry.

5.2 Target Accuracy

For EUVL projection optics, figure aberrations on the scale of 0.1 nm are known to adversely affect both imaging performance and distortion. Detailed analysis has suggested rms figure error tolerances in the range of 30 milliwaves (0.41 nm) for the overall assembled system wavefront,¹¹ with even tighter requirements for the individual mirrors. Although it may be at or beyond the limits of today's best lenses, rms system wavefront accuracy surpassing 0.1-nm has become a central requirement for the continued advancement of EUV lithography tools.¹² Producing lenses of such high quality requires interferometer accuracies to surpass those levels by a comfortable margin.

The tightest specifications fall on the individual aspherical mirror elements and the interferometers that are used to produce them. Here, the starting point for mirror surface specifications may be $1/2N^{1/2}$ times the total system rms wavefront error tolerance, although the errors in any given set of mirrors cannot be considered statistically uncorrelated. Reflection doubles the effect of any height error and necessitates a factor of two reduction in the error tolerance. In practice, having some degrees of alignment freedom, and having the ability to select sets of mirrors that are predicted to be well matched, somewhat reduces the single-element figure requirements.¹³ While it is difficult to generalize about the specifications of four-, six-, or eight-mirror ring-field systems, we can say that the rms figure error tolerances will be below 0.5 nm (37 milliwaves) and possibly below 0.3 nm (22 milliwaves).

During surface figuring, before the deposition of EUV-reflective ML coatings, visible-light (i.e., non-EUV) interferometry is required. Even after the coatings are applied, the high degree of aspheric departure present in most mirror elements makes it seemingly impossible to use EUV light for accurate single-element tests. With each micron of aspheric departure giving rise to two microns of reflected path-length difference, several microns quickly becomes hundreds of EUV fringes in a hypothetical conventional EUV interferometer, which would overwhelm the spatial response of any CCD camera used to record the interferograms.

Interferometry is generally most sensitive to small aberrations when the total path-length differences are small compared to the light wavelength. A conventional approach to the measurement of aspherical elements is to introduce well-characterized *null elements* (conventional or holographic) or a *compensating lens*

to balance and remove the large path-length differences or distortion before projecting the fringes onto the CCD. Such techniques have never been applied to EUV interferometry, nor attempted, because the production quality and placement accuracy required of these elements far exceed the error tolerances on the test elements, and therefore they cannot be independently validated to the necessary accuracy level. Thus, at this time and for the foreseeable future, visible-light testing is still essential to the production of EUV lenses.

It is well known that for a given ML-coated surface, the phase of the reflected light field depends strongly on the wavelength, the angle of incidence, and to a lesser degree, the polarization. To achieve a desired wavefront, ML coatings are applied across large mirror surfaces with spatially graded thickness profiles to compensate for angle-dependent EUV phase changes. Calculations have shown that for small angles of incidence that occur within an EUV optical system, the angle-induced phase changes can be an order of magnitude larger for visible light than for EUV when converted to path-length differences.^{14,15} This fact creates different aberration profiles for the same optical system measured with visible or EUV light; these differences are predictable, and must be carefully compensated during visible-light system alignment to avoid the introduction of aberrations at the operational EUV wavelength.¹⁶

5.3 Techniques for Angstrom-scale EUV Wavefront Measurement Accuracy

During the past 15 years, many groups with common goals have performed successful EUV interferometric measurements by employing a range of experimental techniques and light sources to optical systems ranging in numerical aperture (NA) from 0.08 to 0.3 ($f/6.25$ to $f/1.67$). The introduction of many of these methods predates the advent of high-coherence light sources, and hence they are well suited to light sources with relatively short coherence lengths ($\leq 1 \mu\text{m}$). An overview of the primary techniques and results is presented here with some discussion of the relative merits and shortcomings of each method. A limited number of EUV to visible-light measurement comparisons have been made and will be discussed. Other wavefront tests based on the evaluation of printed images have been applied.¹⁷

To date, the most commonly applied EUV interferometric techniques belong to the class of so-called common path interferometers: those for which the test and reference beams propagate together along largely similar light paths. These interferometers, which include both point diffraction and shearing designs, have enhanced vibration stability, demonstrated high sensitivity, and require only modest coherence lengths. Other nonprinting techniques include the knife-edge or Foucault test,^{18,19} adaptations of the Ronchi test²⁰ applied to single spherical mirrors in reflection, the noninterferometric Hartmann test,²¹ and aerial image monitoring,^{22,23} all discussed below.

To isolate the aberrations in a given lens, it is essential in most techniques to illuminate the lens with a well-controlled, well-known wavefront. Generating such a wavefront relies on the properties and limitations of available sources. Sources are discussed in Chapter 3.

5.3.1 Spherical-wave illumination

The optical systems of greatest interest to photolithography have *fixed conjugates*, meaning that a point-like object produces a point-like image in the appropriate conjugate planes. The most common methods of testing such lenses require that a diverging spherical reference wavefront be produced in one conjugate plane, and the resultant focused spherical wave is measured near the other conjugate plane. Producing a spherical reference wave typically involves creating a point-like secondary source by illuminating a pinhole spatial filter in transmission.

Reciprocity will guarantee that a lens can be tested from either conjugate side, yet there are usually strong advantages to guide the choice we make. Focusing light from an EUV source onto the tiny pinholes required for spherical wave generation (25 to 1000 nm diameter) typically involves high losses, so the slow (i.e., low NA) side of the lens is the one most commonly illuminated. For EUV testing, limitations on the available source *brightness* (see Chapter 3) make it particularly challenging to provide ample flux to a small pinhole spatial filter. For this reason, EUV interferometers illuminate the lens from the low-NA or slow side where the pinhole spatial filter can be larger (100 to 1000 nm diameter).

5.3.2 Basic testing requirements

Most of the testing methods share similar experimental configuration requirements, thereby making it possible to perform different kinds of tests with minimal reconfiguration. Stable, high-precision stages are required on both the object and image sides of the lens to support the nanofabricated optical structures that are specific to each test. For most of the interferometers described below, one additional stage is required. When the field of view is large (as is the case with lithographic lenses), some mechanism must be present to sequentially illuminate all of the points of interest across the field. This is not a trivial requirement.

Diffraction optical elements are typically produced by electron-beam lithography²⁴ on a thin transparent membrane (e.g., silicon-nitride or Si_3N_4), 100 to 200-nm thick, and coated with a thin absorber layer typically made of electroplated gold (Au) or nickel (Ni). These materials can be patterned at nanometer-length scales, have short absorption lengths, and resist oxidation. In some cases the supporting Si_3N_4 membrane may be etched away for additional transmission.

Typically, a scientific-grade, EUV-sensitive CCD camera is positioned to capture the full pupil projected at the exit of the lens. These CCDs are usually back thinned and back illuminated, and designed for high EUV sensitivity. The CCD is used for alignment, to observe the illumination uniformity, and to record the interferograms.

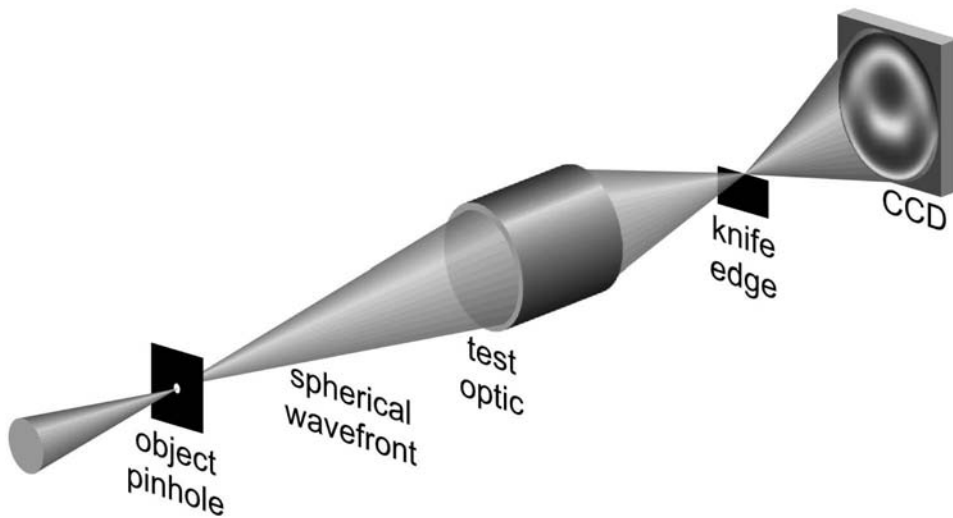


Figure 5.1 Knife-edge or *Foucault* test. Illumination is from the left.

5.3.3 Knife-edge test

The knife-edge test is useful as a preliminary step in any fixed-conjugate interferometry technique, and it can be integrated easily into other testing methods. Originally described by L. Foucault in 1859 or slightly prior, the knife-edge test is one of the simplest tests to implement,²⁵ and it lends itself to unambiguous qualitative analysis (see Fig. 5.1). Using a spherical illuminating wavefront, a nanoscopically sharp opaque edge is placed in the image plane to bisect the focused point image, blocking half of the light. Rays that deviate from the image point in the direction perpendicular to the edge will either be blocked by the edge or allowed to pass. The projected pattern of the illuminated pupil is observed in a far-field plane, and the resultant pattern of light and dark regions reveals the local slope of the wavefront in the direction orthogonal to the edge. This method is also a sensitive technique for identifying the focal plane.

Many researchers have discussed the quantitative analysis of knife-edge measurements,²⁶ but questions remain about the ultimate sensitivity of the technique, and today it is considered a complementary measurement. The fact that the edge runs in only one direction makes the detection of astigmatism particularly difficult. One significant advantage of the knife-edge method is that it does not require sensitive calibration in order to reveal aberrations such as coma and spherical aberration, which produce easily recognizable patterns.

5.3.4 Point-diffraction interferometer

First described by Linnik³ and later by Smartt,²⁷ the point-diffraction interferometry (PDI) technique uses a “reference” pinhole in a semitransparent image-plane membrane to produce a second spherical reference wavefront by diffraction, as

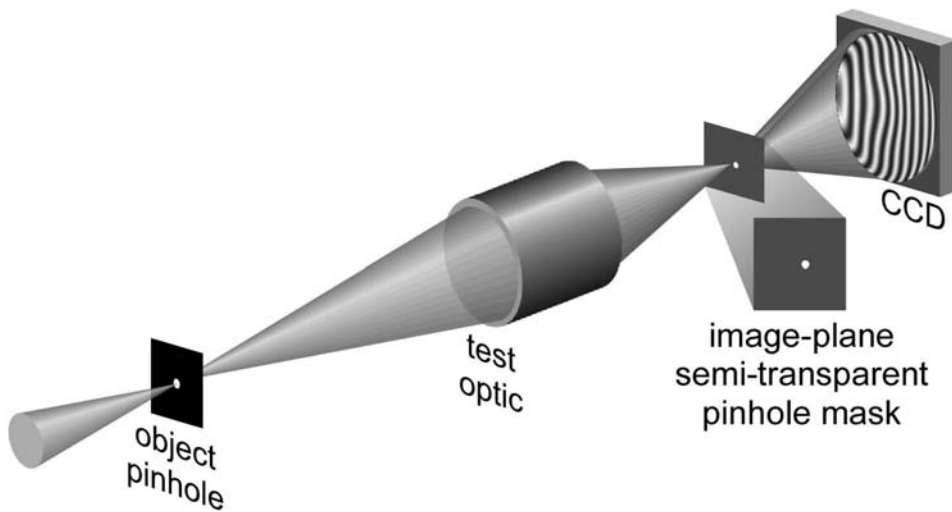


Figure 5.2 Point-diffraction interferometer (PDI), also called the Linnik or Smartt interferometer.

shown in Fig. 5.2. The membrane transmits the focused beam with reduced amplitude, while the pinhole, sized below the resolution of the lens, diffracts a new spherical beam in close proximity to the focus. In this way, the aberrated test beam interferes with the new reference beam to produce an interference pattern.

This method was suggested for EUV applications by Sommargren et al.²⁸ The method works, but suffers from serious deficiencies. Producing a clear analyzable fringe pattern usually requires the user to displace the pinhole from the focus into a region where the intensity is unavoidably lower. With a weak signal transmitted through the pinhole, producing the *reference wave* by diffraction, the semitransparent membrane must be made nearly opaque to achieve a similar intensity in the transmitted *test wave*. (Matched intensities yields the highest signal-to-noise ratio.) Consequently, the overall efficiency of the PDI is extremely low for EUV applications, with most of the available light being absorbed in the membrane. Furthermore, the unpredictable, highly nonuniform illumination pattern in the vicinity of the reference pinhole severely compromises the quality of the reference wave, leading to unpredictable results. For these reasons, the method was abandoned when the phase-shifting point diffraction interferometer (PS/PDI) was invented.

5.3.5 Phase-shifting point-diffraction interferometer

The PS/PDI is a common path design that relies on pinhole diffraction to generate spherical reference waves in both the object and image planes. It overcomes many of the limitations and disadvantages of the PDI. The design, first proposed by Medecki et al.²⁹ and later refined by Goldberg and Naulleau,^{30,31} includes a transmission grating beamsplitter to produce a series of displaced foci in the image plane (see Fig. 5.3). Two of these beams are selected to become the test and reference beams. The test beam is aligned to pass through a relatively large window

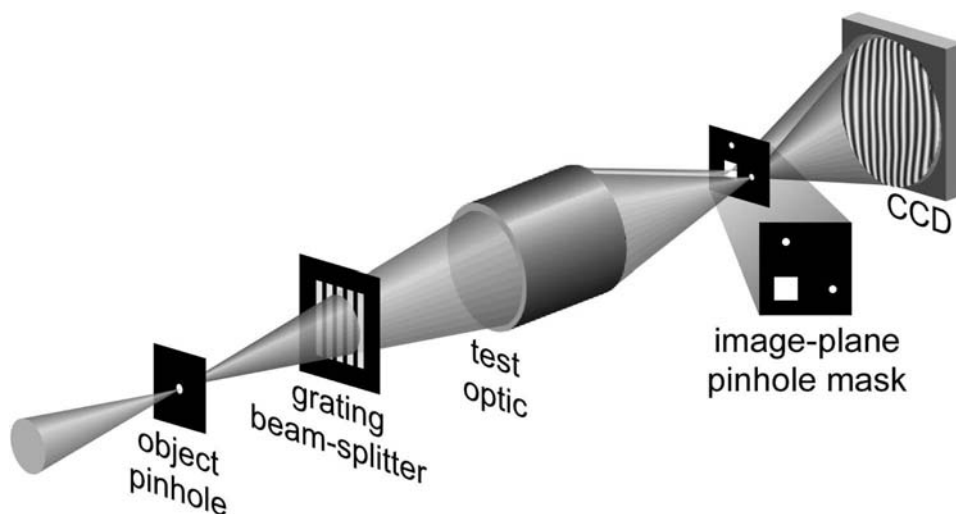


Figure 5.3 Phase-shifting point-diffraction interferometer (PS/PDI).

in an opaque image-plane membrane. The reference beam is brought to focus on a tiny pinhole close to the window where the aberrations are filtered and a spherical reference wave is diffracted. Unlike the conventional PDI, positioning the pinhole at the brightest point of a focused beam creates the highest possible reference wave intensity. The efficiency of this design versus the PDI can be 10 to 100 times higher.

Phase shifting is a powerful interferometric data analysis and measurement technique that enhances the accuracy and precision of phase detection. In phase-shifting methods, a series of interferograms is recorded featuring a controlled path-length (i.e., phase) difference between the interfering beams. All other parameters are held constant. The fringes may appear to *shift* from frame to frame. A vast number of analysis methods are available to extract the relative phase differences of points across the pupil, and many of these techniques can be designed to reject systematic intensity variations and enhance the measurement accuracy.

The phase-shifting aspect of the PS/PDI comes from the fact that translating the grating in-plane, in the direction perpendicular to the grating lines, generates arbitrary, relative, modulo 2π phase shifts between any two diffraction orders.

The PS/PDI is an effective technique for testing high-quality optical systems, provided that pinholes can be fabricated with sizes smaller than the test optics' resolution. For EUV systems with NA values exceeding 0.1, the required pinhole sizes are below 100 nm. At 0.3 NA, the pinhole sizes are below 40 nm, making them challenging to align and use. In the author's experience the PS/PDI can be aligned and used at EUV wavelengths for 0.1 NA test optics with little difficulty, provided high-resolution stages and pinhole arrays with sensible alignment features are available. Holographic methods have been developed to facilitate the otherwise difficult pinhole alignment steps.³¹ At 0.3 NA, we were able to record PS/PDI data,³² but we found that phase-shifting data collection was limited by position stability and pinhole (carbon) contamination issues.

One significant limitation of both the PS/PDI and the PDI techniques is their dynamic range, that is, the range of aberration magnitudes that can be measured. For techniques that rely on pinhole diffraction, the strength of the diffracted wave is a significant concern for fringe formation. When the aberrations are large, the highest available field intensity at the pinhole, as described in a relative sense by the Strehl ratio, drops significantly. In practice, this limits the maximum measurable aberration magnitude (including defocus) to less than one wave, possibly smaller. For this reason, PDIs are best used to achieve high accuracy when the optical system is already somewhat close to diffraction-limited quality. Furthermore, the pinhole can be viewed as a spatial filter, removing some but not all of the incident wave's aberrations via transmission. Since the aberrations present in the test optic reduce the quality of the spherical reference wave, and hence reduce the accuracy of the measurement, the point-diffraction techniques become more and more accurate, in principle, as optical alignment proceeds toward diffraction-limited quality.

In a PS/PDI, the test beam passes through a window in the focal plane, and that window acts as a spatial filter to set the upper limit of the transmitted spatial frequencies. Typically the window is designed to be large enough to transmit all of the spatial frequencies of interest for alignment. The window shape can be extended in the direction perpendicular to the test and reference beam displacement, allowing the PS/PDI to be used to mid-spatial-frequency (i.e., flare) measurement.^{14,33}

Since coherent flux levels are an important concern for interferometry, it is worth mentioning that the PS/PDI used at Lawrence Berkeley National Laboratory (LBNL) was installed on an Advanced Light Source (ALS) undulator beamline optimized for high coherent flux. The beamline delivered approximately 10 μW at a 13.5-nm wavelength, within a 0.5% spectral bandwidth, through a 0.5- μm pinhole at the beamline's focal plane. The power available through smaller entrance pinholes scaled with the pinhole area.

Several interesting variants of the PS/PDI have been proposed to increase the available photon flux,¹⁴ including the line-diffraction interferometer,³⁴ which offers higher transmission efficiency but measures aberrations in only one direction at a time.

5.3.6 Shearing interferometry

Shearing interferometers create interference between the test wave and displaced copies of itself, with no reference wave. In this way, the resultant phase measurements approximate the derivative of the wavefront in the direction of the *shear*. Multiple directions of measurement can be combined to mathematically reconstruct the original wavefront. Compared to the point-diffraction techniques, shearing interferometry offers much higher efficiency, variable sensitivity with higher dynamic range, and less challenging alignment, but at the expense of more complex wavefront analysis and reduced sensitivity near the edges of the pupil.

EUV versions of shearing interferometers use a grating as a low-angle beam-splitter; several variations have been successful. EUV diffraction gratings used as

beamsplitters produce a large number of orders that propagate with relatively small angular deviations. If the grating is placed before the focal plane, these orders can be spatially isolated due to their small focal plane displacements. The version first implemented by Goldberg and Naulleau³⁵ used a cross-grating and no order filtration, as shown in Fig. 5.4. The cross-grating enabled simultaneous measurement of the derivative in two orthogonal directions, improving the measurement of astigmatism. Without a spatial filter to isolate and transmit only two beams, the

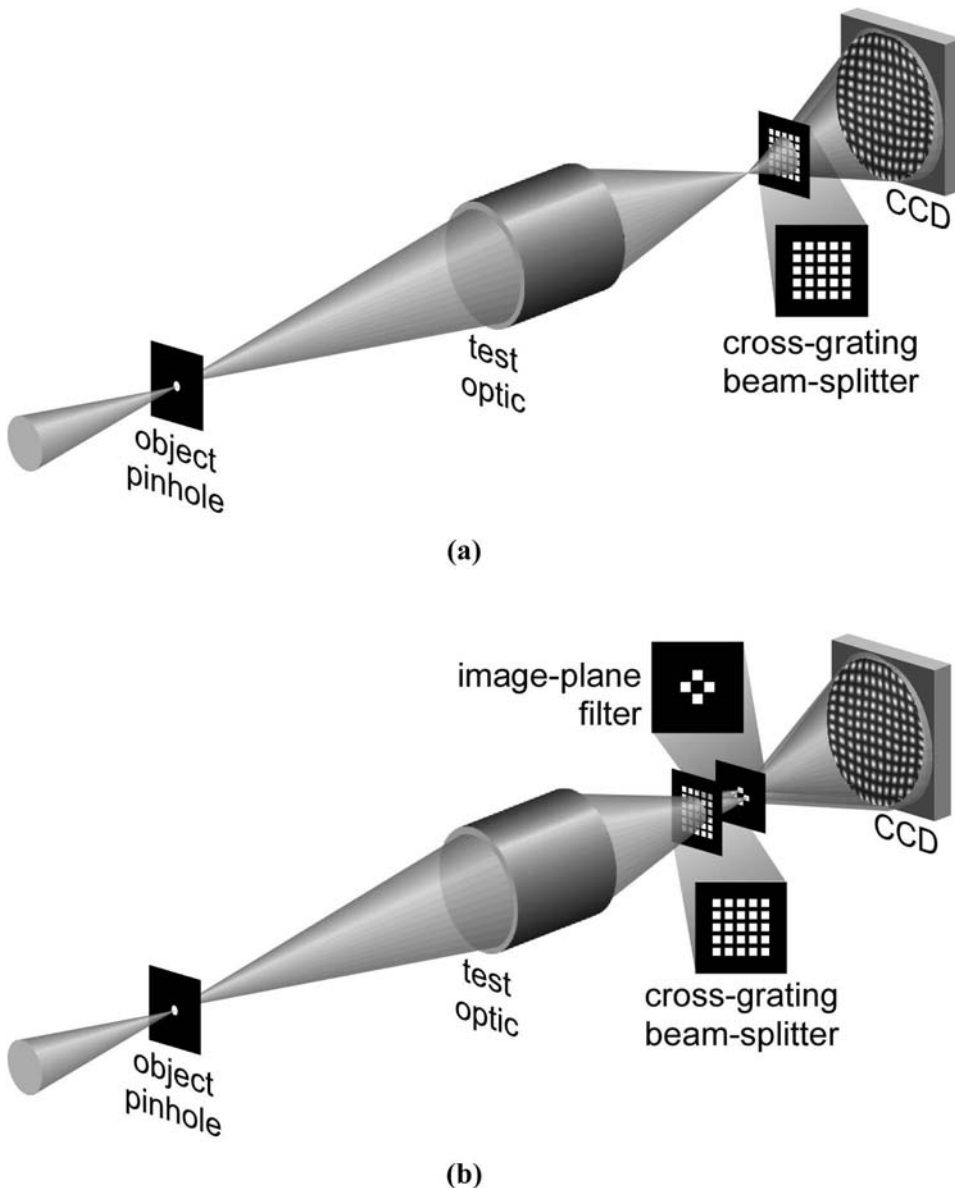


Figure 5.4 (a) Unfiltered, and (b) filtered cross-grating lateral shearing interferometers.

grating must be longitudinally placed so that the focal plane coincides with a Talbot plane of the grating (either before or after the focal plane).³⁶ Otherwise, the fringe pattern cannot be clearly resolved. Sugisaki et al. demonstrated a filtered cross-grating lateral shearing interferometer design in which the image-plane filter contained four windows placed to transmit the two first-order beams in the two lateral directions^{34,37} and to block the undiffracted zeroth-order beam. In both the filtered and unfiltered cases, a pair of perpendicularly ruled one-dimensional gratings can be used to measure the wavefront gradient in two steps, rather than the single step provided by the cross-grating. However, an extreme sensitivity to longitudinal grating displacement reduces the accuracy of the astigmatism measurement.

The spatial frequency response of shearing interferometers is an interesting subject of ongoing research. The magnitude or *displacement* of the sheared beams, which is determined by the period and position of the shearing grating, affects the spatial scale of the aberration slope errors that can be measured. This parameter is selected during the interferometer design and can be adjusted in-situ by having several different gratings available for use in series. For larger shear magnitudes, the sensitivity to low-spatial-frequency aberrations increases, but the high-spatial-frequency cutoff is reduced significantly. The presence of high-spatial-frequency errors may degrade the measurement of slowly varying aberrations by aliasing. Furthermore, with increasing beam displacements, areas near the edges of the pupil become unmeasurable.

Shearing measurements have been found to be almost as accurate as PS/PDI measurements of the same EUV optical systems.^{32,34,38} Aside from the inability of the shearing measurements to measure near the edges of the pupil, the level of agreement observed in Ref. 38 was 0.25 ± 0.06 nm, and in Ref. 32, closer to 0.5 nm. The origin of the differences has never been fully explored nor explained.

5.3.7 Hartmann wavefront sensor

The Hartmann wavefront sensor (HWS) uses a noninterferometric technique with much lower coherence requirements and higher overall efficiency.²¹ This technique dates to 1900.³⁹ A grid of small holes in an opaque screen is placed in the beam path, causing a shadow of the mask to be projected onto a CCD camera (see Fig. 5.5). The hole sizes and separations, and the CCD distance, are designed so that adjacent bright spots in the projected pattern do not overlap and can be isolated. Variations in the test beam's local wavefront slope cause small angular deviations in the projected bright spots, resulting in measurable shifts in the projected pattern. The HWS configuration is technically not an interferometer because the diffracted beams (intentionally) do not overlap and interfere at the detector. Similar to shearing, analysis in two dimensions enables the mathematical reconstruction of the test wavefront. In general, placing the CCD camera farther from the hole array increases the sensor's sensitivity to small angular deviations. Yet for high-NA systems, the distance is constrained by the limited size of the detector and the fixed solid angle of the measurement.

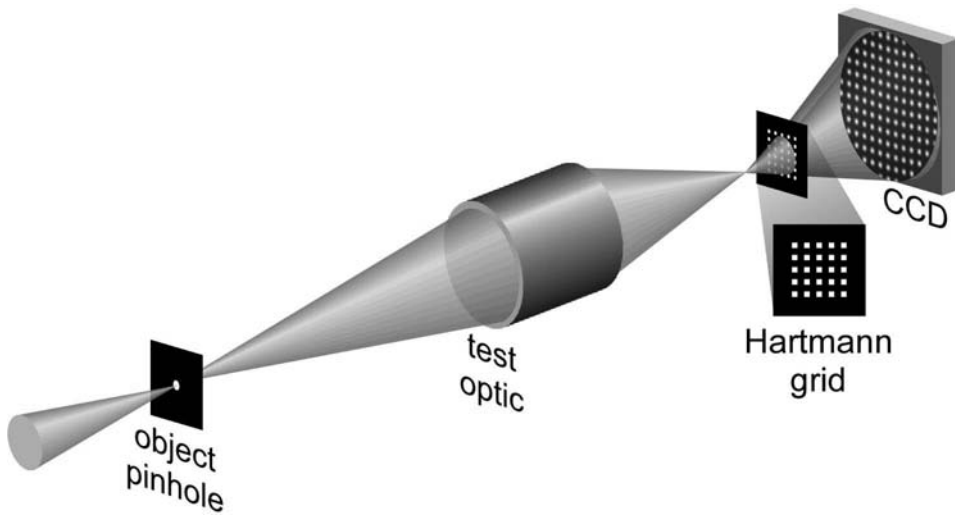


Figure 5.5 Hartmann wavefront sensor (HWS).

The HWS has been successfully applied to the measurement of low-NA EUV optical systems such as synchrotron beamlines,^{40,41} but it has yet to be proven sensitive enough for the measurement of higher-NA lithographic optics.

The HWS is subject to similar spatial frequency concerns as the shearing interferometer. The highest measurable spatial frequencies are set by the limited number of sampled points. Furthermore, the presence of higher spatial frequency aberrations can introduce apparent low-spatial-frequency errors through aliasing. Unlike the shearing methods, there is no simple way to scale the sensitivity of the HWS without increasing the separation distance between the grid and the detector.

The Shack-Hartmann wavefront sensor (SHWS)⁴² is an enhancement to the Hartmann design that is commonly used at visible wavelengths. In the SHWS, the grid is replaced with an array of lenslets, and the grid-to-camera distance can be reduced significantly. While the idea is attractive to consider, the SHWS has yet to be successfully applied at EUV wavelengths for various reasons. One limitation may be the fact that the lenslets used at EUV wavelengths would likely be diffractive lenses (i.e., *zoneplates*). As such, the various diffraction orders of the lenses would contribute noise if they were not blocked from reaching the detector. Furthermore, the decreased distance from the lens array to the CCD, coupled with the relatively large size of EUV CCD camera pixels, may reduce sensitivity to small local wavefront tilt changes.

5.3.8 EUV interferometry examples

In 2003, a series of interferometric measurements was performed at LBNL during the alignment of a prototype EUVL optical system called the *microexposure tool* (MET).^{25,32} Several interferograms from that work and one other experiment⁴⁰ are shown in Fig. 5.6.

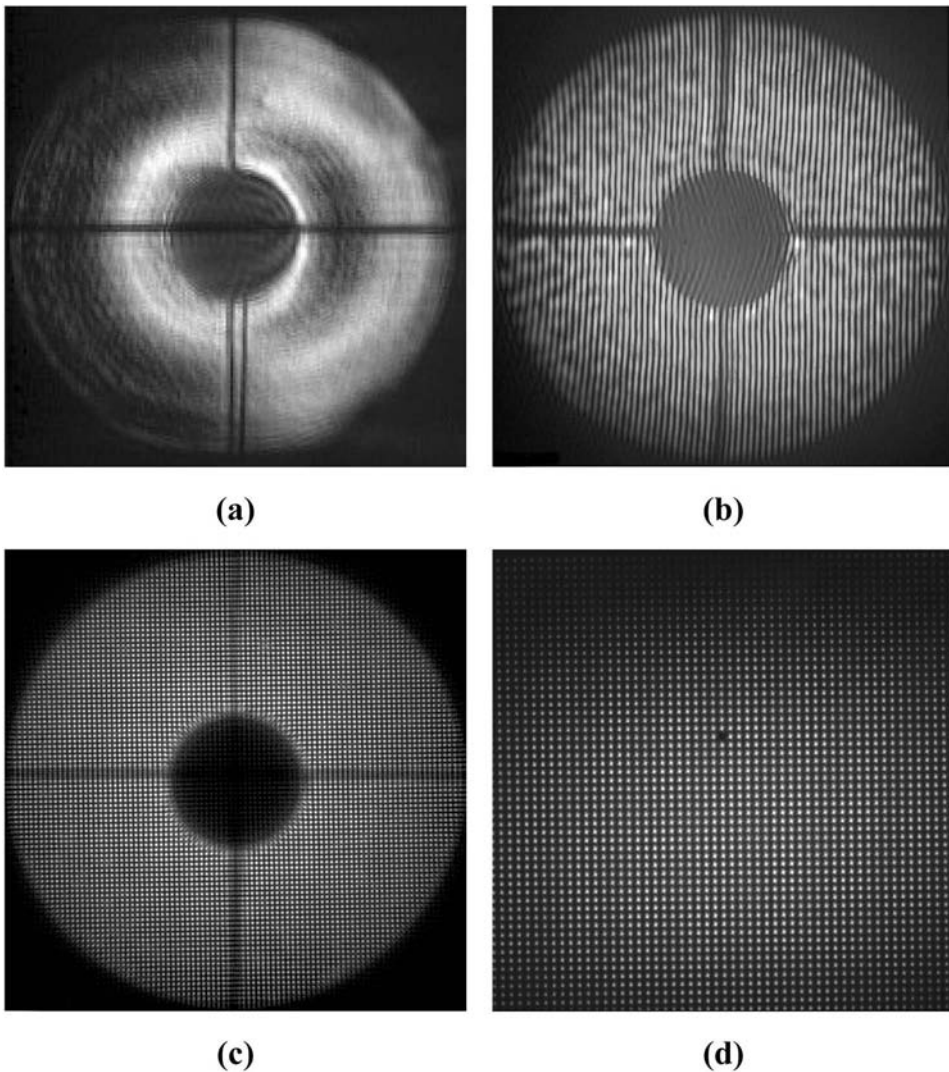


Figure 5.6 Interferograms recorded during various alignment stages of the annular, 0.3-NA, MET optic, and of a Kirkpatrick-Baez mirror pair at ALS Beamline 12.0.1.2. The MET has an annular pupil with thin *spiders*, wires that support a small central light-baffle. (a) MET knife-edge interferogram or *Foucaultgram*. (b) MET PS/PDI interferogram. (c) MET shearing interferogram. (d) Hartmann test data from the measurement of a Kirkpatrick-Baez mirror pair on ALS Beamline 12.0.1.2.⁴⁰ All measurements shown here were performed at 13.5-nm wavelength.

5.3.9 Aerial image monitors

A second noninterferometric class of wavefront sensors may be categorized as aerial image monitors. The goal of these designs is to directly probe the light intensity properties in the focal plane when forming an image of a well-known object. Like the transmission image sensor,²² such a device uses a pattern of open slits above

a photodetector to sample a projected pattern of lines. Measuring the evolution of the light intensity pattern through the focus enables low-spatial-frequency aberrations to be determined, and the method has recently been used in the alignment of commercial lithographic optical systems.⁴³

5.3.10 Calibration techniques

Accuracy is the critical characteristic of all wavefront-measuring interferometers. While precision comes from system stability and high signal-to-noise ratio, achieving high measurement accuracy requires careful calibration. The extension of these techniques from low NA to higher NA values leads to orders-of-magnitude greater difficulty in maintaining accuracy.¹⁴ Many of the compensable systematic error contributions scale as powers of the NA value and can become significantly larger than the wavefront aberrations' magnitudes of interest.

While some systematic errors scale in proportion to the aberrations present in the optic, the most significant errors are geometric in nature and can be removable in principle if they can be well characterized. *Null tests* have been devised to measure the geometric errors in the various EUV interferometers.^{44,45} For some interferometers, the focal plane separation of the test and reference beams creates systematic path-length differences across the measurement domain. Furthermore, the alignment and tilt of the gratings and detectors also contribute errors that must be measured independent of regular wavefront measurements.

In addition to null tests and other in-situ measurements, cross-calibration among different interferometry methods has proven to be valuable,^{34,46} ultimately, proof of accuracy is derived from high-resolution imaging (i.e., lithographic printing in photoresist).

5.4 Intercomparison

A primary method for understanding the relative merits and capabilities of the different available measurement techniques is to perform direct comparisons. To date, several such comparisons have been reported, including comparisons among EUV techniques and EUV versus visible-light measurement of the same optical system.

For the present generation of lithographically relevant EUV optical systems, with NA values between 0.1 and 0.3, the rms difference values typically observed when comparing the measurement techniques has seemingly plateaued since 2003 at approximately 0.25 nm.^{44,46,47} To assess the level of comparison, independent wavefront measurements are compared directly by subtracting one from the other and evaluating the resultant *difference wavefront*. This provides a more detailed assessment than simply comparing net rms wavefront error values among the different techniques.

While it may be true that one specific measurement technique is more accurate than others, independent verification beyond the level of 0.25 nm remains elusive.

Measurement precision, on the other hand, relies on the self-consistency of a given set of measurements and does not require independent verification. Researchers have achieved measurement precision levels below 0.05 Å rms, well beyond the accepted accuracy levels.⁴⁷ The accuracy limitations are likely due to imperfect calibration and data analysis methods that need ongoing improvement.

5.4.1 Visible-light and EUV interferometry

Simultaneous with the development of more-accurate EUV interferometry, visible-light system-measuring interferometry progressed significantly with the development of the phase-shifting diffraction interferometer (PSDI), invented by Som-margren and colleagues at Lawrence Livermore National Laboratory (LLNL); this device can reach close to 0.1-nm accuracy levels.^{48–50} For visible-light measurement of multi-element EUVL optical systems, diffraction plays a significant role, impairing measurements near the edge of the pupil and thereby reducing the wavefront area over which comparisons with EUV measurements can be made. Phillion et al. developed methods to mathematically propagate the measured wavefront to arbitrary surfaces within the test optic, including the exit pupil. This is especially necessary in the absence of pupil re-imaging optics, which were ultimately removed from the LLNL visible-light interferometers to reduce systematic errors. The embodiment of the updated PSDI system by Johnson and Phillion at LLNL has provided calibrated wavefront reference sources for visible-light interferometric alignment of EUV optical systems.^{51,52}

Comparison between visible-light and EUV interferometry has been a subject of extensive research. This comparison was performed on seven EUV prototype lithography optics with NA values from 0.08 to 0.3. The quality of those comparisons was limited, to some extent, by the need in every case to transport the optic from one interferometer to the other. Despite careful handling and the transfer of conjugate positions using kinematic mechanical components attached to the optical housing, a level of uncertainty remained that was comparable to the measured differences, on the order of 0.25-nm rms or more. An example comparison from Ref. 53 is shown in Fig. 5.7. The visible-light measurements were performed with the PSDI at 532.2 nm, and the visible-light measurements with the PS/PDI at a 13.4-nm wavelength. The spatial frequency response of the two interferometers was somewhat different, with the PS/PDI limited by its image-plane aperture size. The comparison and difference assessment was performed using a 37-term Zernike polynomial series.

5.5 Future Directions

The recent development and use of ultra-high-accuracy EUV interferometry has been an essential element in the successful creation of prototype EUVL systems. However, its future role is the subject of active debate. As in all fields of research,

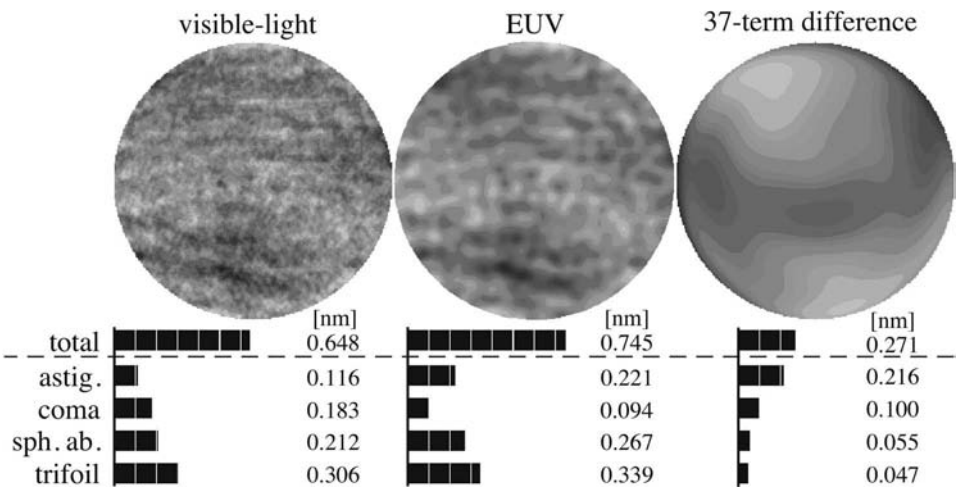


Figure 5.7 Visible-light and EUV interferometric comparison of the Engineering Test Stand (ETS) Set-2 optic, performed at LLNL and LBNL, respectively. Shown is the measurement of the central field point in the 1-in. arc-shaped field of view over a NA of nearly 0.1. Diffraction at the edges reduced the pupil radius available for comparison by several percent; this comparison was performed over a matching region. All values represent rms magnitudes. Despite the relatively close match of the total rms wavefront error values, the subtractive difference wavefront reveals systematic measurement errors that could not be accounted for between the two techniques; astigmatism is the largest component of the differences. (Adapted from Ref. 53.)

the techniques developed for one application can overlap and improve related applications. This may be the case for EUV interferometry where it plays a role in the creation of improved EUV and soft x-ray beamlines, astronomical telescopes, or other synchrotron and free-electron laser (FEL) instrumentation.

5.5.1 At-wavelength optical testing in commercial lithography applications

To date, the EUVL tools that have achieved the highest projection imaging performance have been those aligned using at-wavelength techniques, especially interferometry. Time will tell how well the new *alpha* or *beta* classes of EUVL systems will perform after combining visible-light interferometry and focus-sensor-type noninterferometric at-wavelength techniques for alignment.

There is a general perception that either EUV interferometric techniques are too difficult to apply in a commercial fabrication environment, or that such methods will not be necessary. Since the methods themselves are rather straightforward to apply, the actual difficulty largely depends on the source properties. With weak, incoherent sources, applying the highest-accuracy techniques—those that rely on high coherent flux illumination (PS/PDI, shearing, etc.)—would be extremely challenging. However, a new generation of *table-top* coherent EUV sources⁵⁴ offers the possibility of integrating a compact coherent source into the optics fabrication process. Furthermore, as EUV stand-alone source brightness increases to meet the

demands of commercial lithography tools, it may be possible to extract enough coherent flux to perform interferometric tests.

Separate from the difficulty argument, the necessity of EUV interferometry to fabricate commercial lithography tools depends entirely on the accuracy level achievable by competing methods. The possible accuracy plateau attained by visible-light interferometry, in the 0.25-nm rms wavefront error range, could be overcome by detailed evaluation of printing results²³ or by making additional comparisons with EUV interferometry performed on the same optical systems. However, the printing-evaluation methods are currently limited by the resolution of modern EUV photoresists, which cannot yet resolve patterns at the level necessary for feedback to wavefront errors at the limit of visible-light interferometry^{55,56} (i.e., essentially, diffraction-limited resolution). The experimental determination of the accuracy of visible-light interferometry has been made by comparison with EUV interferometry performed on the same optical system.^{57,58} These tests were affected by the need to transport the test optics (by truck) from one laboratory to another between measurements.

In consideration of the future role of EUV interferometry in the commercial production of EUVL systems, the “difficulty” question is clearly a matter of degrees, relying primarily on the properties of emerging EUV sources. The necessity debate hinges on the accuracy achieved by competing methods. Since the most reliable assessments of the accuracy of any testing techniques for EUV optics come from comparison with ultra-high-accuracy EUV interferometry, common-sense risk minimization dictates that such work should continue with strong support.

5.5.2 EUV optical testing in other areas

One emerging direction for the application of EUV optical testing methods is in the optimization of synchrotron and FEL beamlines, which exist at hundreds of locations around the world. A vast majority of current beamlines were designed to rely on outmoded alignment techniques, and anecdotal evidence suggests that most fall 10 to 100 times below design flux estimates. Depending on the wavelength, all-reflective EUV and soft x-ray synchrotron beamlines could achieve resolutions on the order of 10 to 100 nm using modest NA values (below 0.1), *if* they could achieve diffraction-limited performance.

Some of the most exciting frontiers of materials science exist at the nanoscale. These areas of research are driven forward by new probes and techniques with nanometer to tens of nanometers resolution. Among them, techniques in synchrotron radiation play a central role due to the strongly interacting nature of soft x-ray radiation, and the availability of focusable short-wavelength light generated by extremely high brightness third- or fourth-generation synchrotron light sources such as the ALS. At this point, inadequate metrology limits the brightness preservation and coherence preservation properties of EUV and soft x-ray beamlines.

The visible-light optical metrology techniques that are traditionally used to measure beamline optical elements are being pushed to their limits. Ever present is

the question of how the externally measured mirrors will perform when they are installed and illuminated. Displacements from the intended conjugate positions and thermal distortions from the illumination power loading can dramatically affect the wavefront quality.

The continued development of on-beamline, in-situ optical testing will enhance the available alignment diagnostics and enable improved control of active elements such as bendable mirrors. This, in turn, could move industrial suppliers of beamline optics toward the goal of achieving diffraction-limited short-wavelength optical systems. Applying the highly effective EUV interferometry techniques toward the creation of improved beamlines seems to be a natural outgrowth of this research.

References

1. V. Ronchi, "Due Nuovi Metodi per lo Studio delle Superficie e dei Sistemi Ottici," *Ann. Sci. Norm. Super. Pisa* **15** (1923).
2. V. Ronchi, "Forty years of history of a grating interferometer," *Appl. Opt.* **3**, 437 (1964).
3. W. P. Linnik, "A simple interferometer for the investigation of optical systems," *Proc. Academy of Sci. of the USSR* **1**, 208 (1933).
4. D. Attwood, G. Sommargren, R. Beguiristain, et al., "Undulator radiation for at-wavelength interferometry of optics for extreme-ultraviolet lithography," *Appl. Opt.* **32**(34), 7022–7031 (1993).
5. R. Beguiristain, K. A. Goldberg, and E. Tejnil, "Interferometry using undulator sources," *Rev. Sci. Instrumen.* **67**(9), 3353 (1996).
6. M. Niibe, M. Mukai, T. Tanaka, et al., "Development of EUV point diffraction interferometry using the NewSUBARU undulator radiation," *Proc. SPIE* **4782**, 204–211 (2002).
7. One notable exception is: A. K. Ray-Chaudhuri, K. D. Krenz, R. P. Nissen, et al., "Initial results from an extreme ultraviolet interferometer operating with a compact laser plasma source," *J. Vac. Sci. & Technol. B* **14**(6), 3964–3968 (1996).
8. E. L. Antonsen, K. C. Thompson, M. R. Hendricks, et al., "XCEED: XTREME commercial EUV exposure diagnostic experiment," *Proc. SPIE* **5751**, 1192–1202 (2005).
9. H. C. Kapteyn, M. M. Murnane, and I. P. Christov, "Coherent x-rays from lasers: applied attosecond science," *Physics Today*, p. 39 (March 2005).
10. J. J. Rocca, Y. Wang, M. A. Larotonda, B. M. Luther, M. Berrill, and D. Alessi, "Saturated 13.2 nm high repetition rate laser in nickellike cadmium," *Opt. Lett.* **30**(19), 2581–2583 (2005).
11. C. G. Krautschik, M. Ito, I. Nishiyama, and T. Mori, "Quantifying EUV imaging tolerances for the 70-, 50-, 35-nm modes through rigorous aerial image simulations," *Proc. SPIE* **4343**, 524–534 (2001).
12. D. W. Sweeney, "Status of EUVL enabling technologies," *Proc. SPIE* **5037** (2003), *invited talk*.

13. T. Sasaki, K. Kajiyama, H. Morishima, et al., "Performance estimation of EUV exposure optics for below 32-nm node in consideration of Mo/Si multilayer coating," *Proc. SPIE* **6517**, 65171P (2007).
14. K. A. Goldberg, "Extreme Ultraviolet Interferometry," doctoral dissertation, Physics Department, University of California, Berkeley, p. 271 (1997).
15. K. A. Goldberg, 2001, unpublished.
16. H. N. Chapman and D. W. Sweeney, "A rigorous method for compensation selection and alignment of microlithographic optical systems," *Proc. SPIE* **3331**, 102–113 (1998).
17. H. Nomura and T. Sato, "Techniques for measuring aberrations in lenses used in photolithography with printed patterns," *Appl. Opt.* **38**(13), 2800–2807 (1999).
18. L. M. Foucault, "Description des procedes employes pour reconnaitre la configuration des surfaces optiques," *C. R. Acad. Sci. (Paris)* **47**, 958ff (1858).
19. L. M. Foucault, "Memoire sur la construction des telescopes em verre argente," *Ann. Obs. Imp. Paris* **5**, 197ff (1859).
20. P. Hegeman, X. Christmann, M. Visser, and J. Braat, "Experimental study of a shearing interferometer concept for at-wavelength characterization of extreme-ultraviolet optics," *Appl. Opt.* **40**(25), 4526–4533 (2001).
21. I. Ghozeil, "Hartmann and other screen tests," in *Optical Shop Testing*, D. Malacara, Ed., Wiley, Hoboken, NJ, pp. 367–396 (1992).
22. H. Van der Laan, M. Dierichs, H. van Greevenbroek, et al., "Aerial image measurement methods for fast aberration set-up and illumination pupil verification," *Proc. SPIE* **4346**, 394–407 (2001).
23. F. Wang, X. Wang, M. Ma, et al., "Aberration measurement of projection optics in lithographic tools by use of an alternating phase-shifting mask," *Appl. Opt.* **45**, 281–287 (2006).
24. E. H. Anderson, D. Olynick, B. Harteneck, et al., "Nanofabrication and diffractive optics for high-resolution x-ray applications," *J. Vac. Sci. & Technol. B* **18**(6), 2970–2975 (2000).
25. K. A. Goldberg, P. Naulleau, P. Denham, et al., "EUV interferometric testing and alignment of the 0.3-NA MET optic," *Proc. SPIE* **5374**, 64–73 (2004).
26. J. Ojeda-Castañeda, "Foucault, wire, and phase modulation tests," in *Optical Shop Testing*, 2nd Ed., D. Malacara, Ed., Wiley, Hoboken, NJ, pp. 265–320 (1992).
27. R. N. Smartt and W. H. Steel, "Theory and application of point-diffraction interferometers (telescope testing)," *Jpn. J. Appl. Phys.* **14**(Suppl. 14-1), 351 (1975).
28. K. A. Goldberg, H. R. Beguiristain, J. Bokor, et al., "At-wavelength testing of optics for EUV," *Proc. SPIE* **2437**, 347–354 (1995).
29. H. Medeck, E. Tejn, K. A. Goldberg, and J. Bokor, "Phase-shifting point diffraction interferometer," *Opt. Lett.* **21**(19), 1526–1528 (1996).
30. P. P. Naulleau and K. A. Goldberg, "A dual-domain point diffraction interferometer," *App. Opt.* **38**(16), 3523–3533 (1999).

31. K. A. Goldberg, P. Naulleau, and J. Bokor, "Fourier-transform interferometer alignment methods," *Appl. Opt.* **41**(22), 4477–4483 (2002).
32. K. A. Goldberg, P. Naulleau, P. Denham, et al., "At-wavelength alignment and testing of the 0.3 NA MET optic," *J. Vac. Sci. and Technol. B* **22**(6), 2956–2961 (2004).
33. P. Naulleau, K. Goldberg, E. Gullikson, and J. Bokor, "At-wavelength, system-level flare characterization of EUV optical systems," *Appl. Opt.* **39**(17), 2941–2947 (2000).
34. K. Sugisaki, M. Okada, Y. Zhu, et al., "Comparisons between EUV at-wavelength metrological methods," *Proc. SPIE* **5921**, 59210D (2005).
35. P. P. Naulleau, K. A. Goldberg, and J. Bokor, "Extreme ultraviolet carrier-frequency shearing Interferometry of a lithographic four-mirror optical system," *J. Vac. Sci. & Technol. B* **18**(6), 2939–2943 (2000).
36. D. Malacara and A. Cornejo, "The Talbot effect in the Ronchi test," *Bol. Inst. Tonantzintli* **1**, 193–196 (1974).
37. Y. Zhu, K. Sugisaki, K. Murakami, et al., "Shearing interferometry for at wavelength wavefront measurement of extreme-ultraviolet lithography projection optics," *Jpn. J. Appl. Phys.* **42**(9A), 5844–5847 (2003).
38. P. Naulleau, K. A. Goldberg, E. H. Anderson, et al., "At-wavelength characterization of the extreme ultraviolet Engineering Test Stand Set-2 optic," *J. Vac. Sci. and Technol. B* **19**(6), 2396–2400 (2001).
39. J. Hartmann, "Bemerkungen über den Bau und die Justirung von Spektrographen," *Z. Instrumentenk.* **20**, 47 (1900).
40. P. Mercère, P. Zeitoun, M. Idir, et al., "Hartmann wave-front measurement at 13.4 nm with $\lambda_{\text{EUV}}/120$ accuracy," *Opt. Lett.* **28**(17), 1534–1536 (2003).
41. P. Mercère, M. Idir, T. Moreno, et al., "Automatic alignment of a Kirkpatrick–Baez active optic by use of a soft-x-ray Hartmann wavefront sensor," *Opt. Lett.* **31**(2), 199–201 (2006).
42. R. V. Shack and B. C. Platt, "Production and use of a lenticular Hartmann screen" (abstract only), *J. Opt. Soc. Am.* **61**, 656 (1971).
43. N. Harned, M. Goethals, R. Groeneveld, et al., "EUV lithography with the Alpha Demo Tools: status and challenges," *Proc. SPIE* **6517**, 651706 (2007).
44. P. Naulleau, K. A. Goldberg, S. H. Lee, et al., "Characterization of the accuracy of EUV phase-shifting point diffraction interferometry," *Proc. SPIE* **3331**, 114–123 (1998).
45. K. A. Goldberg, P. Naulleau, S. Lee, et al., "High-accuracy interferometry of EUV lithographic optical systems," *J. Vac. Sci. & Technol. B* **16**(6), 3435–3439 (1998).
46. K. A. Goldberg, P. Naulleau, S. Rekawa, et al., "Ultra-high-accuracy optical testing: creating diffraction-limited short-wavelength optical systems," *Proc. SPIE* **5900**, 114–123 (2005).
47. S. Kato, C. Ouchi, M. Hasegawa, et al., "Comparison of EUV interferometry methods in EUVA project," *Proc. SPIE* **5751**, 110–117 (2006).

48. G. E. Sommargren, D. W. Phillion, M. A. Johnson, et al., “100-picometer interferometry for EUVL,” *Proc. SPIE* **4688**, 316–328 (2002).
49. G. E. Sommargren, “Phase shifting diffraction interferometer,” U.S. Patent 5,548,403 (1996).
50. H. N. Chapman and D. W. Sweeney, “Rigorous method for compensation selection and alignment of microlithographic optical systems,” *Proc. SPIE* **3331**, 102–113 (1998).
51. M. A. Johnson, D. W. Phillion, G. E. Sommargren, et al., “Construction and testing of wavefront reference sources for interferometry of ultra-precise imaging systems,” *Proc. SPIE* **5869**, 5869OP (2005).
52. D. W. Phillion, G. E. Sommargren, M. A. Johnson, et al., “Calibration of symmetric and non-symmetric errors for interferometry of ultra-precise imaging systems,” *Proc. SPIE* **5869**, 5869OR (2005).
53. K. A. Goldberg, P. Naulleau, J. Bokor, and H. Chapman, “Testing EUV optics with visible-light and EUV interferometry,” *J. Vac. Sci. & Technol. B* **20**(6), 2834–2839 (2002).
54. R. A. Bartels, A. Paul, H. Green, et al., “Generation of spatially coherent light at extreme ultraviolet wavelengths,” *Science* **297**, 376–378 (2002).
55. P. Naulleau, J. Cain, and K. Goldberg, “Lithographic characterization of the spherical error in an EUV optic using a programmable pupil fill illuminator,” *Appl. Opt.* **45**(9), 1957–1963 (2005).
56. P. Naulleau, J. Cain, and K. Goldberg, “Lithographic characterization of the field dependent astigmatism and alignment stability of a 0.3 numerical aperture EUV microfield optic,” *J. Vac. Sci. & Technol. B* **23**(6), 2003–2006 (2005).
57. K. A. Goldberg, P. Naulleau, S. H. Lee, et al., “Direct comparison of EUV and visible-light interferometries,” *Proc. SPIE* **3676**, 635–642 (1999).
58. K. A. Goldberg, P. Naulleau, J. Bokor, and H. N. Chapman, “Honing the accuracy of extreme ultraviolet optical system testing: at-wavelength and visible-light measurements of the ETS Set-2 projection optic,” *Proc. SPIE* **4688**, 329–337 (2002).



Kenneth A. Goldberg (AB in Physics and Applied Math; MA and PhD in Physics, University of California, Berkeley) is a staff physicist at Lawrence Berkeley National Laboratory’s Center for X-Ray Optics. He specializes in the development of technologies for EUV wavelengths, including lithography, interferometry, mask inspection, and synchrotron radiation beamlines. He has published over 100 papers on science and technology for EUV wavelengths and has 12 patents.

Chapter 6A

Optics Contamination

Saša Bajt

Contents

6A.1 Introduction	227
6A.1.1 Survey of recent lifetime results	229
6A.2 Fundamentals of Optics Contamination	234
6A.2.1 Causes of projection optics contamination	234
6A.2.1.1 Carbonization, oxidation, and reduction	236
6A.2.1.2 Desirable properties of the capping layer	238
6A.2.2 Theoretical models of optics contamination	239
6A.3 Optics Contamination Control	241
6A.3.1 Measurements of optics lifetime	241
6A.3.1.1 Comparison of Si, Ru, and TiO ₂	245
6A.3.1.2 Pulsed versus continuous radiation	246
6A.3.2 Measurement of optics contamination (in-situ metrology)	246
6A.3.3 Environmental control strategy	247
6A.3.3.1 Gas blend mitigation	247
6A.3.4 Development of contamination-resistant capping layers	247
6A.3.5 Cleaning of optics contamination	249
6A.3.6 Novel approaches to contamination control	250
6A.4 Summary and Future Outlook	250
References	251

6A.1 Introduction

Extreme ultraviolet lithography (EUVL), using a 13.5-nm wavelength, is likely to be the most promising next-generation lithographic (NGL) technique. This technology, which is a natural extension of optical lithography, seems superficially very similar to that technique. However, shorter wavelengths, which enable printing of much smaller features, also create new technological challenges. Radiation at these short wavelengths is strongly absorbed by any matter. For this reason, reflective rather than transmissive optics must be used, and the entire EUVL system must be maintained in a vacuum environment. Reflective optics consist of precisely figured substrates coated with alternating layers of molybdenum (Mo) and

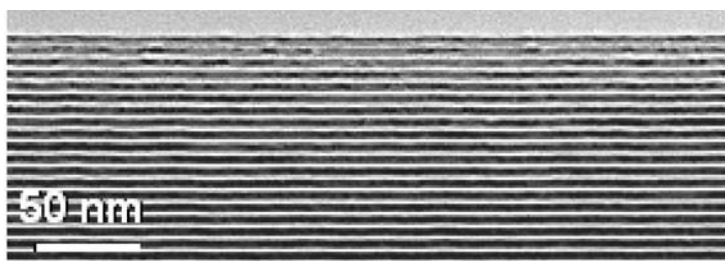


Figure 6A.1 Cross-section transmission electron microscopy (TEM) image of the top part of a typical EUV ML. The ML usually consists of 40 Mo/Si pairs. Silicon (low Z) is less absorbing and shown here as bright layers, while Mo (high Z) layers are dark.

silicon (Si) (Fig. 6A.1). Such multilayer (ML) coatings, invented by Spiller,¹ enable high reflectivity and wavelength selectivity of EUV mirrors. Residual water and other contaminants in the presence of EUV photons oxidize and degrade the optics surface. Both oxidation and carbon deposition on the optical surfaces reduce the reflectivity of the optics and can introduce wavefront aberrations. The overall effect not only decreases the throughput of the exposure tool but also the printing uniformity.²

Optics lifetime is one of the critical issues for the success of EUVL technology. Despite recent progress obtained by combining oxidation-resistant capping layers, and in-situ cleaning strategies that attempt to leverage chamber gas-surface interactions to impede oxidation and contamination,^{3–8} optics lifetimes still fall short of specifications for high-volume manufacturing (HVM) by nearly two orders of magnitude. This is not the first instance when the lifetime and stability of Mo/Si ML-coated optics has come under scrutiny. For example, astrophysicists have been using the reflective properties of Mo/Si MLs for imaging the solar corona⁹ for the last 20 years. The solar and heliospheric observatory (SOHO)¹⁰ was designed to study the dynamics and structure of the solar interior and to image the solar corona. This telescope was launched into space in 1995 and designed nominally to perform for two years, but because of spectacular results, its mission was extended to December 2009. Among other instruments, SOHO has on board an Extreme Ultraviolet Imaging Telescope (EIT)¹¹ that utilizes Mo/Si coatings. Another solar telescope, the Transition Region and Coronal Explorer (TRACE),¹² whose primary mission is to study magnetic fields and the associated plasma structures on the sun, was launched in 1998 and also uses normal-incidence mirrors with EUV coatings. Both SOHO's EIT and TRACE's instruments are still working after 13 and 10 years in space, respectively.

In astrophysics applications, the main concern is the reduction of instrumental throughput at the designed wavelength due to reduction in reflectivity or wavelength shift. Even though the space optics operate in a somewhat different environment than EUVL optics, there is substantial overlap. For instance, studies on temporal stability at room temperature¹³ indicated that the reflectance of Mo/Si MLs was unchanged after 20 months in air. These MLs were terminated with a

Mo layer and capped with a thin carbon layer. Although results were encouraging, the authors remained concerned about degradation at elevated temperatures and the effect of oxygen atom bombardment, a likely environmental hazard for optics used in satellite instruments in the lower Earth orbit. In general, most of the early studies were limited to temporal and thermal stability of these MLs. Since the temperature in EUVL exposure tools needs to be extremely stable, the thermal effects on projection optics coatings are negligible. This chapter focuses only on lifetime stability due to optics contamination.

6A.1.1 Survey of recent lifetime results

Although optics contamination, especially carbon deposition, is a well-known effect¹⁴ that occurs when optics are exposed to x-ray radiation, until recently little information existed on the radiation hardness of the MLs. An early study reported results of Mo/Si MLs exposed to monochromatic undulator radiation and concluded that the MLs do not show any degradation.¹⁵ The corresponding absorbed dose in the exposed mirrors was equivalent to a 1.2-year EUV exposure in the low-throughput lithography system considered at that time. The predicted optics lifetime was based on a nine-hour exposure with an average intensity of 0.75 W/cm^2 and better than a 5×10^{-8} mbar vacuum. However, these results overestimated the optics lifetime because they were performed in high vacuum, not in realistic EUV exposure tool environments with remnants of water vapor and other contaminants. Other lifetime studies performed on Si-capped MLs exposed the optics to EUV radiation doses equivalent to several months of lithographic conditions (assuming a higher than 10 wafers/hr throughput).¹⁶ It was observed that the surface carbon deposition was dependent on the residual gas concentration in the vacuum chamber. However, no structural damage was observed within the bulk of the MLs. In addition, it was demonstrated that the reflectivity was fully recovered with ozone cleaning, although the ozone overexposure can lead to surface-layer oxidation.

The EUV Engineering Test Stand (ETS) developed by the Virtual National Laboratory (VNL), a consortium of three national laboratories—Lawrence Livermore National Laboratory (LLNL), Lawrence Berkeley National Laboratory (LBNL), and Sandia National Laboratories (SNL)—was the first full-field scanning lithographic EUVL exposure tool (see Fig. 6A.2) with diffraction-limited performance. The ETS, which was designed to be an “unbaked” vacuum system, provided a good platform to study how to prevent, mitigate, and rectify EUV-induced contamination by residual gases.¹⁷ The main environmental concern observed in this system was related to carbon and oxygen deposition caused by EUV “cracking” of residual hydrocarbon and water molecules. Recognizing that these two processes tend to nullify each other, Klebanoff et al. proposed an ethanol “gas blend” to balance carbon deposition and oxidation.¹⁸ Optics oxidation due to the presence of residual water was recognized as a major problem, and it became clear that a Si capping layer was not a viable solution. It is believed that the incident electron radiation



Figure 6A.2 Projection optics box from the ETS. All four mirrors are coated with normal-incidence ML coatings.

effectively mimics EUV radiation, and a series of tests using 2 keV electrons was performed on Si-capped MLs.⁵ The 2 keV electrons penetrate much deeper into the ML compared to ~ 100 eV photons. However, the energy distribution of created secondary electrons that cause most of the surface damage is similar for both incident beams on the Si. It was demonstrated that the ETS vacuum environment, which was rich with water vapor, did not pose any risk to the optic in the absence of EUV illumination.¹⁸ There was concern about the observed carbon growth on the optics, but different methods were successfully demonstrated to remove carbon: molecular oxygen (Ref. 5), rf-O₂, rf-H₂ (Ref. 6), and atomic hydrogen (Ref. 19). Oxidation of the top optics surface appeared to be a tougher problem. One proposed solution was to keep the optics in the ethanol gas blend environment such that an equilibrium between oxidation and carbonization¹⁸ would be reached. Another novel idea was to design a capping layer that would act as an effective oxidation barrier.²⁰

To determine the current status and measure progress toward the ultimate solution, the EUVL industry often uses roadmaps. The roadmap in Table 6A.1 was created by the VNL in early 2001.

The calculations assumed peak reflectance of the projection (imaging) optics of 70% with no more than a 1.6% (relative) reflectance loss over 5 years. Table 6A.2 shows SEMATECH's 2005 roadmap related to optics lifetime, which was developed with major input from lithography tool manufacturers. Condenser optics have short lifetimes, but the optics specifications are less stringent than for projection

Table 6A.1 VNL's optics lifetime roadmap.

	Status 2001	Beta tool	Commercial tool
Peak reflectance—optics	65%	68%	70%
Lifetime (imaging optics)	Unknown	1.6%/5 years	1.6%/5 years
Lifetime (first condenser optic)	Unknown	10%/year	10%/year
Lifetime (other condenser optics)	Unknown	2.5%/year	2.5%/year

Table 6A.2 SEMATECH optics lifetime roadmap.

	Alpha Spec	Beta Spec	Gamma Spec
Optics lifetime (nonconsumable)	1 year	3 years	5 years
“Light on hours” (nonconsumable)	1000 to 3000 hrs.	None given	20,000 to 30,000 hrs.
Pulse lifetime (nonconsumable)	5.00E+09	2.9E+10	5.0E+11–7.0E+11
Optics lifetime (consumable)	3 months	3 months	3 months
Pulse lifetime (consumable)	1.3E+09	2.4E+09	3.0E+10

optics. Therefore, these optical components are considered consumable and are exchanged on a regular basis. Projection optics have extremely tight specifications, and they are difficult and time-consuming to make and to align. There is a large effort to make these optics last as long as possible, and if necessary, to remove the contamination in-situ. However, the optics lifetimes still fall short of the 20,000 to 30,000 hours specifications for HVM tools. Without a fundamental understanding of the damage processes, it is impossible to design meaningful accelerated tests and to perform different lifetime test protocols.

Oxidation can be somewhat minimized with protective capping layers. Extended lifetimes have been reported for ruthenium (Ru)-capped^{21,22} and carbon-capped ML mirrors.^{23,24} Ruthenium satisfies many required properties of a good capping layer, which will be discussed in detail later in this chapter. Its optical constants make it a good reflective layer for EUV light, it is a semi-precious metal, and it is expected that the Ru surface will be covered with only a small fraction of a monolayer of water in the EUVL tool environment at room temperature. Oxidation of Ru is complex, but in general, RuO₂ would form only at high temperatures and oxygen pressures. Ruthenium can be deposited with the standard dc-magnetron sputtering technique, and it forms a continuous and relatively smooth layer at a thickness of only a few nm.

The Ru capping layer has been accepted by the international community as a benchmark⁷ for the development and performance of other capping layers. Bajt et al.²² compared performance of Si- and Ru-capped MLs exposed to electron

and synchrotron EUV beams under one set of environmental conditions that involved increased water vapor pressure. The corresponding lifetime calculations, which were based on electron and EUV beam extrapolations, gave lifetimes between a few months for mirrors with high power densities, and 18 years for mirrors with low power densities, assuming that the mirrors were capped with Ru. The calculations were made for a six-mirror, 0.25-NA ring-field optic design^{25–27} and assumed a throughput of eighty 300-mm wafers per hour with a 20% overhead. Initial results²⁸ from titanium oxide (TiO₂)-capped MLs showed up to a 10 times longer lifetime than the Ru-capped MLs. TiO₂ has many promising physical properties, including a hydrophilic and self-cleaning surface, and thus might decompose water and degrade organic macromolecules in the presence of UV light. There is hope that the two major degradation mechanisms of projection optics, namely carbonization and oxidation, can be mitigated using TiO₂ capping layers.

Meiling et al.²⁹ reported that a lifetime of over 1000 hours can be reached under alpha demo tool source power and vacuum conditions based on extrapolations from synchrotron exposure results. This work predicts a noticeable difference in contamination rates for pulsed (typical repetition rate between 5 and 10 kHz) and synchrotron (500 MHz) sources,³⁰ as shown in Fig. 6A.3, although no quantitative data are given. The prediction favors a pulsed versus a semicontinuous source. The authors argue that the high repetition rate of the synchrotron source interrupts the desorption process before it is completed, and therefore the conclusions based on experiments performed with the synchrotron source (or electron beam) might underestimate the optics lifetime. Meiling et al.²⁹ expect carbon growth to be the dominant degradation mechanism at the typical partial pressure for the alpha tool (10^{-9} mbar C_xH_y and 10^{-7} mbar H₂O). In-situ cleaning and carbon mitigation techniques are being developed, and periodic cleaning of the system is expected. Ideally, the cleaning can be repeated many times with no damage to the bulk of the ML (Fig. 6A.4). The system is out of specifications when an irreversible reflectivity loss of greater than 1% per mirror occurs. This is expected to happen due to

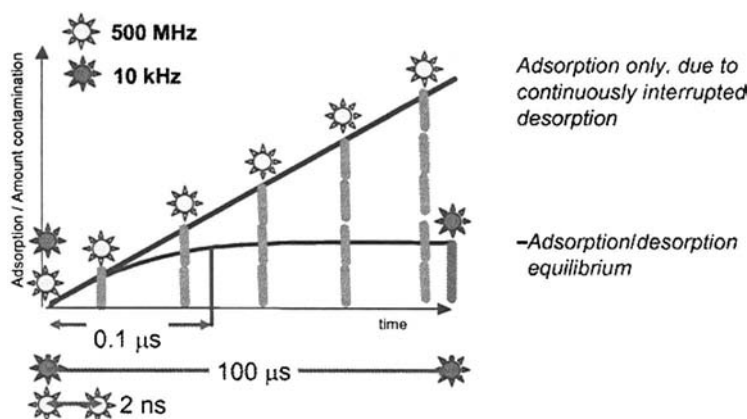


Figure 6A.3 Cumulative adsorbed contaminants for a semicontinuous synchrotron (500 MHz) and pulsed (10 kHz) EUV source. (Reprinted from Ref. 30.)

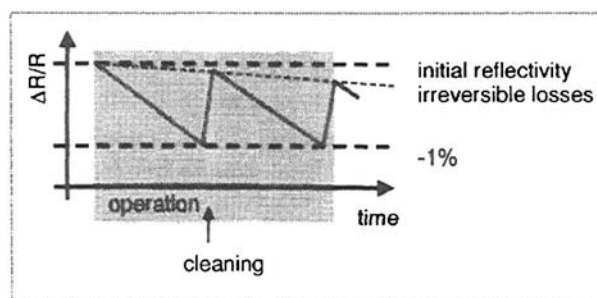


Figure 6A.4 Reflectivity loss as a function of time and planned periodic cleaning based either on in-situ cleaning or a mitigation technique that can partially restore the reflectivity of a carbon-contaminated mirror. After each cleaning cycle, a small accumulative irreversible loss is expected that eventually brings the mirror out of specification, defined as $\Delta R/R = 1\%$. (Reprinted from Ref. 87.)

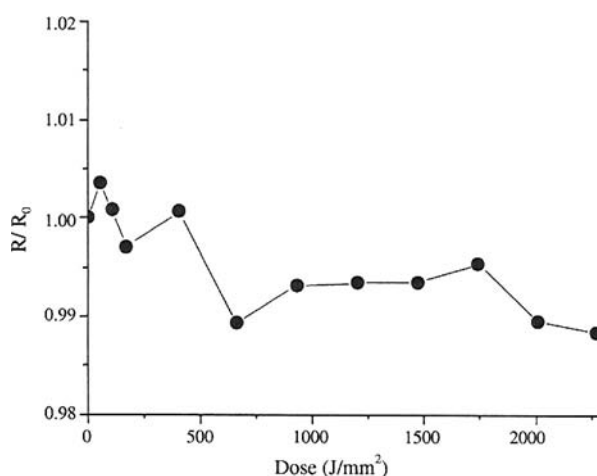


Figure 6A.5 Reflectivity change as a function of accumulated EUV dose on a Ru-capped ML. (Reprinted from Ref. 31 with permission from Elsevier.)

accumulative damage from periodic cleaning, most likely related to oxidation of the optics surface and/or an increase in surface roughness.

In a study by Gomei et al.,³¹ accelerated lifetime tests were performed on Ru-capped MLs utilizing an extremely high synchrotron irradiation dose of 2250 J/mm² (Fig. 6A.5). Such a dose corresponds to about 3500 hours of operation for the highest power density optics in a commercial EUVL tool.²² Because of the difference in the duty cycle between pulsed and synchrotron (quasi-continuous) sources, the incident average power of the synchrotron needs to be 17 to 170 times those of EUVL sources. The exposed spots showed nonuniformity in reflectivity distributions. The reflectivity in the center of the exposed spot was >99% of the original reflectivity and was surrounded by an area with ~96% of the original reflectivity (Fig. 6A.6). However, the beam intensity profile was also nonuniform, with the outer area having a factor of about 50 lower intensity

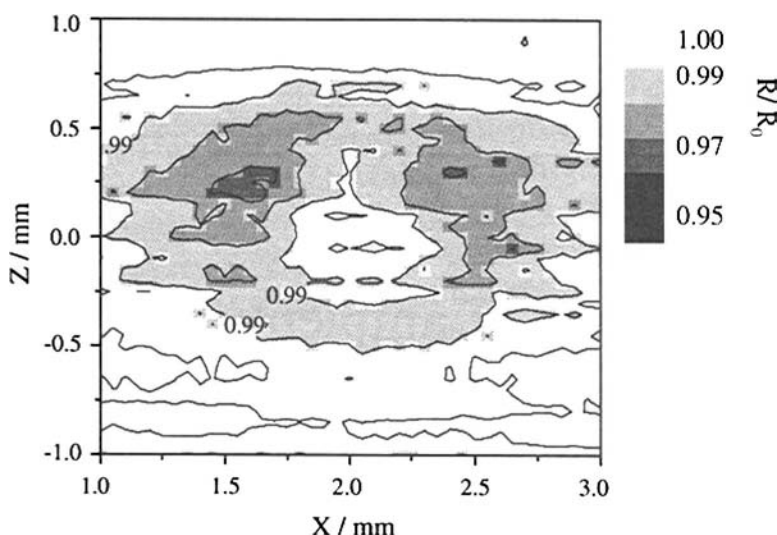


Figure 6A.6 Nonuniform reflectivity drop on EUV exposed optics after a 2250 J/mm^2 accumulated dose. (Reprinted from Ref. 31 with permission from Elsevier.)

than the center part. Contradictory to the notion that mirrors with higher intensity (larger accumulated dose) should experience greater reflectivity loss, these experiments showed a lower reflectivity loss in the center of the exposed spot where the intensity and the dose were the highest. When the authors measured the surface composition in the irradiated area using Auger depth profiling, they noticed that the rims of the exposed spots had a thicker carbon layer than the central part. They speculated that the exposures at a higher water vapor pressure inadvertently introduced small amounts of hydrocarbons in the system, and that under these conditions, carbon deposition (adsorption) and removal (desorption) on Ru surfaces were competing processes.³¹ Similar effects were observed by other research groups.³²

6A.2 Fundamentals of Optics Contamination

6A.2.1 Causes of projection optics contamination

In the absence of an ultra-high-vacuum environment, the projection optics are exposed to water, hydrocarbons, and other contaminants in the presence of EUV photons. Carbon contamination on mirror surfaces irradiated with short-wavelength radiation is a well-known problem in the synchrotron community, and much of the learning in this context has been leveraged by the EUVL community. The carbon contamination process was first described by Boller et al.¹⁴ The interaction between EUV photons and ML material creates secondary electrons in the top layers of the ML. The secondary electrons that reach the surface of the ML and have sufficient energy to break the bonds in water molecules will create free radicals.

These radicals can bond to the surface-layer atoms and form oxides on the surface, or diffuse into or through the top layer and cause oxidation. A small increase in oxide-layer thickness (<1.5 nm) leads to an unacceptable ($>1\%$) reflectance loss on EUV ML mirrors, whether the uppermost layer is Si-terminated or capped with an “oxidation resistant” layer. Until quite recently, this oxide has been largely viewed as immovable. However, recent progress with nondamaging reduction of oxide layers using atomic hydrogen has called this assumption into question.³³ It is important to point out that this method can reduce Ru oxide to Ru metal but cannot reduce SiO_2 back to Si.

Since the exposure of the optics to the EUV light does not seem to cause any measurable damage by itself (with no contaminants present), the straightforward solution would be to eliminate any contaminants in the EUVL chamber. There are numerous reasons why EUVL tools cannot operate in an ultra-high-vacuum environment. The tools cannot be “baked” because of stringent temperature requirements of certain components, and HVM requirements prohibit long pumping after maintenance. Hence, some residual water vapor, hydrocarbons, and possibly some other contaminants will always be present. These residuals, in the presence of EUV photons, can adsorb, dissociate, and react with the optics surface. Ideally, one would like to find a stable process window that would strike an appropriate balance between carbon deposition and oxidation by finding the right combination of protective capping layer and chamber background gases (Fig. 6A.7). But this is not an easy task, as demonstrated by past failed phenomenological approaches to extend the EUV optics lifetime. Although many challenges remain to be solved, it is encouraging to see more papers in which fundamental processes that govern the degradation of EUV optics are studied.^{34–37}

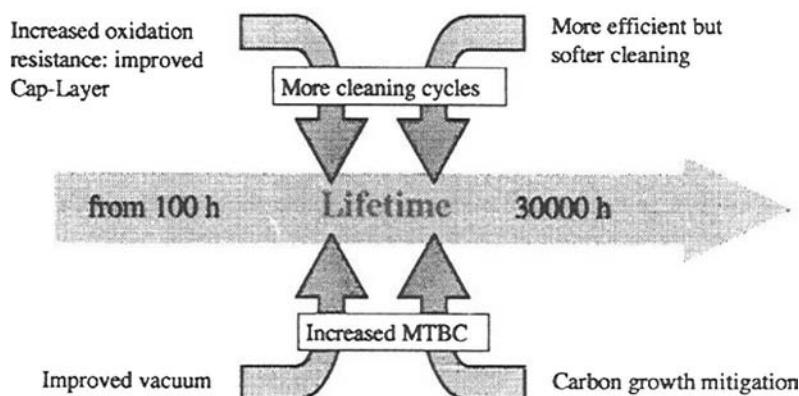


Figure 6A.7 A combination of different mitigation solutions will most likely be necessary to increase optics lifetime. (Reprinted from Ref. 88.)

6A.2.1.1 Carbonization, oxidation, and reduction

Boller et al.¹⁴ determined the thickness of the contaminant (carbon) as a function of exposure time, residual gas pressure, and substrate temperature. The growth process as a function of pressure, temperature, and electron current density was described by a rate equation. The observed results can be understood by a simple model if one assumes that the hydrocarbons are first physisorbed to the surface and then dissociated by secondary electrons that are generated in the substrate by EUV radiation. Their model also predicted that carbon growth rate is almost independent of the pressure above 10^{-7} mbar. We note in passing that carbon contamination can sometimes be useful. For example, carbon contamination enabled electron beam patterning of 8-nm metal structures.³⁸

Other experimental studies observed that carbon growth depends on the type of hydrocarbon molecule and its partial pressure.³⁹ For example, it was found that for light hydrocarbons, the first monolayers of carbon grow much faster than the subsequent ones. However, this nonlinear behavior was not observed for the heavy hydrocarbons. A recent paper disagrees with the conclusion¹⁴ that secondary electrons play a major role in hydrocarbon dissociation.³⁵ In fact, the results from this model suggest that the bond breaking in hydrocarbons is caused primarily by direct EUV photons, not the secondary electrons.³⁵ This model includes physical and chemical processes such as vapor-phase adsorption, surface desorption, surface diffusion, and molecular dissociation by direct photoabsorption, although constant kinetic parameters (energies, pre-exponentials, cross sections, etc.) are assumed (see Fig. 6A.8). However, these quantities are generally coverage-dependent and also vary as a concentration of co-adsorbed species and surface contaminants. Since some of these parameters are not available or not well known, this issue needs further examination. The model predicts that the light (<100 amu) hydrocarbons pose

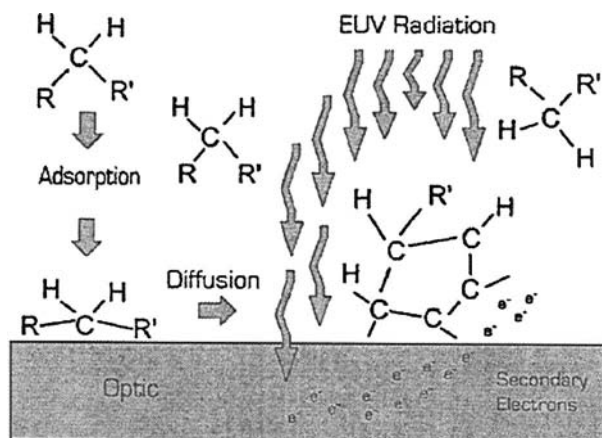


Figure 6A.8 Simple model showing main radiation-induced processes related to carbon contamination. (Reprinted from Ref. 35 with permission from AVS—The Science and Technology Society.)

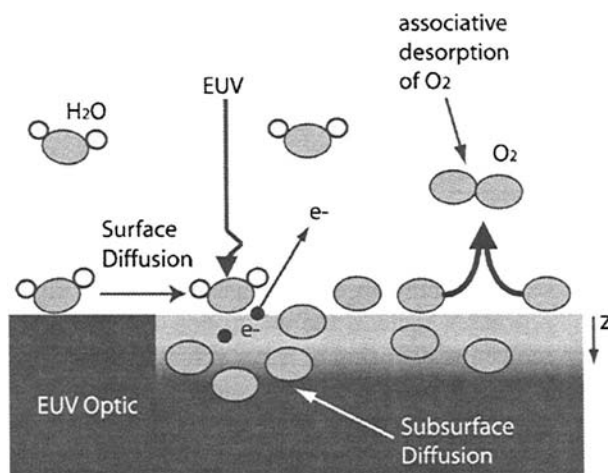


Figure 6A.9 Simple model showing radiation-induced processes leading to oxidation of the optics surface. (Reprinted from Ref. 36 with permission from the AVS—The Science and Technology Society.)

a much smaller risk to EUV optics than heavier hydrocarbons, in agreement with their experimental data, and that a slight temperature increase of the optics ($\sim 30^\circ\text{C}$) substantially reduces optics contamination, as modeled by increased hydrocarbon desorption from the surface. Another interesting outcome of this model is that the surface diffusion of heavier hydrocarbons had a negligible effect. Recent experimental data demonstrate rapid growth of graphitic carbon in the presence of higher alkanes or toluene while linear alkanes up to n-heptane are relatively benign.⁴⁰ Molecules with a higher carbon number generally have longer surface residence lifetimes and higher adsorption enthalpy, and they more easily adhere to the surface. The data also confirm that carbon film growth occurs by electron impact decomposition of molecules adsorbed on graphitic surfaces.

The oxidation of the optics (see Fig. 6A.9) is considered more serious than carbon deposition, because once oxides are formed, they are difficult to remove. Also, oxides strongly absorb EUV light; for example, a thin (1.5 nm) oxide layer on Ru will cause an absolute reflectance decrease of 1.6%—more than the entire budget for 30,000 hours of EUV exposure. However, recent work by Nishiyama et al. demonstrated the successful reduction of Ru oxide by exposure to atomic H, raising hopes for a practical mitigation method.³³ Mirror lifetime also can be extended by suppressing oxidation using gas blends. Different strategies include mixing C-containing gases⁴ such as ethanol and methanol with H_2O vapor.⁴¹ When discussing mitigation strategies and mirror lifetime, it is important to realize that the surface chemistry is material specific and that oxidation can also be suppressed by choosing an appropriate oxidation resistant capping layer material that acts as a protective barrier between the ML stack and the environment.

6A.2.1.2 Desirable properties of the capping layer

Figure 6A.10 shows the cross-sectional surface region of a Ru-capped ML as imaged with TEM. An ideal capping layer must satisfy many requirements.⁴² First, the optical properties of the capping layer material must be considered. A suitable capping layer should increase or have no effect on the reflectivity (at $\lambda = 13.5$ nm) of the entire ML coating. Such materials can be selected using appropriate software and optical constants data,^{43,44} but in practice, this is not a trivial matter. This is because there is a lack of reliable optical constants in the EUV region, especially for compounds and alloys. In most cases the available optical constants for compounds and alloys are derived from calculated atomic scattering factors of single elements. There are noticeable discrepancies among data reported by different researchers on the same material because of a number of difficulties inherent to the EUV spectral region. Strong absorption, especially above the absorption edges, prevents reliable transmission measurements unless very thin, unsupported films can be fabricated and a radiation source with high photon flux and spectral purity is available. Most of the experimental data collected in the past also suffer from errors or uncertainties due to poor sample preparation, such as contamination and surface roughness and poor source quality. Because sample preparation usually requires significant materials development, the available data are merely a collection of materials that were of interest for past projects.

An additional requirement for the capping layer is that the layer be continuous and smooth (~ 0.2 nm high spatial frequency roughness) even though the layer is only 2 to 3 nanometers thick. To avoid intermixing in the underlying ML stack, this capping layer must also be deposited at low temperatures ($< 200^\circ\text{C}$). The nanostructure of the capping layer, which plays a crucial role in surface chemistry, needs to be well known and controllable. Ideally, the surface of the capping layer material is designed such that carbon and oxygen atoms recombine on optics

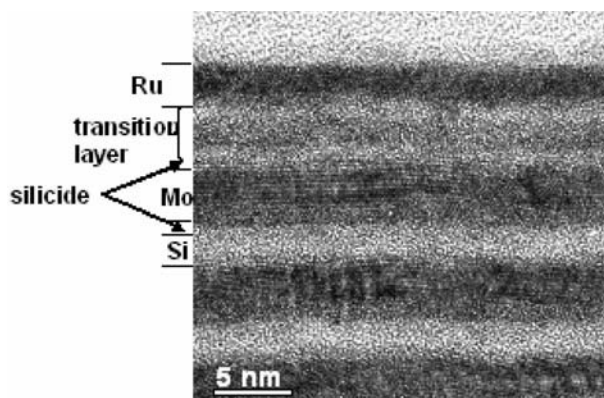


Figure 6A.10 Cross-section TEM image of an EUV ML showing the microstructure of the surface layers. The very top, dark layer is Ru, a polycrystalline layer, deposited on the top of the transition layer. Polycrystalline Mo and amorphous Si layers are separated by thin, amorphous silicide layers.

surfaces to form carbon dioxide (CO_2), which could then be desorbed thermally or by electron- or photon-stimulated desorption processes associated with the incident EUV flux. A “protective” capping layer should be impermeable to carbon or oxygen diffusion, either into the ML or out, from the ML to the surface. If the capping layer is polycrystalline, this might require a specific crystallographic texture. Likewise, if the capping layer is amorphous, it should be defect-free, where the defects are represented by mobile vacancies. Capping layer materials should also be chemically inert with respect to the stack materials underneath; they must be thermally stable, and they also must generate minimal stresses in the film stack during deposition. Finally, EUV optics capping layers should be cost-effective and in accordance with environmental, health, and safety regulations during their manufacture and use.

Once potential candidates have been selected based on the aforementioned criteria, other properties related to their surface chemistry should be considered such as their stability in the air, their reactivity with background vacuum gases (H_2 , H_2O , CO , CO_2 , hydrocarbons), and their stability against EUV radiation-induced processes. Different materials will also respond in different ways to mitigation and removal methods. Unfortunately, most of the existing surface science data are derived from well-characterized single-crystal sample surfaces. In practice, the capping layers are amorphous or polycrystalline, likely with high concentrations of defects and vacancies, so ideal properties based on single-crystal surfaces might be quite different from the properties of realistic capping layer surfaces.

6A.2.2 Theoretical models of optics contamination

One of the most comprehensive articles about surface phenomena that led to mirror degradation, with special emphasis on Ru surfaces, is a review article by Madey et al.³⁴ Ruthenium is of particular interest because it has emerged as the most suitable material for a capping layer, though other alternatives are being explored. In this article the authors survey the aspects of the thermal and radiation-induced surface chemistry of Ru. It is known that Ru surfaces are very effective as heterogeneous catalysts.^{45,46} Surface chemistry of small molecules, such as H_2O , O_2 , CO_2 , H_2 and N_xO_y , on Ru surfaces has been studied extensively.^{47–53} However, the bulk of the data were collected under ideal conditions (clean, single-crystal surfaces). Most of the studies were done on Ru (0001) surfaces, although limited data exist for a Ru ($10\bar{1}0$) surface. TEM studies revealed that a 2-nm-thick Ru capping layer is polycrystalline with a variety of crystallographic orientations and that there is a correlation between crystallography and lifetime performance.⁵⁴ The best-performing Ru capping layers had larger grains and (0001) orientation (see Fig. 6A.11). This close-packed plane is expected to be less reactive with background gases than other planes, such as Ru($10\bar{1}0$) and ($10\bar{1}1$).

The model describing the bonding of water to Ru and other metal surfaces is a subject of ongoing debate and controversy.^{55–65} Extensive review articles by Thiel and Madey⁴⁸ and Henderson⁴⁹ describe interactions of H_2O with all transition metal surfaces, including Ru. Ruthenium appears to be a typical “borderline”

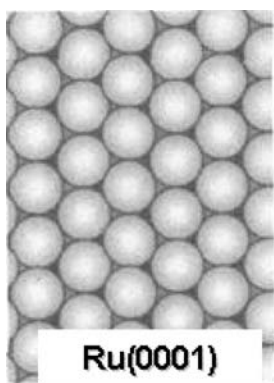


Figure 6A.11 Ru(0001) has a closed packed structure that is atomically smooth.

metal for which water absorbs and desorbs mainly in molecular form, although partial dissociation (e.g., $\text{H} + \text{OH}$) occurs at fractional monolayer coverages. These processes depend on the surface temperature and crystallographic orientation of the metallic surface. Partial coverage of the metal surface by impurities, such as oxygen or carbon, affects the binding energy of water. While carbon usually weakens the adsorption of the water, the presence of oxygen on the metal surface seems to increase the binding energy of water.⁴⁸ However, when the oxygen coverage reaches one monolayer on Ru, the water binding energy decreases below the clean-surface value.^{66,67}

Since EUVL optics do not operate in an ultra-high vacuum, their surface is always covered with some impurities. These impurities weaken water adsorption and block dissociation. Madey et al.³⁴ estimated the binding energies and average lifetimes that a water molecule resides on different Ru surfaces at room temperature. These estimates, for clean Ru(10 $\bar{1}$ 0), clean Ru(0001), carbon-covered Ru(10 $\bar{1}$ 0), and air-exposed Ru(10 $\bar{1}$ 0), are currently being used to understand lifetime testing results and to optimize capping layer performance.⁶⁸

It is believed that the Ru capping layers degrade due to a combination of oxidation caused by the interaction of water vapor and EUV radiation, and carbon deposition associated with hydrocarbon dissociation. These processes can be caused by thermal and nonthermal excitations. To date, no work has been done on thermally induced oxidation of Ru surfaces in a water vapor environment. In the following discussion we will focus on surface chemistry affected by nonthermal excitations. Optics exposed to EUV light absorb photons, which cause valence and core photoexcitations of electrons in surface and subsurface atoms.^{69–72} The effects of EUV radiation-induced processes can be separated as indirect and direct excitations. Literature on surface photochemistry reports that for most cases, the indirect processes involving secondary electrons dominate over direct photoexcitations.⁷³ The low-energy secondary electrons (<10 eV) have very high cross sections for molecular dissociation and therefore play an important role in radiation-induced processes at surfaces. A substantial fraction of these electrons reach the surface and

escape as secondary electrons. These secondary electrons induce electronic excitations in surface molecules (or in adsorbed molecules), which in turn cause their dissociation and reaction. In contrast, direct processes involving photoexcitation of substrate core electronic levels by EUV photons can cause photon-stimulated desorption of oxygen from oxides, which can affect the stoichiometry, lifetime, and surface chemistry of such materials.³⁴ It is assumed that for EUVL projection optics, the background water vapor is in equilibrium with the mirror surface and the coverage is very low (<0.01 monolayer) under typical conditions.³⁴ The EUV photons excite the adsorbed water by direct and indirect processes and cause dissociation; the resultant atomic oxygen may react with the mirror surfaces. However, because the coverage is low, the reflectivity degradation occurs slowly. Similar excitations will lead to radiation-induced dissociation of other residual gas molecules. A simple model describing the effects of electron beams on gas adsorption was presented by Danielson et al.⁷⁴ Recently, kinetic models have been proposed of EUV mirror degradation that include key processes contributing to oxide growth^{36,37,68} and carbon deposition.³⁵ In summary, the main radiation damage mechanism for oxygen-covered surfaces and oxides is the formation of oxygen vacancies (i.e., creation of surface defects). Background gas molecules (water, hydrocarbons, etc.) are generally more chemically reactive with defects than with stoichiometric surfaces, so the surface chemistry is altered and accelerated on realistic capping layer surfaces. These factors must be considered when choosing a capping layer for a specific EUV environment (gas composition, partial pressures, radiation load).

6A.3 Optics Contamination Control

6A.3.1 Measurements of optics lifetime

The majority of optics lifetime tests were performed with electron (see Fig. 6A.12) and synchrotron EUV beams (see Fig. 6A.13) in specially built test chambers. The contamination test chambers, which could accommodate high gas pressures (up to 10^{-2} mbar), are typically separated from the electron gun or the beamline through differential pumping. The use of electron-beam irradiation was justified with the evidence that irradiation with electrons (a few kV) and EUV (95.3 eV) photons resulted in similar oxidation rates on Si-capped MLs. In addition, easier access and availability made electron gun setups more attractive than exposures on synchrotron beamlines. However, results on Ru-capped MLs²⁰ showed differences due to the different surface chemistry and damage mechanisms. Electron-beam testing was gradually replaced with EUV photon exposures, initially using synchrotron beams, and more recently pulsed EUV sources. After initial work^{5,75} at LBNL's Advanced Light Source (ALS), the testing of optics lifetimes proceeded on dedicated synchrotron beamlines. These included the BL-3 beamline in the NewSUBARU synchrotron facility in Japan,⁷⁶ the U180 beamline at the PTB Radiometry Laboratory, BESSY II, in Germany,⁷⁷ and the SURF III beamline at the National Institute of Standards and Technology (NIST) in the U.S.⁷⁸

The relationship between electron- and photon-caused oxidation on Si-capped MLs was examined by Malinowski et al.⁷⁵ followed by scaling studies covering a larger parametric space of Si- and Ru-capped MLs.⁷⁹ Similar studies done elsewhere^{7,37,77,80–83} included proprietary environment and capping layer solutions. To enable the measurement of progress in optics contamination,

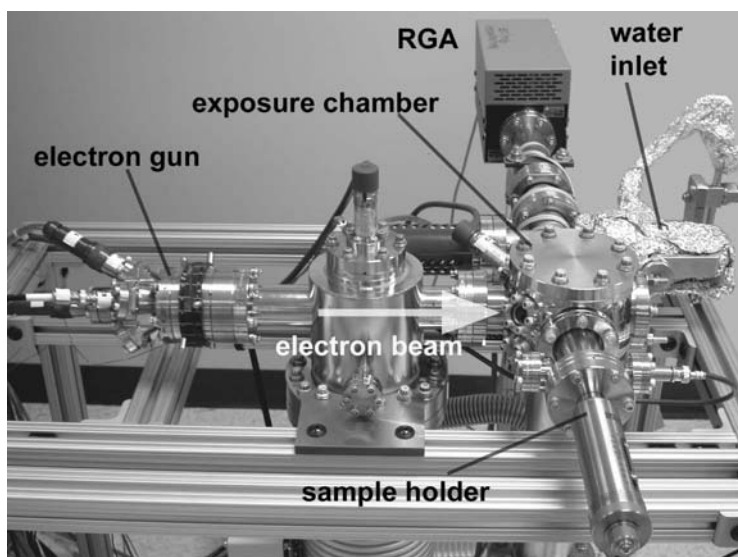


Figure 6A.12 Initial lifetime experiments were performed with electron beams. This photograph shows a setup at SNL.

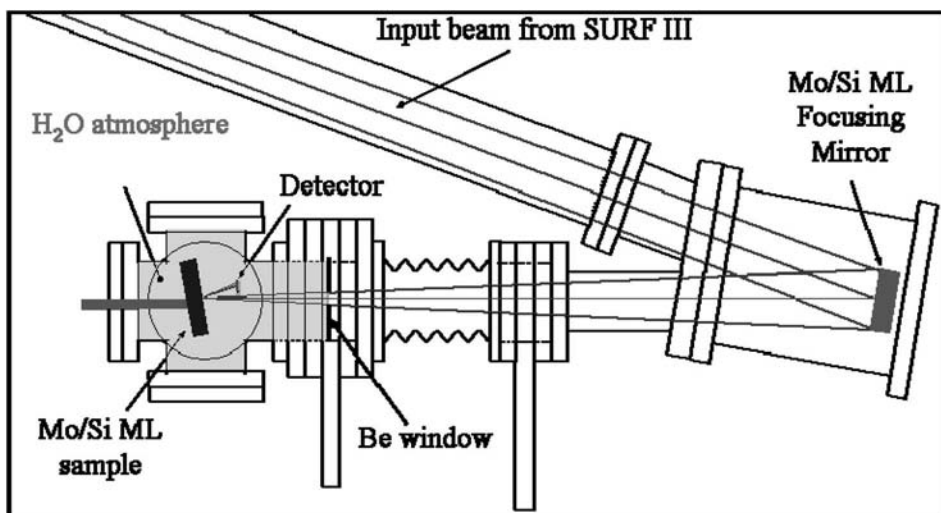


Figure 6A.13 Typical setup for lifetime studies attached to a synchrotron beamline. This schematic view shows the setup of SURF (at NIST). (Reprinted from Ref. 78 with permission from the American Institute of Physics.)

SEMATECH proposed the use of Ru-capped MLs^{20,21} as the standard benchmark capping layer for optics lifetime tests.

At-wavelength reflectivity is the most sensitive, nondestructive way to measure changes on mirror surfaces. Reflectivity changes as small as 0.2% can be detected with state-of-the-art reflectometers.^{76,84,85} The in-situ reflectivity monitors that are needed to monitor real-time changes usually lack the sensitivity to detect small changes in reflectivity; but even more important, they are not reliable for absolute measurements over long exposures due to the aforementioned nonuniform spatial distribution of damage. Therefore, post-exposure reflectivity measurements on dedicated reflectometry beamlines are performed after the exposure. The same is true for electron-beam exposures. During the electron-beam exposures, secondary emission from the sample is usually tracked, and the reflectivity change is measured after the exposure is completed. Accelerated exposures require high-intensity focused beams. The exposed areas are usually only a few hundred microns across, which complicates post-exposure analysis.

It is crucial that the reflectivity and wavelength of unexposed mirrors are uniform so the changes can be clearly correlated with exposure conditions. Unlike condenser optics, where the ML experiences thermally induced diffusion, ion implantation, and erosion, the interior of the projection optics ML is not affected by thermal effects. Physical and chemical processes that lead to a decrease in reflectivity are all happening on the optical surface or very close to it. Hence, the ML wavelength, due to the interference of many layers, does not change in EUV-exposed areas on projection optics. Reflectivity maps at a constant wavelength (13.5 nm) as a function of position can be obtained. Such reflectivity maps are nonuniform (see Fig. 6A.14). This nonuniformity correlates with the incident beam intensity

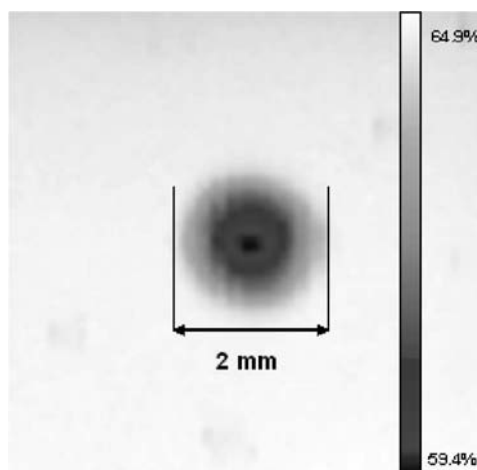


Figure 6A.14 Reflectance map at a constant wavelength shows nonuniform distribution. The highest reflectivity drop is observed in the center of the beam. This is a Si-capped ML that was exposed with 1.5 keV electrons using a $5 \mu\text{A}/\text{mm}^2$ beam current in the presence of 2×10^{-6} Torr water. Exposures were performed at SNL and the reflectivity was measured at LBNL's ALS.

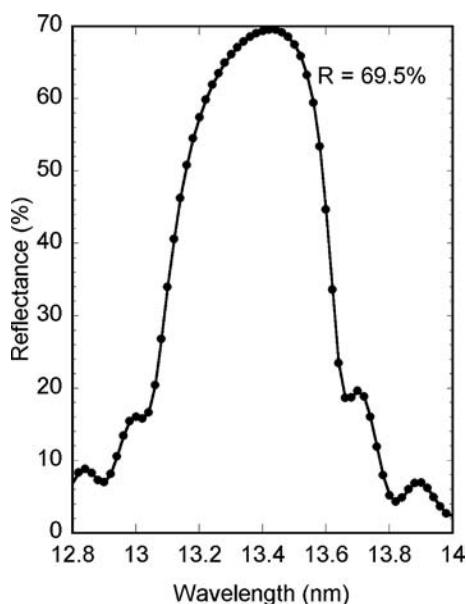


Figure 6A.15 Reflectivity data as a function of wavelength from a Ru-capped ML with diffusion barriers.

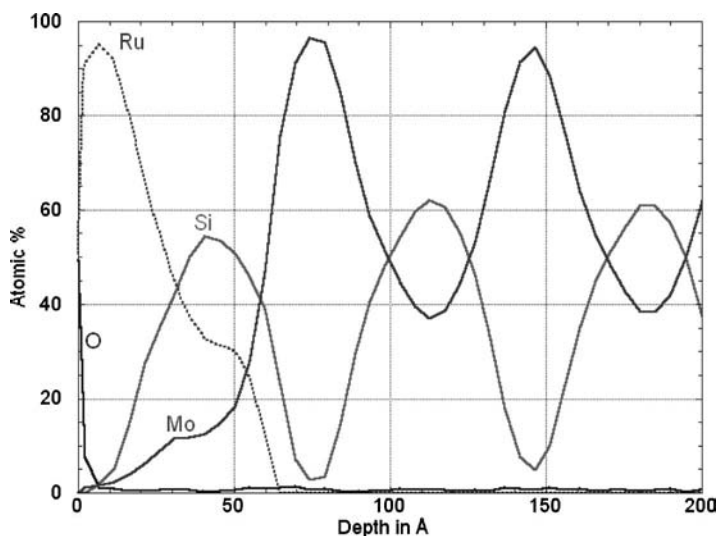


Figure 6A.16 Depth Auger profile of a Ru-capped ML.

distribution (more intense in the center and weaker on the edges) and/or the presence of surface defects, grain boundaries, and changes in crystallographic orientation (for examples, see Refs. 7, 22, 32, 54, 82 and 83). After nondestructive reflectivity measurements (see Fig. 6A.15), the exposed samples may be studied further with surface-sensitive techniques such as depth Auger spectroscopy (see

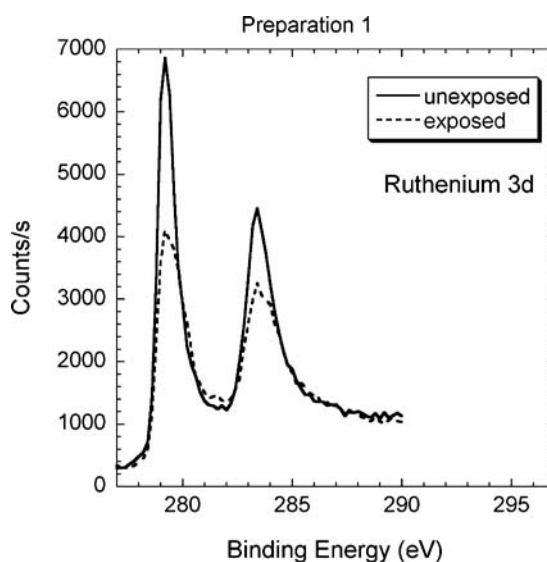


Figure 6A.17 High-resolution XPS data of Ru 3d peaks before and after the EUV exposure.

Fig. 6A.16), x-ray photoemission spectroscopy (XPS) (see Fig. 6A.17), or TEM to evaluate the extent of the damage and find correlations between the exposure parameters and optics modifications.^{33,54,79,81,86}

6A.3.1.1 Comparison of Si, Ru, and TiO₂

Initial lifetime studies that examined EUV-induced oxidation were performed on Si-capped MLs^{3,5} using both electron and EUV exposures. The results implied that the oxidation produced by 1 μ A of an electron-beam current causes the same damage as 1 mW of EUV exposure; hence, the more widely available electron beams can be used to perform environmental testing instead of EUV photons. However, the aforementioned relationship between electron and EUV exposure is different for Ru-capped MLs²⁰ and most likely other capping layer materials. Ruthenium-capped MLs showed longer lifetimes in an oxidizing environment than Si-capped MLs²² (see Fig. 6A.18). Interestingly, lifetime testing performed under “real” tool conditions showed that ambient hydrocarbons play an important role in reducing oxidation in Ru capping layers.³¹ In some accelerated experiments where water vapor pressures were high ($>5 \times 10^{-7}$ Torr), the EUV-induced damage on Ru-capped MLs decreased with increasing levels of water.³² These contradictory results were explained by the presence of low-mass carbon-containing species in the chamber.^{32,34} The results indicate that a proper balance between water vapor and hydrocarbons and/or catalytic properties of the capping layer can substantially increase optics lifetime, which was also demonstrated on other proprietary solutions.^{82,87–90}

Another capping layer of interest is TiO₂. Preliminary results suggest that in an oxidizing environment, this capping layer material is as good if not better

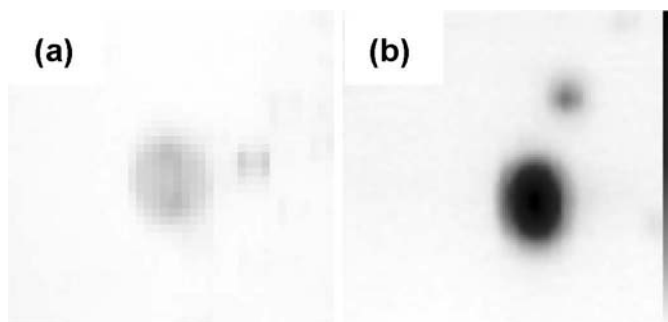


Figure 6A.18 Performance of (a) Ru-capped, and (b) Si-capped MLs exposed to EUV (8 mW/mm^2) for 60 hours at 2×10^{-6} Torr H_2O . The Ru-capped ML lost 1.5% in reflectivity compared to its initial value while the Si-capped ML lost 16.4% in reflectivity under the same experimental conditions. Experiments were performed at NIST's beamline and reflectivity maps measured at LBNL's ALS.

performing than Ru.²⁸ However, since less effort has been put into optimizing and testing this capping layer, it is hard to make any conclusions at this point. Compared to polycrystalline Ru, this capping layer is amorphous and already oxidized. Without a fundamental understanding of surface chemistry in realistic environments, one would find it extremely difficult to choose the best material for the capping layer.

6A.3.1.2 Pulsed versus continuous radiation

The ASML reported that there is a distinct difference between contamination rates from a pulse EUV source (5 to 10 KHz) and from a high-frequency synchrotron source (500 MHz), as shown schematically in Fig. 6A.3.³⁰ The contamination rate for 5- to 10-KHz sources saturates with time; however, contamination from synchrotron radiation seems to continue to scale up with time. For this reason, one must differentiate between scaling laws that were generated on an EUV source and those that were generated on a synchrotron.

6A.3.2 Measurement of optics contamination (in-situ metrology)

Because of its substantial added cost, in-situ metrology is usually considered only in cases where traditional “post-mortem” analytical characterization is not possible. Because EUV projection optics still do not meet HVM specifications, in-situ control and monitoring should be considered independent of how costly, disruptive, or effective various candidate metrologies might be. Edwards et al.⁹¹ reviewed different candidate technologies by taking into consideration ex-situ detection limits of “thin” carbon and oxide layers on ML EUV optics samples. Where possible, they reported data from EUV-exposed SEMATECH Ru-capped benchmark optics samples. The feasibility assessment of in-situ metrology for controlling contamination of projection optics included Auger electron spectroscopy (AES), reflectance

difference spectroscopy, secondary-ion mass spectroscopy (SIMS), x-ray reflectivity, backscattering methods such as elastic recoil detection of light elements, XPS, ellipsometry, reflectometry, Fourier transform infrared spectroscopy (FTIR) and Raman spectroscopy, and low-energy ion scattering. To assess the feasibility of in-situ metrology, it is important to understand exactly what is being measured, to what sensitivity it must be measured, what metrology options are available, how disruptive these options are to an EUVL tool, and what the cost is for each option. Because of their nondestructive nature, optical techniques have an advantage over electron- and ion-beam-based techniques. Considerations to narrow down the candidates include understanding the capping layer surface chemistry, the role of background chamber contaminants, the cost of ownership, and the extent of process disruption for each of the candidate techniques.⁹¹

6A.3.3 Environmental control strategy

Because of the potential for process disruption, active mitigation schemes are largely viewed as less desirable than chamber contamination control and/or physical protection of the mirrors with oxidation-resistant layers.

6A.3.3.1 Gas blend mitigation

Gas blend mitigation is one of several possible mitigation schemes to reduce optics contamination. Initially, an ethanol gas blend was proposed to reduce oxidation of Si-capped MLs by allowing the growth of a thin, protective carbon coating.⁹² Since Si forms a thin (~ 1.5 nm) native oxide when exposed to the air, it was assumed that the Si surface would be terminated by silanol groups, and that ethyl alcohol as a gas blend in the system would bind well on hydroxyl terminated surfaces and grow a thin, void-free carbon protective layer. This assumption was based on the idea that the rate of film growth would likely be sharply reduced after the formation of several carbon monolayers, and that water molecules would not bind to such nonpolar, inert carbon film. Hence, the whole oxidation process would be substantially reduced. Ethanol was used successfully in the ETS to protect optics from oxidation.¹⁸ However, other researchers who tried this mitigation technique reported that it was not effective, most likely because the carbon layer that formed on the surface was not void-free.⁸¹

6A.3.4 Development of contamination-resistant capping layers

Because of the proprietary nature of capping layer design, most of this section will be devoted to the development of Ru capping layers, which originated at LLNL as part of the VNL project.^{20,22} Further work on Ru capping layers to establish the baseline structural, optical, and surface properties was supported by SEMATECH.⁹³ These Ru-capped, Mo/Si-based EUVL MLs are also known as Multilayer 1 in the EUVL community. Differently prepared Ru capping layers

(changes in voltage/current, sputtering gas, and material) were tested for their oxidation and thermal stability. The best-performing Ru capping layer structure was prepared using argon (Ar) sputtering gas and a metallic Ru target. The microstructure of this capping layer was analyzed in detail with TEM.⁵⁴ Compared to other Ru capping layer preparations, it is the only one that shows grains with preferential orientation. Ruthenium in this capping layer preparation is polycrystalline with an average grain size of ~ 3.5 nm and has a preferential growth orientation with Ru(0001) crystal planes parallel to the specimen surface. Based on limited TEM data, it appears that the Ru capping layers of other preparations have smaller, randomly oriented, and mostly oxidized grains.

As part of the SEMATECH-funded project, LLNL also fabricated and tested five more capping layer candidates that included palladium (Pd), palladium-gold (PdAu), SiC, YSZ (Y_2O_3 stabilized ZrO_2), and MoSi_2 .⁹⁴ These samples listed from the highest to the lowest reflectivity values are SiC, YSZ, MoSi_2 , PdAu, and Pd, and these values are consistent with their rankings based on calculated reflectivities. The capping layer deposition processes were not optimized, and the capping layers had different deficiencies. For example, Pd and PdAu capping layers both showed island growth formation with associated surface roughness and incomplete coverage. In addition, Pd and Au were detected in the layers below the capping layer, suggesting diffusion of these elements into the ML. The insertion of a diffusion barrier between the Si and Pd (PdAu) limited the diffusion into the ML and increased the reflectivity by 20%. Even though noble metals are impervious to oxidation in bulk form, substantial development is required to overcome island growth and to limit diffusion into the ML interior. While a thicker Pd(PdAu) layer will completely cover the surface, such a thick layer (>4 nm) leads to unacceptably low reflectivity. Both SiC and MoSi_2 formed smooth capping layers but appeared to have defects that facilitated the oxidation process. YSZ appeared very smooth and was most likely amorphous. For the particular alloy used in this experiment, the oxygen diffusion rate through the layer was very high. Even though the YSZ composition remained unchanged, a few layers of Si and Mo underneath were oxidized, which led to the highest reflectivity loss among the capping layer materials that were tested. Although none of these materials outperformed Ru, much was learned about different degradation mechanisms. This feedback was useful for improving the properties of these and other capping layer materials.

Another tested capping layer material with favorable optical and surface reactivity properties is titanium oxide (TiO_2). A 2-nm-thick TiO_2 capping layer reduces reflectivity by only 0.8% compared to a Si-capped ML. TiO_2 belongs to the class of semiconductors with a relatively wide bandgap. Because TiO_2 is exposed to the light of the energy corresponding to its bandgap, charge carriers such as electrons and holes are produced, and oxidation-reduction reactions on the TiO_2 surface occur. A TiO_2 thin film has a strong oxidizing power and high photocatalytic activity for hydrocarbon oxidation,⁹⁵ and therefore is also of interest as a potential self-cleaning capping layer. Previous work on TiO_2 indicates that the use of reactive magnetron sputtering provides more control over the structure, composition, and

properties of TiO₂ films than other methods, such as plasma-enhanced chemical vapor deposition (PECVD), thermal oxidation of metal, sol-gel, etc. When TiO₂ films were fabricated by magnetron sputtering with TiO₂ as targets, parameters such as the Ar/O₂ ratio, deposition power, and substrate temperature were found to strongly influence the formation of TiO₂ films.

In LLNL studies, TiO₂ was prepared in three different ways: (1) depositing a metallic Ti layer and then oxidizing it with pure O₂, (2) radio-frequency (RF) sputtering of the TiO₂ target, and (3) reactive RF sputtering of the TiO₂ target with an Ar:O₂ sputtering gas. The third method produced >66% reflectivity MLs, and the preliminary exposure results with water vapor indicated a longer lifetime compared to Ru-capped MLs.²⁸ Based on TEM studies, the TiO₂ capping layer prepared with reactive RF-sputtering was amorphous and completely covered the MLs. The TiO₂ layer also formed a sharp interface with Si so no diffusion barrier was necessary. However, XPS and STEM analysis indicated that Ar gas was incorporated in the TiO₂ capping layer and lead the stoichiometry of TiO_{2/4}. Further work is needed on deposition processes, such as on the Ar/O₂ gas mixture and the energy of the incoming ions, to improve the performance of this capping layer material.

6A.3.5 Cleaning of optics contamination

Once the optics are contaminated, it is possible to recover the reflectivity by cleaning the mirror surfaces by removing carbon^{3,96} or even some oxides.³³ The current plan for some lithography tool manufacturers⁸⁷ is to keep the projection optics in an environment in which carbon deposition is the dominant degradation mechanism. This approach avoids any oxidation, which is still perceived to be irreversible, especially if the bonds between the metal and oxygen are as strong as in SiO₂. Initial results after five cycles of exposure and carbon removal indicate that the reflectivity of ML samples do not suffer any permanent damage.³⁰ However, it is not clear how the optics must be cleaned. Based on preliminary results, it seems that the combination of a pulsed EUV source, the right environment (mixture of hydrocarbons and oxygen), and the appropriate capping layer provides sufficiently long optical lifetimes between cleanings. The cleaning methods include the use of molecular oxygen,⁵ RF-O₂, RF-H₂, and atomic hydrogen.^{19,96} Hydrogen-based cleaning has been demonstrated in molecular beam epitaxy surface preparation of Si^{97,98} and compound semiconductors.⁹⁹ Other methods to remove deposited carbon include in-situ cleaning using EUV light and high oxygen pressure (5×10^{-2} Pa).⁸

The only successful removal of the Ru oxide layer was reported by Nishiyama et al.³³ using atomic hydrogen. XPS analysis and AES data were used to confirm that the atomic hydrogen removed the Ru oxide. No increase in surface roughness was observed on the Ru. Atomic hydrogen seems to be the most likely candidate for cleaning mirrors contaminated with either carbon or oxide.

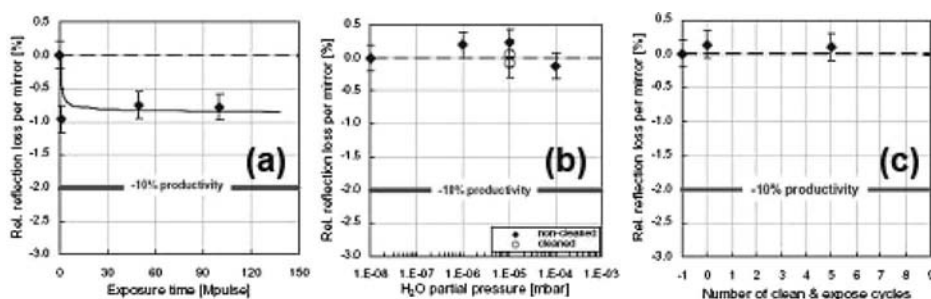


Figure 6A.19 (a) Saturation of carbon growth, and (b) no oxidation of ML mirrors under pulsed EUV irradiation observed. The oxidation experiments were done both on as-received samples and on samples that were cleaned in-situ before exposure. (c) Sample reflectivity after multiple cycle exposure and cleaning. There is no evidence of reflectivity loss after five cycles. (Reprinted from Ref. 30.)

6A.3.6 Novel approaches to contamination control

From the modeling and experiments in ASML's alpha demonstration tool,³⁰ ASML has verified that reflectivity loss is primarily from carbon deposition only, and no oxidation is expected. In-situ cleaning processes have been shown to be effective to recover the reflectivity loss (see Fig. 6A.19). The extent of long-term irreversible loss from in-situ cleaning has not been determined and is still a topic of research. ASML's cleaning techniques have not been disclosed; however, other researchers have shown that atomic hydrogen can be effectively used to remove oxide deposition¹⁰⁰ and carbon deposition¹⁰¹ on Ru-coated mirror surfaces.

Today, research on optics contamination is focused on the study of scaling laws^{37,102} and fundamental research^{34,103–105} on the photoelectrons emitted from the mirror surfaces.

The carbon deposition rate increases with the organic gas pressure in the chamber.¹⁰² This rate also increases with the EUV light intensity but then saturates at higher EUV light intensities.¹⁰² Because the details of chamber conditions are proprietary among EUVL scanner makers, one must use the scaling laws because the carbon deposition rates may correspond to specific experimental conditions only.

Various researchers have now reported that “much of the radiation-induced chemistry on the surfaces of capping layers is induced by low-energy secondary electrons rather than direct photoionization”.^{34,104} Future research will study the generation of these secondary electrons and potential mitigation techniques to reduce the reflectivity loss.¹⁰⁵

6A.4 Summary and Future Outlook

The lifetime predictions and results obtained by different research groups are inconsistent, and they are difficult to compare and interpret because the experimental

details are often not reported. Comparisons between lifetime data using pulsed versus semicontinuous EUV sources suggest that exposure to the pulsed source results in less damage than exposure to the synchrotron source. Because of limited data on optics lifetime for exposure to the pulsed source, such statements are considered premature, and the 30,000-hour optics lifetime is still an extremely challenging goal. The design of meaningful accelerated lifetime tests requires understanding the surface processes of mirrors exposed to EUV radiation and sufficient time to perform the tests. Optics contamination of EUV mirrors is affected by the contaminants in the environment, the EUV source, and the mirror surfaces. Depending on these parameters, the mirror might grow a carbon layer or become oxidized, and both processes lead to reflectivity loss. Under ideal parameters these effects will cancel, and the mirror will remain clean and highly reflective. Finding this parameter space is not a trivial task; past failed phenomenological approaches clearly underline the need for a fundamental understanding of degradation processes.

As discussed in this chapter, several methods can minimize optics degradation processes, including mitigation, protection with capping layers, and in-situ cleaning of the optics. It appears that a combination of all three might be necessary to achieve desired lifetimes. There is hope that ongoing surface chemistry experiments on Ru and a few other capping layer candidates⁴² will provide the missing adsorption, reaction, and desorption rates, steady-state coverages, and adsorption lifetimes to model EUV degradation and mitigation. It is important to keep in mind that Ru is a benchmark material for the development of other capping layers. Even though other capping layers might have different surface chemistries, the knowledge gained from studying Ru is valuable, and most importantly, can be used as a platform to discuss the results of other proprietary capping layers.

References

1. E. Spiller, "Low-loss reflectivity coatings using absorbing materials," *Appl. Phys. Lett.* **20**, 365–367 (1972).
2. A. Barty and K. A. Goldberg, "Effects of radiation induced carbon contamination on the performance of an EUV lithographic optic," *Proc. SPIE* **5037**, 450–459 (2003).
3. M. Malinowski, C. Steinhaus, M. Clift, L. E. Klebanoff, S. Mrowka, and R. Soufli, "Controlling contamination in Mo/Si multilayer mirrors by Si surface-capping modifications," *Proc. SPIE* **4688**, 442–453 (2002).
4. M. E. Malinowski, *SEMATECH Project LITH113: EUV Optics Contamination Control Gas Blend Carbon Mitigation Data and Final Report*, Report to International SEMATECH, Project LITH113, Agreement 399509-OJ.
5. M. Malinowski, P. Grunow, C. Steinhaus, M. Clift, and L. Klebanoff, "Use of molecular oxygen to reduce EUV-induced carbon contamination of optics," *Proc. SPIE* **4343**, 347–356 (2001).

6. S. Graham, C. Steinhaus, M. Clift, and L. Klebanoff, "Radio-frequency discharge cleaning of silicon-capped Mo/Si multilayer extreme ultraviolet optics," *J. Vac. Sci. Technol. B* **20**(6), 2393–2401 (2002).
7. B. Mertens, B. Wolschrijn, R. Jansen, N. Koster, M. Weiss, M. Wedowski, R. Klein, R. Bock, and R. Thornagel, "EUV time resolved studies on carbon growth and cleaning," *Proc. SPIE* **5037**, 95–102 (2003).
8. K. Hamamoto, T. Tanaka, T. Watanabe, N. Sakaya, M. Hosoya, T. Shoki, H. Hada, N. Hishinuma, H. Sugahara, and H. Kinoshita, "Cleaning of extreme ultraviolet lithography optics and masks using 13.5 nm and 172 nm radiation," *J. Vac. Sci. Technol. B* **23**, 247–252 (2005).
9. A. B. C. Walker Jr., T. W. Barbee Jr., R. B. Oover, and J. F. Lindblom, "Soft x-ray images of the solar corona with a normal-incidence Cassegrain multilayer telescope," *Science* **241**, 1781–1787 (1988).
10. <http://sohowww.nascom.nasa.gov/>
11. J.-P. Delaboudiniere, G. E. Artzner, J. Brunaud, A. H. Gabriel, J. F. Hochedez, F. Millier, X. Y. Song, B. Au, K. P. Dere, R. A. Howard, R. Kreplin, D. J. Michels, J. D. Moses, J. M. Defise, C. Jamar, P. Rochus, J. P. Chauvineau, J. P. Marioge, R. C. Catura, J. R. Lemen, L. Shing, R. A. Stern, J. B. Gurman, W. M. Neupert, A. Maucherat, F. Clette, P. Cugnon, and E. van Dessel, "EIT: Extreme-Ultraviolet Imaging Telescope for the SOHO mission," *Solar Physics* **162**, 291–312 (1996).
12. <http://trace.lmsal.com/>
13. T. W. Barbee Jr., J. C. Rife, W. R. Hunter, M. P. Kowalski, R. G. Cruddace, and J. F. Seely, "Long-term stability of a Mo/Si multilayer structure," *Appl. Opt.* **32**, 4852–4854 (1993).
14. K. Boller, R. P. Haelbich, H. Hogrefe, W. Jerk, and C. Kunz, "Investigation of carbon contamination of mirror surfaces exposed to synchrotron radiation," *Nucl. Instrum. Method.* **208**, 273–279 (1983).
15. D. Gaines, R. C. Spitzer, N. M. Ceglio, M. Krurey, and G. Ulm, "Radiation hardness of molybdenum silicon multilayers designed for use in a soft x-ray projection lithography system," *Appl. Opt.* **32**, 6991–6998 (1993).
16. M. Wedowski, S. Bajt, J. A. Folta, E. M. Gullikson, U. Kleinberg, L. E. Klebanoff, M. E. Malinowski, and W. M. Clift, "Lifetime studies of Mo/Si and Mo/Be multilayer coatings for extreme ultraviolet lithography," *Proc. SPIE* **3767**, 217–224 (1999).
17. D. A. Tichenor, G. D. Kubiak, W. C. Replogle, L. E. Klebanoff, J. B. Wronsky, L. C. Hale, H. N. Chapman, J. S. Taylor, J. A. Folta, C. Montcalm, R. M. Hudyma, K. A. Goldberg, and P. Naulleau, "EUV Engineering Test Stand," *Proc. SPIE* **3997**, 48–69 (2000).
18. L. E. Klebanoff, M. E. Malinowski, P. Grunow, W. M. Clift, C. Steinhaus, A. H. Leung, and S. J. Haney, "First environmental data from the EUV Engineering Test Stand," *Proc. SPIE* **4343**, 342–346 (2001).
19. S. Graham, M. E. Malinowski, C. E. Steinhaus, P. A. Grunow, and L. E. Klebanoff, "Studies of EUV contamination mitigation," *Proc. SPIE* **4688**, 431–441 (2002).

20. S. Bajt, J. B. Alameda, T. W. Barbee Jr., W. M. Clift, J. A. Folta, B. Kaufmann, E. A. Spiller, "Improved reflectance and stability of Mo-Si multilayers," *Opt. Eng.* **41**, 1797–1804 (2002).
21. S. Bajt, H. N. Chapman, N. Nguyen, J. Alameda, J. C. Robinson, M. Malinowski, E. Gullikson, A. Aquila, C. Tarrio, and S. Grantham, "Design and performance of capping layers for EUV multilayer mirrors," *Proc. SPIE* **5037**, 236–248 (2003).
22. S. Bajt, H. N. Chapman, N. Nguyen, J. Alameda, J. C. Robinson, M. Malinowski, E. Gullikson, A. Aquila, C. Tarrio, and S. Grantham, "Design and performance of capping layers for extreme-ultraviolet multilayer mirrors," *Appl. Opt.* **42**, 5750–5758 (2003).
23. B. M. Mertens, N. Koster, R. Jansen, A. van de Runstraat, H. Werij, F. Stietz, M. Wedowski, H. Meiling, R. Klein, R. Thornagel, F. Scholze, G. Ulm, R. Kurt, P. Zalm, E. Louis, and A. Yakshin, in ASET/SEMATECH Workshop on EUV Lithography, Matsue, 2001, O4-5.
24. A. E. Yakshin, E. Louis, E. L. G. Maas, F. Bijkerk, R. Klein, F. Scholze, P. Zalm, F. Stietz, M. Wedowski, S. Muellender, B. Mertens, and H. Meiling, in ASET/SEMATECH Workshop on EUV Lithography, Matsue, 2001, P6-6.
25. R. Hudyma, "An overview of optical systems for 30 nm resolution lithography at EUV wavelengths," *Proc. SPIE* **4832**, 137–148 (2002).
26. R. Hudyma, "High numerical aperture ring field projection system for Extreme Ultraviolet Lithography," U.S. Patent 6,033,079, March 7, 2000.
27. R. Hudyma and D. Shafer, "High numerical aperture ring field projection system for Extreme Ultraviolet Lithography," U.S. Patent 6,188,153, February 13, 2001.
28. S. Bajt, S. Hau-Riege, J. Alameda, F. Dollar, M. Chandhok, and M. Fang, "Protective capping layer for EUVL optics using TiO_2 ," 4th International Extreme Ultraviolet Lithography Symposium, San Diego, California, November 7–10, 2005.
29. H. Meiling, V. Banine, N. Harned, B. Blum, P. Kürz, and H. Meijer, "Development of the ASML EUV alpha demo tool," *Proc. SPIE* **5751**, 90–102 (2005).
30. H. Meiling, H. Meijer, V. Banine, R. Moors, R. Groeneveld, H.-J. Voorma, U. Mickan, B. Wolschrijn, B. Mertens, G. van Baars, P. Kürz, and N. Harned, "First performance results of the ASML alpha demo tool," *Proc. SPIE* **6151**, 615108-12 (2006).
31. Y. Gomei, Y. Kakutani, H. Takase, M. Niibe, S. Terashima, T. Aoki, and S. Matsunari, "The role of ambient hydrocarbon species to reduce oxidation in Ru capping layers for EUVL optics mirrors," *Microelectron. Eng.* **83**, 676–679 (2006).
32. S. B. Hill, I. Ermanoski, S. Grantham, C. Tarrio, T. B. Lucatorto, T. E. Madey, S. Bajt, M. Chandhok, P. Yan, O. Wood, S. Wurm, and N. V. Edwards, "EUV testing of multilayer mirrors: critical issues," *Proc. SPIE* **6151**, 61510F-1 (2006).

33. I. Nishiyama, H. Oizumi, K. Motai, A. Izumi, T. Ueno, H. Akiyama, and A. Namiki, "Reduction of oxide layer on Ru surface by atomic-hydrogen treatment," *J. Vac. Sci. Technol. B* **23**, 3129–3131 (2005).
34. T. E. Madey, N. S. Faradzhev, B. Y. Yakshinskiy, and N. V. Edwards, "Surface phenomena related to mirror degradation in extreme ultraviolet (EUV) lithography," *Appl. Surf. Sci.* **253**, 1691–1708 (2006).
35. J. Hollenshead and L. Klebanoff, "Modeling radiation-induced carbon contamination of extreme ultraviolet optics," *J. Vac. Sci. Technol. B* **24**, 64–82 (2006).
36. J. Hollenshead and L. Klebanoff, "Modeling extreme ultraviolet/H₂O oxidation of ruthenium optic coatings," *J. Vac. Sci. Technol. B* **24**, 118–130 (2006).
37. Y. Gomei, H. Takase, T. Aoki, Y. Kakutani, and M. Niibe, "Scaling law in acceleration test of extreme ultraviolet lithography projection optics mirror contamination," *J. Vac. Sci. Technol. B* **23**, 2848–2851 (2005).
38. A. N. Broers, W. W. Molzen, J. J. Cuomo, and N. D. Wittels, "Electron-beam fabrication of 80Å metal structures," *Appl. Phys. Lett.* **29**, 596–598 (1976).
39. R. Kurt, M. van Beek, C. Crombeen, P. Zalm, and Y. Tamminga, "Radiation induced carbon contamination of optics," *Proc. SPIE* **4688**, 702–708 (2002).
40. G. Kyriakou, D. J. Davis, R. B. Grant, D. J. Watson, A. Keen, M. S. Tikhov, and R. M. Lambert, "Electron impact-assisted carbon film growth on Ru(0001): Implications for next-generation EUV lithography," *J. Phys. Chem. C* **111**, 4491–4494 (2007).
41. L. E. Klebanoff, M. E. Malinowski, W. M. Clift, C. Steinhaus, and P. Grunow, "Use of gas-phase ethanol to mitigate extreme UV/water oxidations of extreme UV optics," *J. Vac. Sci. Technol. A* **22**, 425–432 (2004).
42. S. Bajt, N. V. Edwards, and T. E. Madey, "Properties of ultrathin films appropriate for optics capping layers exposed to high energy photon irradiation," *Surf. Sci. Rep.* **63**, 73–99 (2008).
43. D. L. Windt, "IMD: Software for modeling the optical properties of multi-layer films," *Computer in Physics* **12**, 360–371 (1998).
44. http://www-cxro.lbl.gov/optical_constants/ web page, maintained by E. M. Gullikson.
45. S. E. Siporin, R. J. David, W. Rarog-Pilecka, D. Szmiegl, and Z. Kowalczyk, "Isotopic Transient Analysis of Ammonia Synthesis over Ba or Cs-Promoted Ru/Carbon Catalysts," *Catal. Lett.* **93**(1–2), 61–65 (2004).
46. R. B. Anderson, *The Fischer-Tropsch Synthesis*, Academic Press (1984).
47. D. L. Doering, T. E. Madey, "The adsorption of water on clean and oxygen-dosed Ru(011)," *Surf. Sci.* **123**, 305–337 (1982).
48. P. A. Thiel and T. E. Madey, "The interaction of water with solid surfaces: Fundamental aspects," *Surf. Sci. Rep.* **7**, 211–385 (1987).
49. M. Henderson, "The interaction of water with solid surfaces: fundamental aspects revisited," *Surf. Sci. Rep.* **46**, 1–308 (2003).
50. I. J. Malik and J. Hrbek, "Very high atomic oxygen coverages on Ru(001)," *J. Vac. Sci. Technol. A* **10**, 2565–2569 (1992).

51. A. Bottcher, H. Conrad, and H. Niehus, "Characterization of oxygen phases created during oxidation of Ru(0001)," *J. Chem. Phys.* **112**(10), 4779–4787 (2000).
52. H. Over and A. P. Seitsonen, "Oxidation of metal surfaces," *Science* **297**, 2003–2005 (2002).
53. A. Baraldi, S. Lizzit, G. Comelli, and G. Paolucci, "Oxygen adsorption and ordering on Ru(101 $\bar{0}$)," *Phys. Rev. B* **63**, 115410 (2001).
54. S. Bajt, Z. R. Dai, E. J. Nelson, M. A. Wall, J. B. Alameda, N. Q. Nguyen, S. L. Baker, J. C. Robinson, J. S. Taylor, A. Aquila, and N. V. Edwards, *J. Microlithogr. Microfabr. Microsyst.* **5**, 023004 (2006).
55. P. J. Feibelman, "Partial Dissociation of Water on Ru(0001)," *Science* **295**, 99–102 (2002).
56. D. Menzel, "Water on a Metal Surface," *Science* **295**, 58–59 (2002).
57. A. Michaelides, A. Alavi, and D. A. King, "Insight into H₂O-ice adsorption and dissociation on metal surfaces from first-principles simulations," *Phys. Rev. B* **69**, 113404 (2004).
58. G. Materzanini, G. F. Tantardini, J. D. Lindan, and P. Saalfrank, "Water adsorption at metal surfaces: A first-principles study of the ($\sqrt{3} \times \sqrt{3}$)R30° H₂O bilayer on Ru(0001)," *Phys. Rev. B* **71**, 155414 (2005).
59. K. Andersson, A. Nikitin, L. G. M. Pettersson, A. Nilsson, and H. Ogasawara, "Water Dissociation on Ru(001): An Activated Process," *Phys. Rev. Lett.* **93**, 196101 (2004).
60. J. Weissenrieder, A. Mikkelsen, J. N. Andersen, P. J. Feibelman, and G. Held, "Experimental Evidence for a Partially Dissociated Water Bilayer on Ru{0001}," *Phys. Rev. Lett.* **93**, 196102 (2004).
61. N. S. Faradzhev, K. L. Kostov, P. Feulner, T. E. Madey, and D. Menzel, "Stability of water monolayers on Ru(0 0 0 1): Thermal and electronically induced dissociation," *Chem. Phys. Lett.* **415**(1–3), 165–171 (2005).
62. G. Held and D. Menzel, "The structure of the p($\sqrt{3} \times \sqrt{3}$)R30° bilayer of D₂O on Ru(001)," *Surf. Sci.* **316**(1–2), 92–102 (1994).
63. G. Held and D. Menzel, "Isotope effects in structure and kinetics of water adsorbates on Ru(001)," *Surf. Sci.* **327**(3), 301–320 (1995).
64. C. Clay, S. Haq, and A. Hodgson, "Intact and dissociative adsorption of water on Ru(0 0 0 1)," *Chem. Phys. Lett.* **388**(1–3), 89–93 (2004).
65. S. Meng, E. G. Wang, and S. Gao, "Water adsorption on metal surfaces: A general picture from density functional theory studies," *Phys. Rev. B* **69**, 195404 (2004).
66. B. V. Yakshinskiy, T. Graber, and T. E. Madey, unpublished data.
67. M. M. Thiam, T. Kondo, N. Horimoto, H. S. Kato, and M. Kawai, "Initial Growth of the Water Layer on (1 $\times$ 1)-Oxygen-Covered Ru(0001) in Comparison with that on Bare Ru(0001)," *J. Phys. Chem. B* **109**, 16024–16029 (2005).
68. I. Nishiyama, "Model of Ru-surface oxidation for the lifetime scaling of EUVL projection optics mirror," *Proc. SPIE* **6151**, 61510G (2006).

69. N. Itoh and A. M. Stoneham, *Materials Modification by Electronic Excitation*, Cambridge University Press, Cambridge, 2001.
70. L. Sanche, *Excess Electrons in Dielectric Media*, CRC Press, Boca Raton, FL, p. 1 (1991).
71. A. D. Bass and L. Sanche, "Reactions induced by low energy electrons in cryogenic films (Review)," *Low. Temp. Phys.* **29**(3), 270–285 (2003).
72. A. D. Bass and L. Sanche, "Dissociative electron attachment and charge transfer in condensed matter," *Radiat. Phys. Chem.* **681**(1–2), 3–13 (2003).
73. X. L. Zhou, X. Y. Zhu, and J. M. White, "Photochemistry at adsorbate/metal interfaces," *Surf. Sci. Rep.* **13**(3–6), 73–220 (1991).
74. L. R. Danielson, M. J. Dresser, E. E. Donaldson, and D. R. Sandstrom, "Effects of an electron beam on adsorption and desorption of ammonia on ruthenium (0001)," *Surf. Sci.* **71**(3), 615–629 (1985).
75. M. E. Malinowski, C. A. Steinhaus, D. E. Meeker, W. M. Clift, L. E. Klebanoff, and S. Bajt, "Relation between electron- and photon-caused oxidation in EUVL optics," *Proc. SPIE* **5037** 429–438 (2003).
76. Y. Kakutani, M. Niibe, K. Kakiuchi, H. Takase, S. Terashima, H. Kondo, S. Matsunari, T. Aoki, Y. Gomei, and Y. Fukuda, "A reflectance measurement system for investigating radiation damage to EUVL mirrors in New-SUBARU," *Proc. SPIE* **5533**, 47–57 (2004).
77. R. Klein, A. Gottwald, F. Scholze, R. Thornagel, J. Tümmeler, G. Ulm, M. Wedowski, F. Stietz, B. Mertens, N. Koster, and J. van Elp, "Lifetime testing of EUV optics using intense synchrotron radiation at the PTB radiometry laboratory," *Proc. SPIE* **4506**, 105–112 (2001).
78. C. Tarrio and S. Grantham, "Synchrotron beamline for extreme-ultraviolet multilayer mirror endurance testing," *Rev. Sci. Instrum.* **76**, 056101-1 (2005).
79. W. M. Clift, L. Klebanoff, C. Tarrio, S. Grantham, O. R. Wood II., S. Worm, and N. V. Edwards, "Scaling studies of capping layer oxidation by water exposure with EUV radiation and electrons," *Proc. SPIE* **5374**, 666–674 (2004).
80. R. Klein, F. Scholze, R. Thornagel, J. Tümmeler, M. Wedowski, R. Jansen, B. Mertens, A. van de Runstraat, and G. Ulm, "Irradiation of EUV multilayer optics with synchrotron radiation of different time structure," *Proc. SPIE* **4782**, 292–299 (2002).
81. N. Koster, B. Mertens, R. Jansen, A. Van de Runstraat, F. Stietz, M. Wedowski, H. Meiling, R. Klein, A. Gottwald, F. Scholze, M. Visser, R. Kurt, P. Zalm, E. Louis, and A. Yakshin, "Molecular contamination mitigation in EUVL by environmental control," *Microelectron. Eng.* **61–62**, 65–76 (2002).
82. B. Mertens, M. Weiss, H. Meiling, R. Klein, E. Louis, R. Kurt, M. Wedowski, H. Trenkler, B. Wolschrijn, R. Jansen, A. van de Runstraat, R. Moors, K. Spee, S. Plöger, and R. van de Kruijs, "Progress in EUV optics lifetime expectations," *Microelectron. Eng.* **73–74**, 16–22 (2004).
83. Y. Kakutani, M. Niibe, Y. Gomei, H. Takase, S. Terashima, S. Matsunari, T. Aoki, K. Murakami, and Y. Fukuda, "Effect of residual gas atmosphere on lifetime of Ru-capped EUVL projection optics mirror," *Proc. SPIE* **6151**, 61510H (2006).

84. J. H. Underwood and E. M. Gullikson, "High-resolution, high-flux, user friendly VLS beamline at the ALS for the 50–1300 eV energy region," *J. Electron. Spectrosc. Relat. Phenom.* **92**, 265–272 (1998).
85. J. Tümmler, F. Scholze, G. Brandt, B. Meyer, F. Scholz, K. Vogel, G. Ulm, M. Poier, U. Klein, and W. Diete, "New PTB reflectometer for the characterization of large optics for the extreme ultraviolet region," *Proc. SPIE* **4688**, 338347 (2002).
86. H. Takase, Y. Gomei, S. Terashima, H. Kondo, T. Aoki, S. Matsunari, M. Niibe, and Y. Kakutani, "Characterization of capped multilayer mirrors using XPS, AES and SIMS," *Proc. SPIE* **5751**, 1084–1091 (2005).
87. H. Meiling, V. Banine, P. Kürz, B. Blum, G. J. Heerens, and N. Harned, "The EUV program at ASML: an update," *Proc. SPIE* **5037**, 24–35 (2003).
88. H. Meiling, V. Banine, P. Kürz, and N. Harned, "Progress in the ASML EUV program," *Proc. SPIE* **5374**, 31–42 (2004).
89. H. Takase, Y. Gomei, S. Terashima, H. Kondo, T. Aoki, S. Matsunari, M. Niibe, and Y. Kakutani, "Characterization of capped multilayer mirrors using XPS, AES and SIMS," *Proc. SPIE* **5751**, 1084–1091 (2005).
90. H. Meiling, B. Mertens, F. Stietz, M. Wedowski, R. Klein, R. Kurt, E. Louis, and A. Yakshin, "Prevention of MoSi multilayer reflection loss in EUVL tools," *Proc. SPIE* **4506**, 93–104 (2001).
91. N.V. Edwards, A. Diebold, T. Madey, Y. Chabal, S. Bajt, D. Theodore, R. Gregory, M. Canonico, D. E. Aspnes, N. Singh, J. Hilfiker, T. Lucatorto, and S. Hill, "Ex Situ Detection Limits of Contamination Metrology on EUV Multilayer Mirrors: A First Step Toward an In Situ Metrology Feasibility Assessment," poster presented at the 4th EUV symposium, available from SEMATECH upon request.
92. L. E. Klebanoff, W. M. Clift, M. E. Malinowski, C. Steinhaus, P. Grunow, and S. Bajt, "Radiation-induced protective carbon coating for extreme ultraviolet optics," *J. Vac. Sci. Technol. B* **20**(2), 696–703 (2002).
93. S. Bajt, et al., "Lifetime Benchmarking of Extreme Ultraviolet (EUV) Multilayer Optics (LITH160)," SEMATECH Tech Transfer Document 03114454A–ENG, December, 2003.
94. S. Bajt, et al., "Benchmarking Reflectivity of EUV Multilayer Optics (LITH160)-Multilayer 2," SEMATECH Tech Transfer Document 03114455A–ENG, December 2003.
95. S.-H. Kim, et al., "Influence of sputtering parameters on microstructure and morphology of TiO₂ thin films," *Mat. Lett.* **57**, 343–348 (2002).
96. S. Graham, C. Steinhaus, M. Clift, L. E. Klebanoff, and S. Bajt, "Atomic hydrogen cleaning of EUV multilayer optics," *Proc. SPIE* **5037**, 460–469 (2003).
97. R. E. Thomas, M. J. Mantini, R. A. Rudder, D. P. Malta, S. V. Hattangady, and R. J. Markunas, "Carbon and oxygen removal from silicon (100) surfaces by remote plasma cleaning techniques," *J. Vac. Sci. Technol. A* **10A**, 817–822 (1992).

98. H. Hirayama and T. Tatsumi, "Si(111) surface cleaning using atomic hydrogen and SiH₂ studied using reflection high-energy electron diffraction," *J. App. Phys.* **66**, 629–633 (1989).
99. V. A. Kagadei and D. I. Proskurovsky, "Use of a new type of atomic hydrogen source for cleaning and hydrogenation of compound semiconductor materials," *J. Vac. Sci. Technol. A* **16** 2556–2561 (1998).
100. K. Motai, H. Oizumi, S. Miyagaki, I. Nishiyama, A. Izumi, T. Ueno, Y. Miyazaki, and A. Namiki, "Atomic hydrogen cleaning of Ru-capped EUV multilayer mirrors," *Proc. SPIE* **6517**, 65170F (2007).
101. H. Oizumi, H. Yamanashi, I. Nishiyama, K. Hashimoto, S. Ohsono, A. Masuda, A. Izumi, and H. Matsumura, "Contamination removal from EUV multilayer using atomic hydrogen generated by heated catalyzer," *Proc. SPIE* **5751**, 1157–1154 (2005).
102. S. Matsunari, T. Aoki, K. Murakami, Y. Gomei, S. Terashima, H. Takase, M. Tanabe, Y. Watanabe, Y. Kakutani, M. Niibe, and Y. Fukuda, "Carbon Deposition in multi-layer mirrors by extreme ultraviolet radiation," *Proc. SPIE* **6517**, 6512X (2007).
103. S. B. Hill, I. Ermanoski, C. Tarrío, T. B. Lucatorto, T. E. Madey, S. Bajt, M. Fang, and M. Chandhok, "Critical parameters influencing the EUV-induced damage of Ru-capped multilayer mirrors," *Proc. SPIE* **6517**, 65170G (2007).
104. B. V. Yakshinskiy, R. Wasielewski, E. Loginova, and T. E. Madey, "Carbon accumulation and mitigation process, and secondary electron yield of ruthenium surfaces," *Proc. SPIE* **6517**, 65172Z (2007).
105. J. P. Allain, M. Nieto, M. Hendricks, A. Hassanein, C. Tarrío, S. Grantham, and V. Bakshi, "Energetic and thermal Sn interactions and their effect on EUVL source collector mirror lifetime at high temperatures," *Proc. SPIE* **6517**, 6517V (2007).



Saša Bajt received her PhD in Physics at the University of Heidelberg in Germany. She worked for The University of Chicago at the National Synchrotron Light Source (NSLS) developing x-ray fluorescence microprobe and micro x-ray spectroscopy. She joined Lawrence Livermore National Laboratory in 1996 where she was a principal investigator of a multilayer development team. As of 2008, she leads a Novel x-ray Optics group at DESY (Hamburg, Germany). She was a recipient of the Hawley

medal in 1999, given by The Mineralogical Association of Canada, for the innovation and application of microbeam XAFS to mineralogical research, and she has also received several LLNL awards. She holds several US and international patents on novel multilayer structures. Her protective capping layer design to extend the lifetime of the EUV multilayers was accepted as a benchmark by the semiconductor industry. Her research interests include multilayer optics for EUV and x-ray regions, optics damage and lifetime, physics of surfaces and interfaces, and x-ray

microscopy and spectroscopy. She is currently developing optics for short pulsed Free Electron Lasers (FELs) and is studying the damage of the coatings exposed to extreme conditions.

Chapter 6B

Grazing Angle Collector Contamination

Valentino Rigato

Contents

6B.1	Introduction	261
6B.1.1	EUV lithography challenges	261
6B.1.2	EUV sources	263
6B.1.3	EUV collector optics	263
6B.1.3.1	Collector materials	264
6B.1.3.2	Collector design and performance	265
6B.2	Collector Lifetime Status and Challenges	269
6B.2.1	Mechanism of reflectivity degradation	269
6B.2.2	Erosion and deposition: a binary collision approximation study of Sn interaction with Ru surfaces	271
6B.2.3	Sn chemical removal	279
6B.3	Summary	281
	Acknowledgments	281
	References	281

6B.1 Introduction

6B.1.1 EUV lithography challenges

Optical lithography using deep ultraviolet (DUV) light with a wavelength of 193 nm, together with immersion technology, is extendable down to the 45-nm node. However, using this technology to achieve half-pitch resolutions of 32 nm and below for future generations of even denser devices would require double exposure or double-imaging techniques that would halve wafer production throughput while markedly increasing mask set prices.

Extreme ultraviolet lithography (EUVL), with a wavelength of 13.5 nm, is today considered the most viable solution to replace optical lithography for high-volume chip manufacturing at the 32-nm node and below.

The extension of EUVL technology to future nodes will require the alignment of subsystem supplier's technological roadmaps to ensure full comprehension in the following areas:

- Physics of EUV power scaling
- Debris generation and control
- Processes that determine EUV optics lifetime
- Metrology to support/enhance EUV optics cleaning strategies
- Optical transmission of optical train
- Resist performance
- Defect inspection down to 22 nm and below

To ensure implementation of EUVL in high-volume manufacturing (HVM), the industry must achieve these key objectives:

- Scale up the EUV source in-band power to meet the throughput requirements with a source lifetime of more than 30,000 hours.
- Reduce EUV plasma emission size below 1 mm to avoid étendue losses.
- Enhance the performance of the debris mitigation system to enable a very high optical transmission and a collector lifetime on the order of 3000 to 5000 hours, or 10^{10} to 10^{11} shots. This requires an efficient suppression of the source debris by a factor higher than 10^4 . The debris mitigation system should also have an optical transmission of at least 50% with emission angles up to 70 deg.
- Improve the collector reflective coating to ensure high reflectivity and collector lifetime after debris mitigation. This includes the development of new materials that are compatible with wet as well as gas-phase chemistry for debris removal (cleaning), and the development of more rugged EUV layers to endure sputter erosion from energetic particles.
- Maximize collector efficiency in terms of transmitted power from the source to the intermediate focus (IF), including the debris mitigation system. This includes a careful match between the optical parameters of the illuminator and projector on one side and the source/debris mitigation system on the other.
- Provide collector optical systems stability under operation—i.e., under high thermal radiative loads and progressive deterioration of the mirrors due to debris and contaminants. In particular, for collector optics the variation of EUV power from a few percent (for calibration purposes) to the 100% full-rated power (for wafer writing at high throughput) will require a temperature-controlled collector to guarantee the minimum deformation of the optical surface as a function of the broadband source irradiated power. The optical stability also must be preserved during exposure to debris that may diminish the reflectivity of the EUV coatings in certain collector regions.

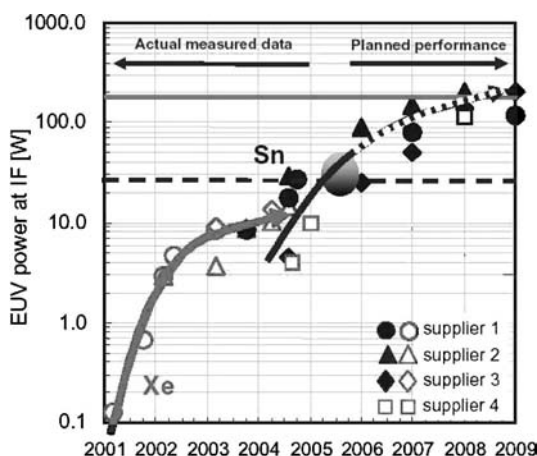


Figure 6B.1 Actual and planned performance of Sn- and Xe-fueled EUV sources. (Reprinted from Ref. 2.)

In parallel with the above objectives, new resist materials with enhanced sensitivity must be developed to guarantee sensitivity on the order of 10 mJ/cm^2 or better to match the line edge roughness (LER) requirements.

6B.1.2 EUV sources

The throughput of EUVL tools critically depends on the available in-band power at the IF. The different types and performances of laser-produced plasma (LPP) and discharge-produced plasma (DPP) EUV sources have been extensively treated in Ref. 1. By extrapolating from actual measured data on xenon-(Xe) and tin-(Sn) fueled sources to the desired performance for the next few years, it appears that Sn is the most viable candidate to guarantee the needed in-band power, as shown in Fig. 6B.1. This is principally, but not exclusively, due to the higher efficiency of Sn compared to Xe in generating in-band photons.

DPP Sn sources, in association with high-transmission grazing-incidence (GI) angle collectors and high-performance debris mitigation systems, are the leading candidates for high-power sources. A first example of a collector integrated in a high-power DPP Sn source was presented recently in Ref. 3. The results so far obtained for in-band power, debris mitigation performance and thermal management are in line with models and predictions developed in laboratory experiments.

6B.1.3 EUV collector optics

EUV GI collector modules are designed to transmit in-band EUV light (at $13.5 \text{ nm} \pm 1\%$) from the source to the rest of the optical train through the IF aperture with a certain photon pattern at the IF, and a well-defined pattern stability in the far field (FF). Thus, the source-to-collector module is physically separated from the

illuminator and projection mirrors by the small IF aperture, so the working environments are very different from a debris, contamination, and vacuum point of view.

6B.1.3.1 Collector materials

To use the radiation at 13.5 nm, the optical train of an EUVL tool is made of reflective optics (mirrors), as opposed to the refractive optics used in DUV lithography⁴. EUV radiation is primarily absorbed by solid surfaces unless photons impinge on the surface at grazing angles (below the critical angle) or multilayer mirrors (MLMs) are used to efficiently reflect the incoming radiation.^{4,5}

Grazing-incidence mirrors rely on the “total external reflection,” which occurs at grazing angles below the critical angle⁴. The reflectance of an optical coating on a GI mirror for EUV radiation is determined by the optical constants of the coating materials.⁵ The optical constants of mixtures are approximately equal to the sum of the optical constants of composing elements of the mixture weighted with their atom density; chemical effects can usually be neglected. Therefore, it is desirable to have as many “good reflecting” species and as few debris atoms (Sn, contaminant atoms such as oxygen and carbon, or other metallic debris elements) as possible at the reflecting surface of the mirror. Good reflecting species for 13.5-nm EUV radiation are molybdenum (Mo), ruthenium (Ru), zirconium (Zr), rhodium (Rh), palladium (Pd), and niobium (Nb). The theoretical reflectivities (at 13.5 nm) of thin films made of these materials are shown in Fig. 6B.2 (using optical constants given in Ref. 6) as a function of the GI angle. For some of these materials, the usable angular range for efficient reflection extends up to 15 to 25 deg, allowing the design of compact mirrors with very high collection efficiency.

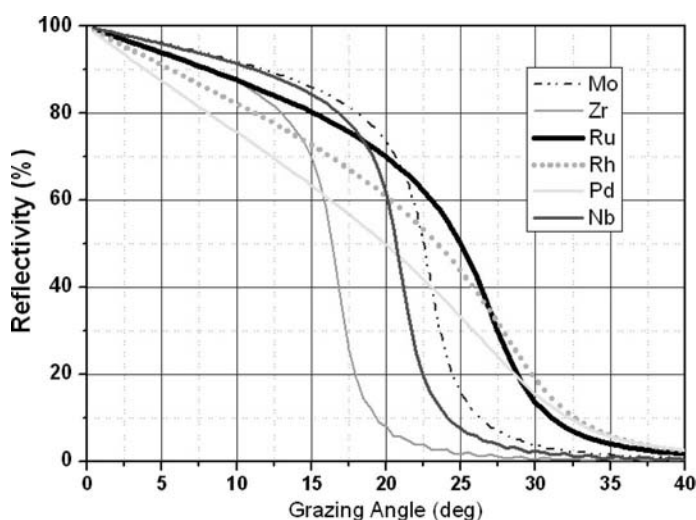


Figure 6B.2 Calculated reflectivity of selected thin films materials at $\lambda = 13.5$ nm (200 nm thickness, 0.3 nm random roughness rms) as a function of GI angle.

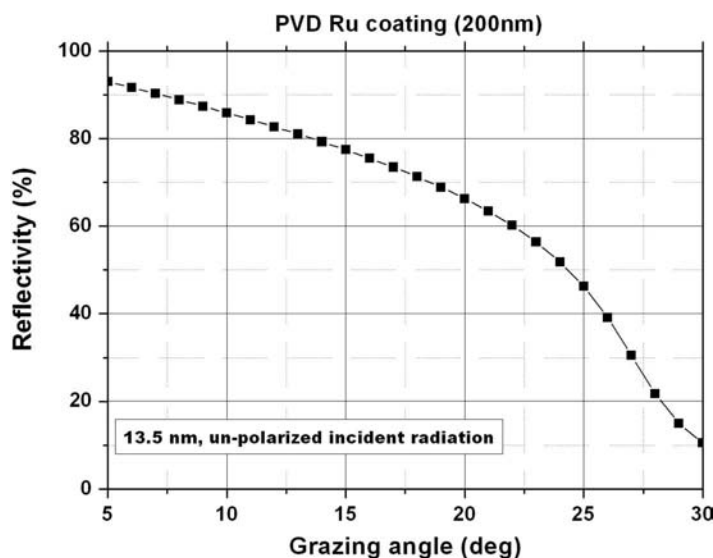


Figure 6B.3 Reflectivity of PVD Ru industrial coatings as measured by synchrotron reflectometer. (Reprinted from Ref. 7.)

Reflectivity degradation is due primarily to surface contamination and oxidation, lack of packing density, surface composition changes, and surface roughening. Physical vapor deposition (PVD) technology is used to obtain uniform coatings of these materials with high reflectivity on a wide range of mirror shapes. Ru-reflecting layers (Fig. 6B.3) characterized by high density (about 12 g/cm^3) and low roughness (0.5 to 1.0 nm RMS) are industrially deposited onto electroformed mirror shells. These coatings are currently used in GI mirror technology in the prototype EUVL tools.

6B.1.3.2 Collector design and performance

A collector mirror module is normally a GI Wolter I⁸ or elliptical telescope (or a combination) consisting of many coated, nested mirrors, perfectly aligned and integrated in a mechanically stiff structure (Fig. 6B.4). Each shell in a Wolter-type mirror consists of a truncated ellipsoid and an associated truncated hyperboloid, which are replicated together from a high-accuracy mandrel in one piece to facilitate alignment and integration.⁹ The manufacturing process for nested GI mirrors is based on electroforming,^{9–11} by which each mirror is replicated from a negative master (the mandrel). The separation process produces optics with similar figure and roughness to that of the high-accuracy mandrel. The optical specifications of the collector, in terms of numerical aperture (NA) and étendue, must match the input optical requirements for the illuminator: the collector is designed to maximize the efficiency (i.e., the ratio between the in-band power at the IF and the total in-band power radiated by the source in $2\pi \text{ sr}$) while matching the illuminator optical

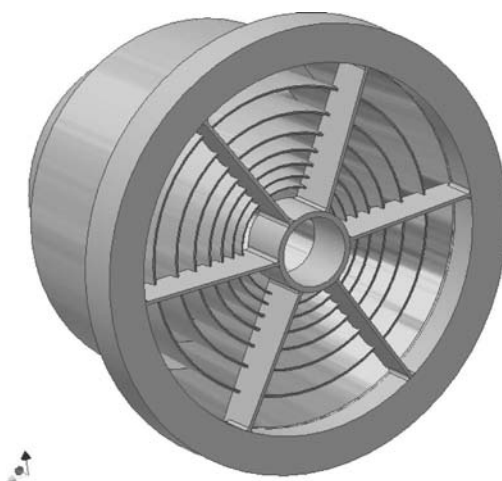


Figure 6B.4 Schematic model of a GI collector module made of many Wolter-type nested shells.

specifications on one side and withstanding the thermal load and debris impact from the source on the other side.

Under operating conditions, collector optics for EUVL tools are expected to be exposed to several kilowatts of radiated power in the EUV and vacuum ultraviolet (VUV) spectral regions. To withstand such high thermal loads while maintaining the stable optical performance required by the lithography tools, the collector module must be equipped with an integrated cooling system that is the result of complex analyses, simulations, and design tradeoffs (Fig. 6B.5). These analyses require accurate knowledge of the spectral distribution of the radiation from the EUV source and of the opto-mechanical features of the debris migration tool, which absorbs part of the energy and re-radiates in the infrared (IR) due to its high temperature. The final mirror design is the result of an iterative process: finite element analysis (FEA) of the transient and steady-state deformations induced by the thermal load for a given set of cooling layout, shell thicknesses and materials is used to evaluate the optical performance at the IF and FF by means of Monte Carlo ray tracing until convergence is reached.

The final cooling layout design takes into account the optical performance variations that result from the elastic deformations induced by the highly variable thermal load of the source and debris mitigation tool.

Temperature fields and slope errors are calculated for different mirror shell thicknesses (Fig. 6B.6) to guarantee the maximum collection efficiency of the mirror.

The FF photon distribution is also iteratively computed to evaluate the FF stability of the pattern at different power loads (Fig. 6B.7). At the end of the iterative process, the full thermo-opto-mechanical design of the collector is produced, including obscurations due to cooling lines, spider spokes, and mechanical fixturing.

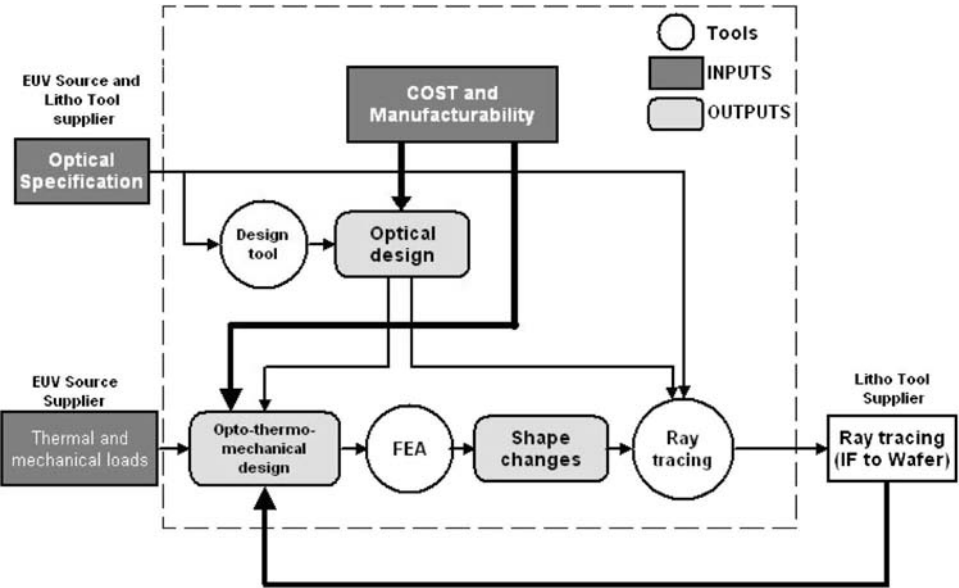


Figure 6B.5 Block diagram illustrating the complex iterative process of analyses, simulations, and design tradeoffs to obtain the final thermo-opto-mechanical design of a collector for EUV lithography tools. (Reprinted from Ref. 12.)

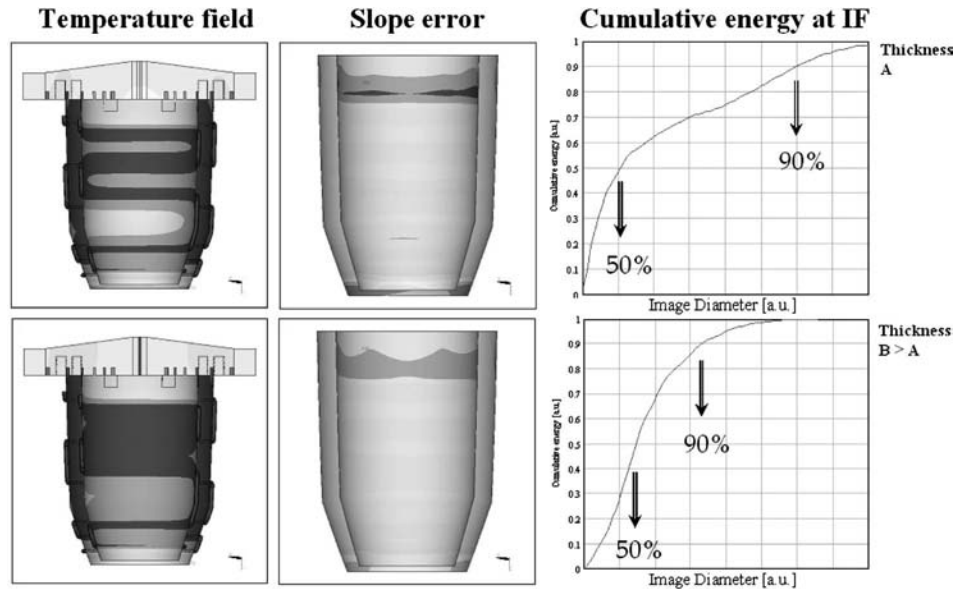


Figure 6B.6 Temperature field, slope error distribution, and cumulative energy on the focal plane (at the IF) for the point source of a two-mirror nested Wolter I collector for two different mirror thickness values (lower for upper plots). Peak temperature and slope error occur at the entrance edge (smaller diameter, closest to the source) of the collector. Cumulative energy diameters of 50% and 90% are indicated. (Reprinted from Ref. 13.)

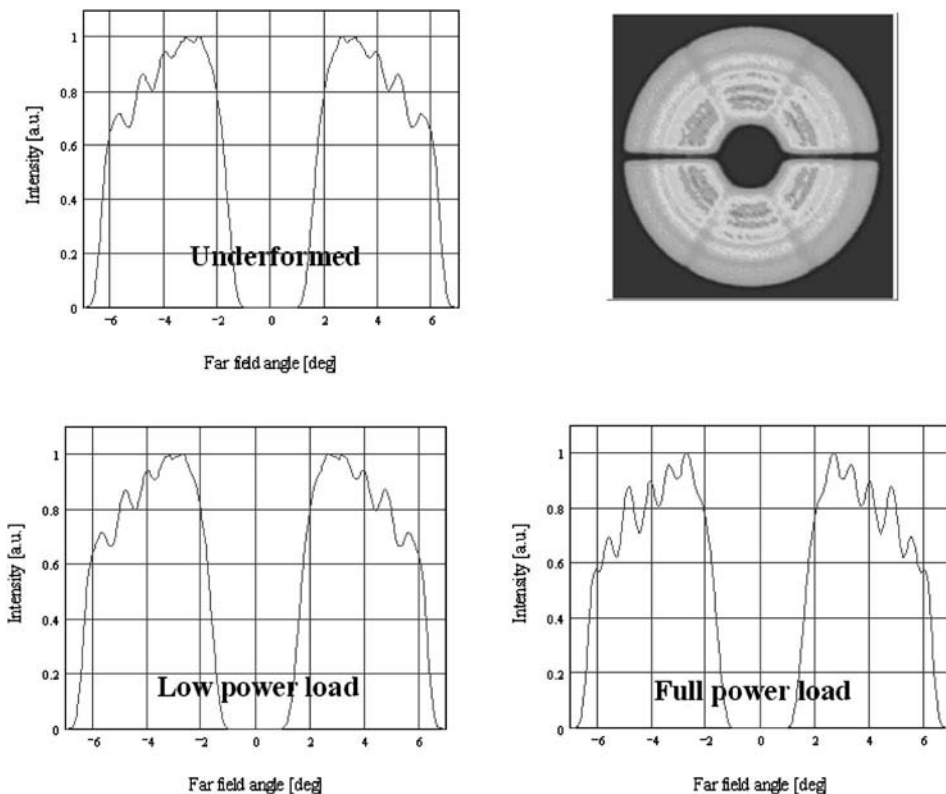


Figure 6B.7 Calculated FF patterns of a multishell collector at different thermal loads. (Reprinted from Ref. 14.)

To assess the thermal and mechanical design and validate the thermal, structural, and optical models used to predict collector performance, Media Lario Technologies teamed with source and litho-tool suppliers to test several engineering GI collectors in near-operational conditions.^{15–18} The tests achieved good agreement with the model predictions, allowing the EUVL industry to assess the thermal and mechanical designs and to validate the scaling of the cooling system to alpha level EUVL scanner thermal loads.

Further efforts are necessary for HVM tools designed to work at high throughput (100 wafers per hour). In fact, assuming 300-mm diameter wafer size and no revolutionary changes in illuminator and projection performance with respect to the alpha tools, and a resist sensitivity of 10 mJ/cm², the necessary in-band power at IF is estimated to be 180 W.^{19,20} That is almost one order of magnitude higher than that of an alpha tool. Such a high level of EUV power at IF can be obtained only by using the most advanced source, debris suppression, and collector mirror technologies.

From the optical point of view, the conservation of system étendue, defined primarily by objective and field size on the wafer, defines the optical design and performance of the source-collector module. In order to maximize the in-band

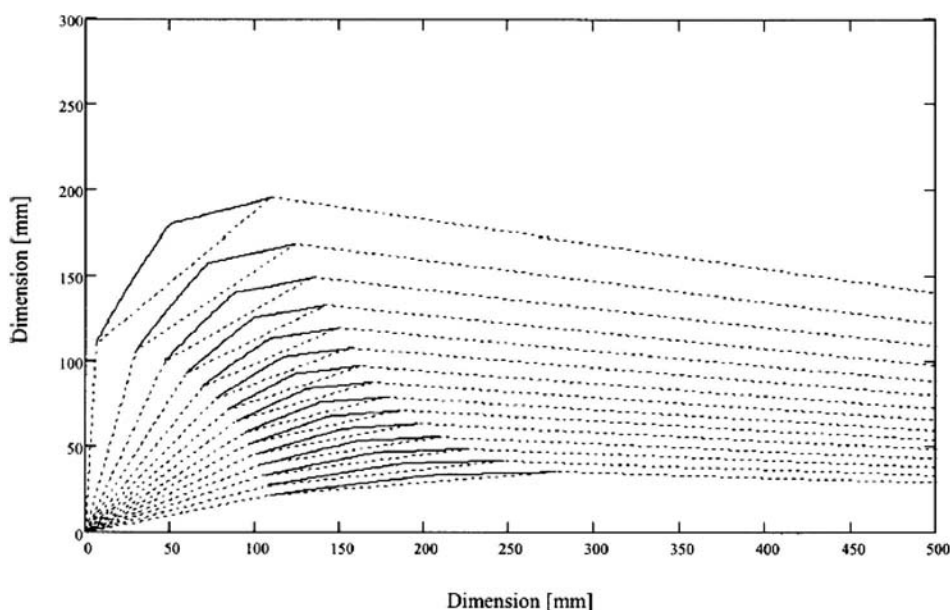


Figure 6B.8 High-efficiency design of non-Wolter collector whose calculated efficiency is 50%. (Reprinted from Ref. 21 with permission from the Optical Society of America.)

power transmitted from source to wafer in a HVM tool, an open collaboration must exist among the engineering teams that design the optics building blocks of the EUVL system: a joint effort between the source, debris suppression and collector manufacturers on one side and illuminator optics suppliers on the other side is needed.

Recently, high-efficiency double-reflection collector designs have been proposed in which the two reflections take place at the same grazing angle thus enhancing the reflectivity.^{21,22} These designs are not of Wolter type and are characterized by higher calculated efficiencies (up to 50% on ideal conditions). An example is shown in Fig. 6B.8.

6B.2 Collector Lifetime Status and Challenges

6B.2.1 Mechanism of reflectivity degradation

A complex strategy is required to guarantee long-lasting collector optics with a given source and debris mitigation system. Power requirements for the EUV source have increased considerably over the past few years and will increase steadily in the coming years. Therefore, debris mitigation will also become a bigger challenge. Improving the collector optics lifetime is one of the main challenges of EUVL to ensure its implementation in HVM. Various kinds of debris are generated by the source, such as fuel particles in the thermal to high energy [Xe, Sn, lithium (Li)

ions, neutrals] ranges, eroded electrode (and other) materials from the source itself, and electrons and photons from the EUV to IR.

Different debris reduction concepts must be investigated for the different combinations of source technology (DPP or LPP) and for the different fuels (Xe, Sn), then reliably implemented in source-collector technology. Furthermore, methods must be studied to minimize the intrinsic debris generation by each specific source, while increasing the radiated in-band EUV power. Ultimately, a combination of source parameters and debris mitigation schemes will form the most effective debris mitigation concept.

As stated above, DPP Sn sources based on the renewable electrode concept are the leading candidates for HVM prototype tools. As reported in Refs. 23–25, this kind of Sn source emits essentially two types of massive debris: Sn microparticles and Sn thermal atoms as well as fast ions. By adopting an efficient debris mitigation system, the Sn microparticles are essentially eliminated; but fast atoms and thermal Sn atoms can still pass through the debris mitigation system to interact with the collector optics and degrade optical performance. By varying the debris mitigator parameters, the interaction of Sn atoms with the Ru collector surface can be driven from net Ru erosion to net Sn deposition onto collector surfaces, as shown in Fig. 6B.9.²⁴

Figure 6B.9 shows that under certain operating conditions the erosion of the Ru reflective material can be on the order of several nm/100 Mshots. A typical Sn deposition rate is of order of 1 nm/100 Mshot.

While the interaction of Xe with various EUV reflecting layers has been studied by several authors,²⁶ the oblique-incidence interaction of Sn atoms with EUV reflective surface materials has not been yet studied in detail; a first computational assessment will be given in the following section. It is clear that experimental validation must be done as soon as possible using existing EUV Sn sources and test stand tools.

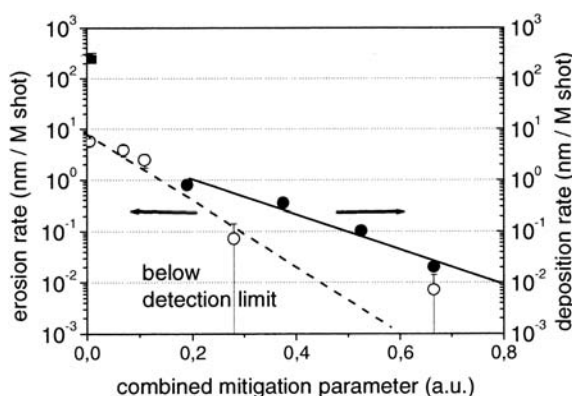


Figure 6B.9 Erosion rates (hollow circles) and deposition rate (solid circles) measured with Ru witness samples (10-deg GI at 15 cm from the plasma). The solid square in the upper left corner represents the situation without any mitigation. (Reprinted from Ref. 24.)

6B.2.2 Erosion and deposition: a binary collision approximation study of Sn interaction with Ru surfaces

This section summarizes the results of computational studies of the interaction of Sn particles with the Ru surface at different grazing incidence angles (5 to 20 deg) and at different Sn particle energies (thermal, 0.5 keV, 5.0 keV, 15 keV, and 30 keV).

The interactions of Sn particles with Ru can be evaluated initially by using Monte Carlo codes that simulate the dynamic thickness and/or composition changes of multicomponent targets during high-dose ion irradiation or ion-beam-assisted deposition. These codes, which are based on TRIM.SP²⁷ using the binary collision approximation (BCA) model for ballistic transport, are applied mainly to the fields of high-fluence ion implantation, ion beam synthesis, sputtering and ion mixing of polyatomic solids, ion-beam- or plasma-assisted deposition of thin films, and ion-beam or plasma-assisted etching.

One of these codes, TRIDYN,^{28–32} allows users to calculate the depth profiles of all atomic species in the target as a function of the incident fluence. Additionally, sputtering yields, total area densities (atoms/cm²), surface concentrations, and re-emitted amounts are calculated as a function of fluence, as well as the surface erosion (when sputtering prevails) or the deposited layer thickness (in the deposition regime). Ballistic effects such as projectile deposition and reflection, sputtering, and ion mixing are computed for a target at zero-temperature. Radiation damage is not considered. The target and the deposited layers are assumed to be amorphous, and surface roughness is not included in the calculation.

With the above-mentioned features, TRIDYN and TRIM.SP have been used to assess the main features of the Sn-Ru interaction. More specifically, the outputs of these calculations are:

- Calculated erosion rate of Ru as a function of incidence angle and Sn energy;
- Net deposition rates of Sn under Sn self-sputtering at different angles for some example cases of ion spectra;
- Sn self-sputtering rate evaluation as a function of incidence angle and energy;
- Surface depth profiles of $\text{Sn}_x\text{Ru}_{(1-x)}$ generated at different angles and different ion spectra;
- Angular azimuthal and polar distributions of sputtered Ru atoms;
- Angular azimuthal and polar distributions of Sn particles reflected from the Ru surface.

Finally, the impact on reflectivity of $\text{Sn}_x\text{Ru}_{(1-x)}$ /Ru layers during Sn bombardment is calculated.

The model assumed for the calculations is shown in Fig. 6B.10. A Sn spectrum consisting of Sn atoms with four different energies—500 eV, 5.0 keV, 15 keV (or 30 keV) and thermal Sn (below sputtering threshold)—and variable intensity are assumed.

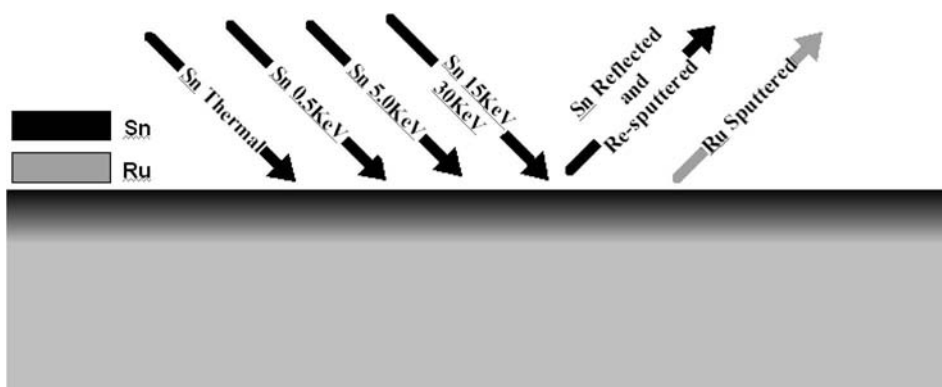


Figure 6B.10 Schematic model showing the interaction of Sn particles with the Ru surface.

The X1-X2-X3-X4 terminology is used in this section to indicate a Sn flux made of X1% thermal Sn, X2% 0.5 keV Sn, X3% 5.0 keV, X4% 15.0 keV or 30.0 keV bombarding the solid surface at a given angle at the same time.

The interaction of all the different particles among themselves and with Ru is computed based on the proper choice of interaction potentials and binding energies.

Reflected and sputtered particles' azimuthal (ϕ) and polar (β) distribution are computed by Monte Carlo code TRIM.SP for different incidence angles (α) and energies (E_0), as shown in Fig. 6B.11.

This study shows that the global calculated sputtering rate of Ru (when Ru erosion is the dominant effect) varies from 0.6 to about 9 particles/ion in the angular range 5 to 15 deg, and particle energy from 0.5 to 30 keV. For the same Sn spectrum, the calculated sputtering rate varies by a factor of 3 to about 6 as a function of the grazing angle in the range 5 to 15 deg. It is an increasing function of the incidence angle; i.e., at 15 deg it is systematically higher than at 5 deg so that, if Sn polar and azimuthal emissions from the source and debris mitigator are assumed isotropic, mirror shells with incidence angles from 15 to 20 deg will be subject to more erosion by Sn energetic particles than the innermost shells (characterized by smaller incidence angles—see Fig. 6B.8) at the investigated energies.

It is demonstrated that Sn particles are reflected from the Ru surface at almost specular angle. Depending on the Sn energy, the reflection coefficient varies from 40% to 99%, and is highest for the lowest energies (Tables 6B.1 to 6B.4). This reflection of fast particles may also cause erosion in the innermost regions of the mirror, in particular on the second (elliptical) part of the collector. This erosion cannot be neglected in most cases, especially for particles of high keV energy whose reflection approaches 99%. The erosion depends on the ion spectrum and on how much Sn thermal vapor arrives on the exposed surfaces. The gas thermalization of the energetic particles plays a fundamental role in defining the net debris flux on the innermost regions of the collector: this will depend critically on the gas working pressure of the debris suppression system. The scenario during source operation is represented schematically in Fig. 6B.12.

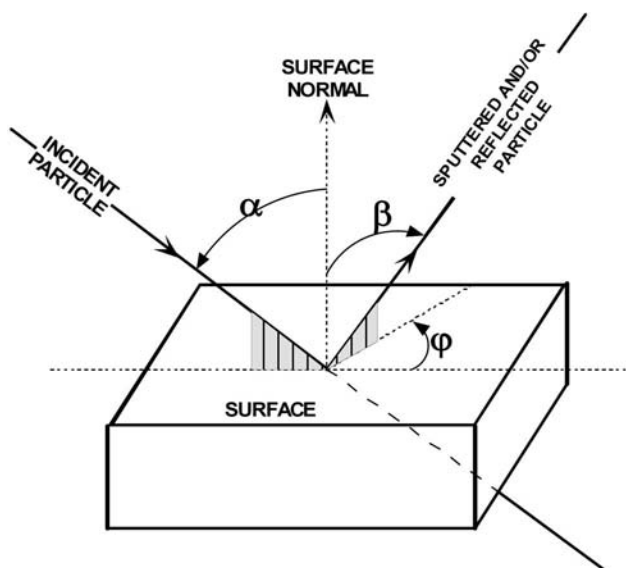


Figure 6B.11 Definition of azimuthal (ϕ), polar (β), and incidence (α) angles used in the calculations.

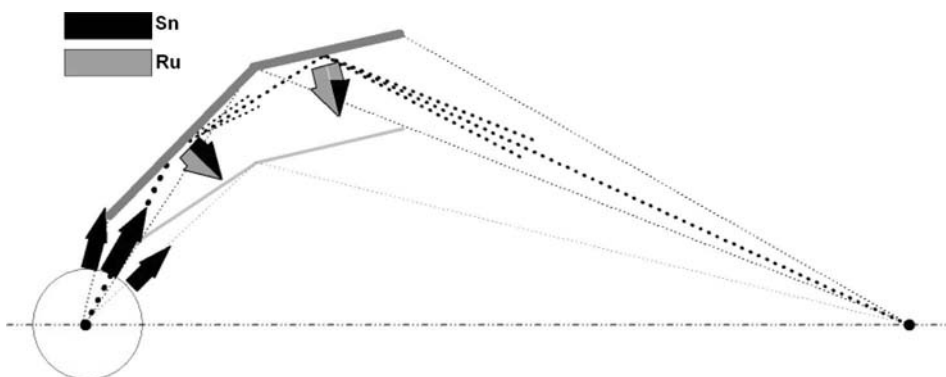


Figure 6B.12 Schematic drawing of a two-reflection Ru mirror subject to Sn particle bombardment.

Ru erosion is always accompanied by Sn self-sputtering. Therefore, the material (i.e., Ru and Sn) eroded from the reflecting surface deposits onto the outer surface of the facing internal shell.

Tables 6B.1 to 6B.4 show several cases relative to X1-X2-X3-X4 (15 keV) where the sputtering rate of Ru, the re-sputtering rate of Sn, and the reflection coefficient (R_N) of Sn are quantified. Similar results are obtained by increasing the maximum energy from 15 to 30 keV. However, these data are not reported here and will be treated in more detail in future publications.

Sputtered Ru atoms are predominantly ejected from the surface at polar angles β from about 0 to 45 deg from surface normal. At 0.5 keV, the maximum proba-

Table 6B.1 Sn reflection coefficients (R_N), Sn re-sputtered doses, and Ru global sputtering doses for different incidence angles from normal (0, 75, 80, and 85 deg) and different Sn energies. Sn total fluence: 5×10^{16} at/cm², population 40-20-20-20.

Element	Sn total fluence: 5×10^{16} at/cm ² ; Sn thermal (40%), 500 eV (20%), 5 keV (20%), 15 keV (20%)							
	0 deg		75 deg		80 deg		85 deg	
	R_N	Sputtered dose (10^{16} at/cm ²)	R_N	Sputtered dose (10^{16} at/cm ²)	R_N	Sputtered dose (10^{16} at/cm ²)	R_N	Sputtered dose (10^{16} at/cm ²)
Sn (thermal)		1.79		1.96		1.93		1.86
Sn (500 eV)	0.015	0.81	0.795	0.19	0.923	0.07	0.99	0.09
Sn (5 keV)	0.012	0.65	0.525	0.44	0.717	0.26	0.952	0.04
Sn (15 keV)	0.011	0.49	0.421	0.52	0.571	0.38	0.824	0.13
Ruthenium		6.40		20.37		16.39		6.98

Table 6B.2 Sn reflection coefficients (R_N), Sn re-sputtered doses, and Ru global sputtering doses for different incidence angles from normal (0, 75, 80, and 85 deg) and different Sn energies. Sn total fluence: 5×10^{16} at/cm², population 70-10-10-10.

Element	Sn total fluence: 5×10^{16} at/cm ² ; Sn thermal (70%), 500 eV (10%), 5 keV (10%), 15 keV (10%)							
	0 deg		75 deg		80 deg		85 deg	
	R_N	Sputtered dose (10^{16} at/cm ²)	R_N	Sputtered dose (10^{16} at/cm ²)	R_N	Sputtered dose (10^{16} at/cm ²)	R_N	Sputtered dose (10^{16} at/cm ²)
Sn (thermal)		2.50		3.29		3.23		2.90
Sn (500 eV)	0.015	0.29	0.773	0.10	0.909	0.04	0.986	0.05
Sn (5 keV)	0.015	0.17	0.510	0.20	0.694	0.12	0.928	0.02
Sn (15 keV)	0.01	0.10	0.419	0.23	0.558	0.16	0.791	0.05
Ruthenium		2.3		9.10		7.17		2.76

Table 6B.3 Sn reflection coefficients (R_N), Sn re-sputtered doses, and Ru global sputtering doses for different incidence angles from normal (0, 75, 80, and 85 deg) and different Sn energies. Sn total fluence: 15×10^{16} at/cm², population 85-5-5-5.

Element	Sn total fluence: 15×10^{16} at/cm ² ; Sn thermal (85%), 500 eV (5%), 5 keV (5%), 15 keV (5%)							
	0 deg		75 deg		80 deg		85 deg	
	R_N	Sputtered dose (10^{16} at/cm ²)	R_N	Sputtered dose (10^{16} at/cm ²)	R_N	Sputtered dose (10^{16} at/cm ²)	R_N	Sputtered dose (10^{16} at/cm ²)
Sn (thermal)		7.94		12.01		11.76		9.93
Sn (500 eV)	0.020	0.31	0.735	0.18	0.874	0.09	0.97	0.016
Sn (5 keV)	0.020	0.17	0.496	0.32	0.655	0.23	0.89	0.044
Sn (15 keV)	0.014	0.09	0.41	0.35	0.545	0.26	0.76	0.07
Ruthenium		1.12		8.83		6.65		1.49

Table 6B.4 Sn reflection coefficients (R_N), Sn re-sputtered doses, and Ru global sputtering doses for different incidence angles from normal (0, 75, 80, and 85 deg) and different Sn energies. Sn total fluence: 15×10^{16} at/cm², population 97-1-1-1.

Element	Sn total fluence: 15×10^{16} at/cm ² ; Sn thermal. (97%), 500 eV (1%), 5 keV (1%), 15 keV (1%)							
	0 deg		75 deg		80 deg		85 deg	
	R_N	Sputtered dose (10^{16} at/cm ²)	R_N	Sputtered dose (10^{16} at/cm ²)	R_N	Sputtered dose (10^{16} at/cm ²)	R_N	Sputtered dose (10^{16} at/cm ²)
Sn (thermal)		1.98		5.12		4.40		2.56
Sn (500 eV)	0.023	0.003	0.669	0.01	0.821	0.005	0.961	–
Sn (5 keV)	0.023	0.001	0.465	0.006	0.625	0.003	0.872	–
Sn (15 keV)	0.016	–	0.414	0.004	0.547	0.002	0.746	–
Ruthenium		0.03		0.13		0.09		0.04

bility of ejection is about 45 deg from normal, while for Sn particles of 5 keV the ejection maximum is around the surface normal. This can be seen in Figs. 6B.13 and 6B.14, where the azimuthal and polar distributions of reflected Sn and sputtered Ru atoms are reported for the incidence angles $\alpha = 70$ and 75 deg. Quite similar results apply to the case $\alpha = 80$ and $\alpha = 85$ deg.

For the same spectrum of impinging Sn particles, net Sn deposition or Ru net erosion can take place at different angles. This statement is proved by the data in the example of Figs. 6B.15 and 6B.16, where Sn surface accumulation is computed as a function of the incoming energetic particle fluence for different angles and energies. When the Sn surface dose is constant, a surface equilibrium composition is reached, and Ru erosion takes place. This is relevant to the final operating conditions of the collector under Sn bombardment. For certain operating conditions on some shell regions (i.e., at certain incidence angles), Ru erosion may be the predominant effect, while on other shells (or other shell regions), Sn deposition will take place. This has important implications for the way the debris mitigation system and source are operated.

The Sn deposition rate depends on the incidence angle as well as the energy spectrum of Sn. Sn is also self-sputtered from the surface by energetic Sn particles. This simply means that, when Sn net deposition occurs, the Sn coating grows at different rates in different positions. The reflectivity of the EUV layer is strongly affected by the growth of a few Sn monolayers, so the collector performance is strongly affected by this nonhomogeneous Sn growth and may have a big impact on collection efficiency and FF pattern stability. As a matter of fact, if the obscuration of the Ru reflecting layer happens in a nonhomogeneous way, then the FF photon pattern will evolve with time as well. The accepted rule by which the collector cleaning procedure is used whenever the collection efficiency drops 10% below the initial value may not apply if the FF pattern is not stable due to nonuniform Sn deposition. We cannot exclude, for example, that the FF variations potentially induced by thermal deformations that are produced by the heat load will be of the same (or lower) intensity than those induced by the nonhomogeneous Sn

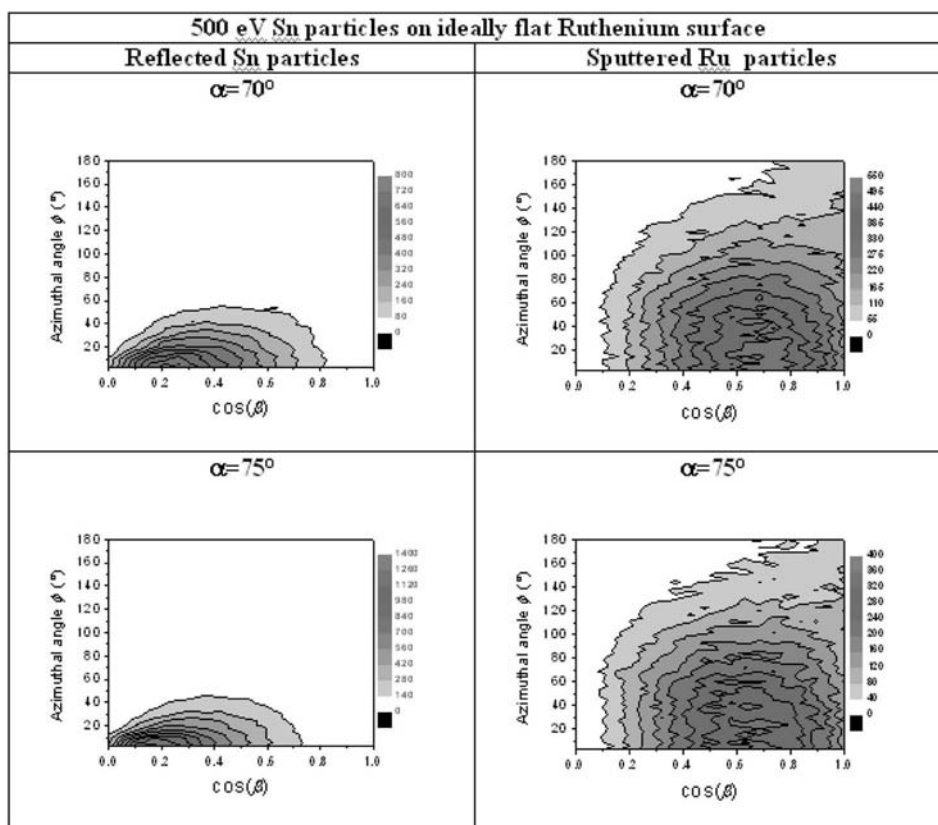


Figure 6B.13 Azimuthal and polar distributions of reflected Sn and sputtered Ru at $\alpha = 70$ and 75 deg, with Sn energy $E_0 = 500$ eV.

deposition. This must be assessed by additional modeling and experiments. Furthermore, Sn deposition occurs cumulatively at lower thermal loads (i.e., lower repetition frequency, lower IF power), which creates the potential problem of a collector with no thermal deformations while giving an out-of-specification performance at the FF as a function of exposure time (i.e., number of pulses).

When Ru erosion takes place as the predominant effect, we quantify the formation of an equilibrium profile at the Ru surface made of the $\text{Sn}_x\text{Ru}_{(1-x)}$ compound whose exact composition depends on the incidence angle and Sn ion spectrum. The same Sn spectrum could display Ru erosion that not only differs from place to place, but also impacts the surface composition in a different way: some Ru erosion conditions preserve the EUV layer initial reflectivity quite well, while others (still dominated by Ru erosion) adversely impact the reflectivity. So the debris mitigation system operating parameters must be chosen appropriately. This is demonstrated by Fig. 6B.17, where surface profiles are computed for two interaction models characterized by Ru net erosion at all angles, and the corresponding

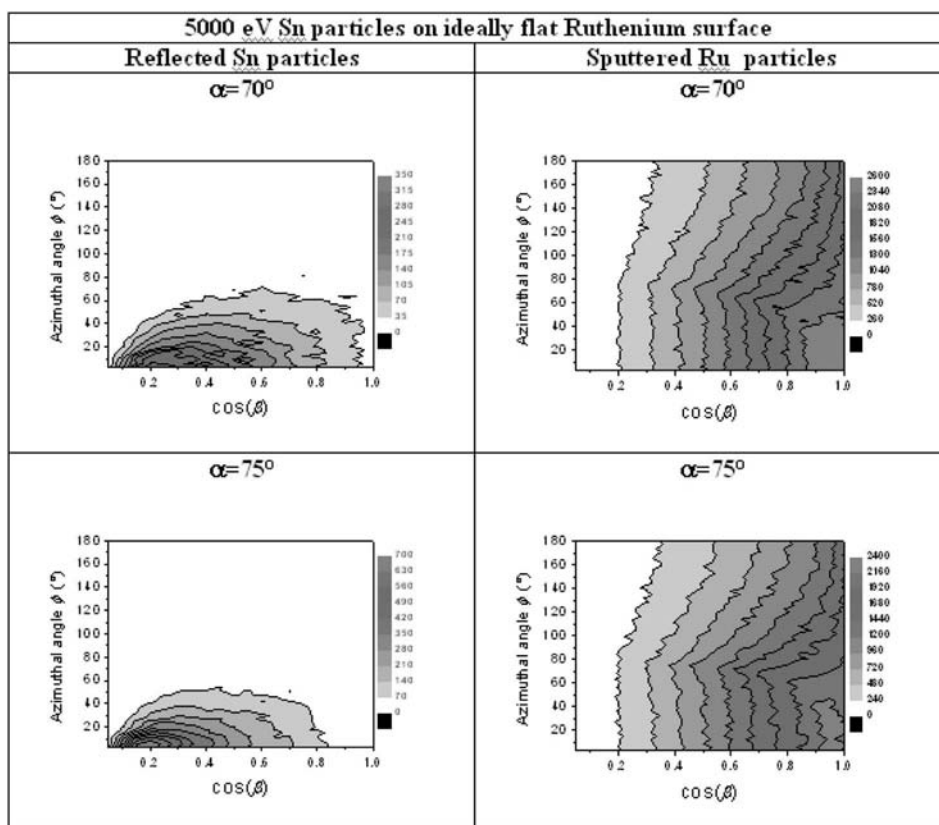


Figure 6B.14 Azimuthal and polar distributions of reflected Sn and sputtered Ru at $\alpha = 70$ and 75 deg, with Sn energy $E_0 = 5000$ eV.

reflectivity curves are calculated by taking into account both the stoichiometry and surface layer density.

Very similar results are obtained by increasing the maximum Sn energy from 15 keV to 30 keV.

This study conceptually demonstrates that the collection efficiency and FF pattern stability of the collector can be strongly affected by the debris mitigation working parameters, and suggests the use of a set of suppression parameters to reach the steady-state erosion mode, which is characterized by low impact on the Ru reflectivity. This will, of course, require the use of much thicker reflective layers to endure the particle erosion and guarantee the required lifetime required for HVM tools.

Experimental data are urgently needed to validate the calculations in the field and to learn more about this complex subject. Nevertheless, these data may serve as a guideline to define the collector lifetime concepts in future experiments among collector, source, debris mitigator, and lithography tool teams.

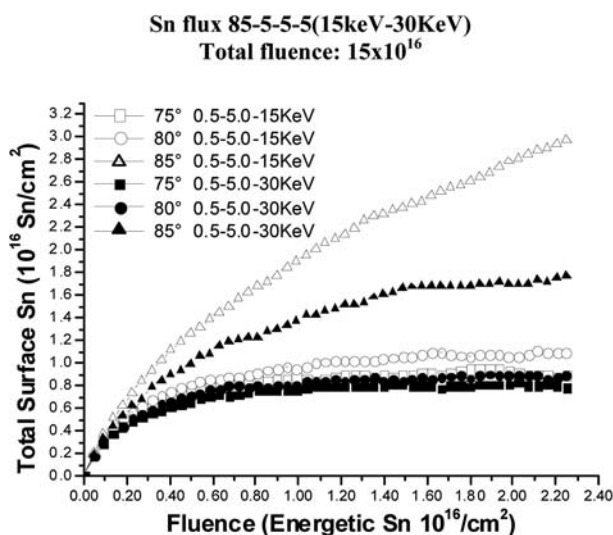


Figure 6B.15 Total Sn surface dose as a function of impinging Sn fluence at different incidence angles. Only Sn particles with energy above the sputtering threshold are considered in the bombarding fluence. The surface equilibrium is reached at about 0.7×10^{16} ions/cm² for 75 and 80 deg where Ru erosion is the predominant effect. At 85 deg, the mechanism goes from Sn deposition to Ru erosion by increasing the maximum energy of Sn flux from 15 keV to 30 keV.

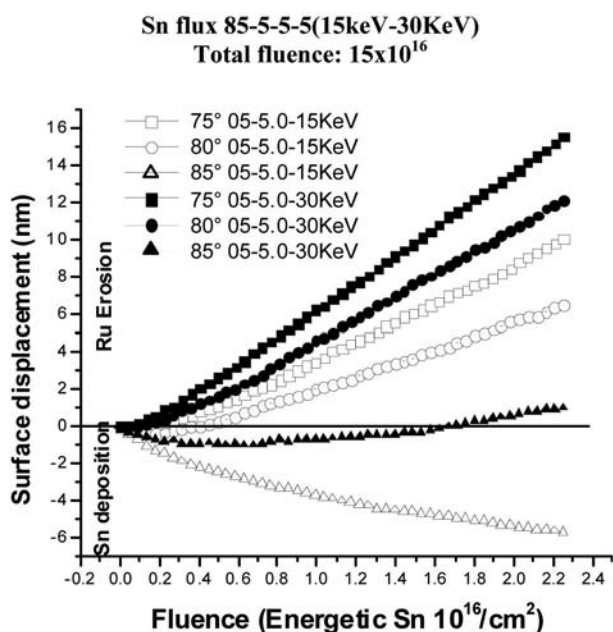


Figure 6B.16 Surface displacement versus energetic particle fluence for the computational model in Fig. 6B.15. Positive displacement means Ru erosion, while negative displacement means Sn deposition.

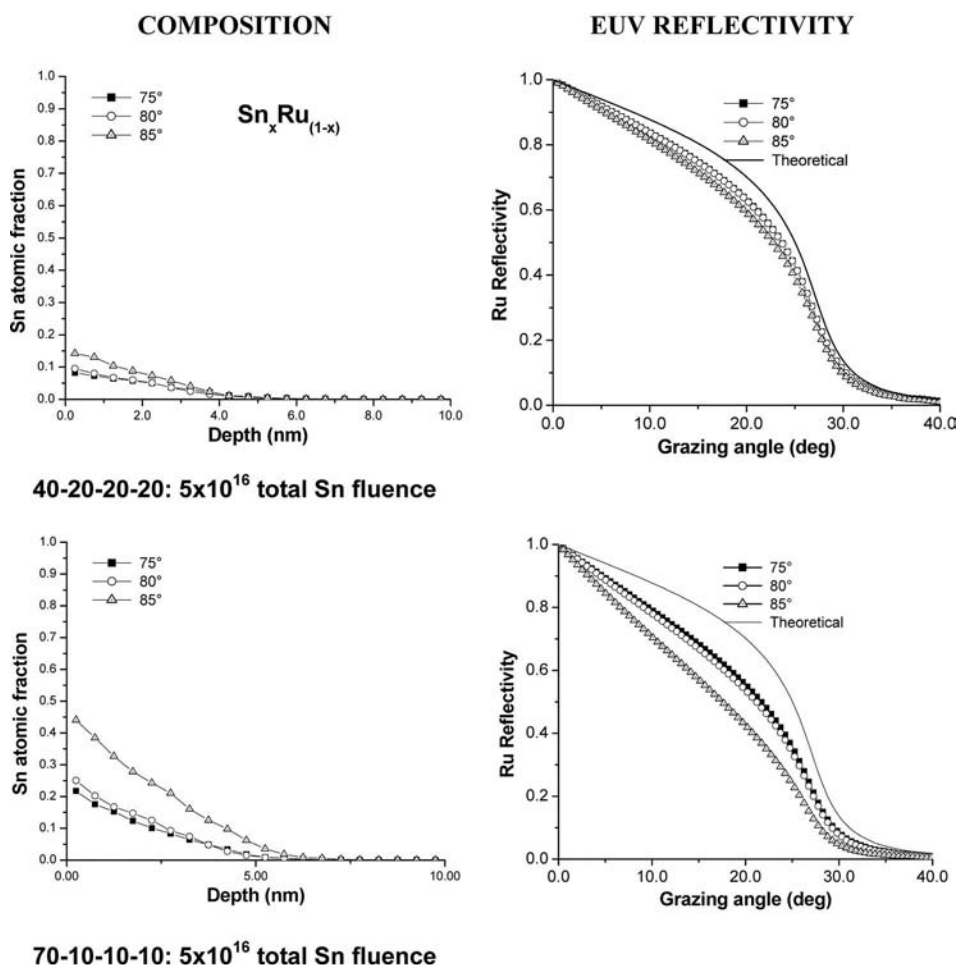


Figure 6B.17 Surface composition versus reflectivity (at 13.5 nm) for two different $X_1-X_2-X_3-X_4$ (15 keV) models. Both models are characterized by net Ru erosion for all incidence angles. The equilibrium surface composition affects the steady state reflectivity of the coating.

6B.2.3 Sn chemical removal

While it is necessary to obtain enough EUV power, the use of Sn as fuel for the EUV source adds additional complexity to the protection of the collector optics. As explained in Sec. 6B.2.2, Sn can deposit on the collector optics and reduce the EUV reflectivity. As reported in Refs. 24 and 33, a double strategy solves this issue by reducing the Sn emission from the source and applying efficient debris mitigation to minimize the amount of Sn reaching the collector. By operating the source and debris mitigation system in such a way that Sn deposits on the collector, the accumulated amounts must be cleaned after a certain time—say, when the reflectivity drops by 10%, which is the collector lifetime criterium, or whenever the FF pattern profile becomes unacceptable. The cleaning is currently done by chemical

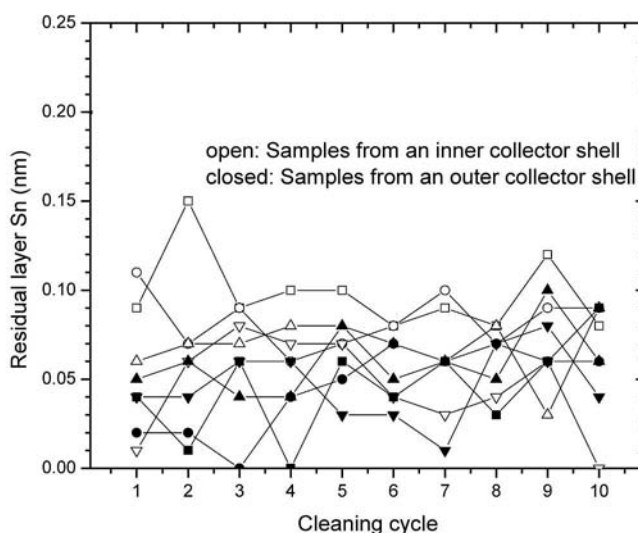


Figure 6B.18 Sn residues after repeated vapor deposition (1 nm Sn)/cleaning cycles on collector samples with no accumulation of Sn residuals. (Reprinted from Ref. 33.)

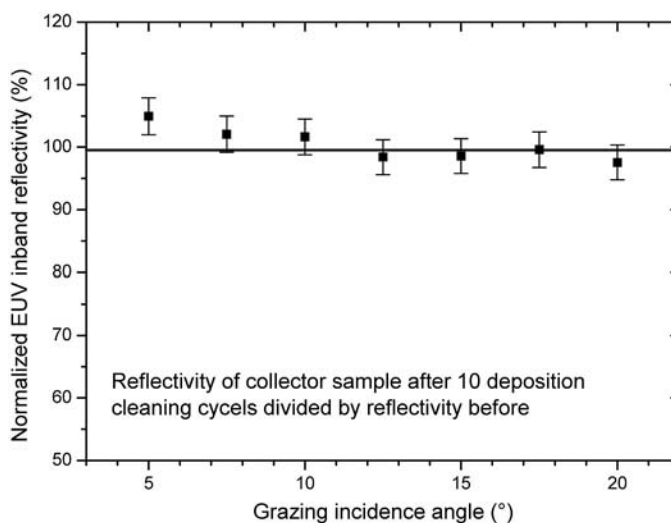


Figure 6B.19 EUV reflectivity for a collector sample after 10 repeated deposition/cleaning cycles divided by the reflectivity of a virgin sample. (Reprinted from Ref. 33.)

reaction of Sn to Sn halides, which are volatile and can be pumped away.³³ It has been reported that after Sn contamination, it is possible to efficiently remove the Sn many times (Fig. 6B.18) and the Ru layer reflectivity will be maintained, as shown in Fig. 6B.19.

Because no irreversible degradation of the samples was observed after repeated deposition/cleaning cycles, the researchers concluded that significantly more than 10 cleaning cycles are possible. If the number of shots between cleaning can be

made on the order of 10^9 or higher (which seems the case as reported in Ref. 33 for certain source/debris suppression parameters), the collector lifetime, deduced by combining debris mitigation and Sn cleaning, will already be much more than 10 Gshots. In order to withstand these highly proprietary cleaning treatments, the entire collector module must be made compatible with the required temperatures and chemicals.

6B.3 Summary

Sn DPP sources, in association with high-transmission grazing angle collectors and high performance debris mitigation systems, are the leading candidates to deliver the necessary amount of EUV in-band power at IF for HVM tools.

Methods must be studied to reduce the intrinsic debris generated by the specific source. A combination of source parameters with lower debris mitigation schemes will ultimately form the most effective debris mitigation concept.

The GI collector is designed to maximize the efficiency and the stability while matching the optical specifications of the illuminator on one side, and withstanding the thermal load and debris impact from the source and debris mitigator on the other. The lifetime of the GI collector depends on the debris mitigation and source parameters.

The impact of Sn debris on collector lifetime and optical performance has been analyzed theoretically in regard to Sn erosion/deposition physical mechanisms. This conceptual study must be validated in the field through experiments carried out using the few existing high-power Sn sources and associated test stands. A lifetime on the order of 10^{11} shots can be achieved for DPP Sn sources, based on rotating electrodes in a liquid Sn bath, using collector materials that are compatible with chemical Sn cleaning and with thick reflective coatings (which endure Ru erosion) while still preserving the reflectivity. A careful choice of debris suppression parameters will extend the collector lifetime and guarantee IF and FF stability of the optical performance.

Acknowledgments

The author acknowledges the entire Media Lario Technologies team and its contributions to the design, building, and performance testing of the GI collectors. Special acknowledgments are also extended to the Philips Extreme UV (Aachen) team, the ASML (Veldhoven) SoCoMo team, and the team at Xtreme Technologies (Gottingen) and NIKON for providing feedback and valuable data for the continuous improvement of collector technology.

References

1. V. Bakshi (Ed.), *EUV Sources for Lithography*, SPIE Press, Bellingham, Washington, USA (2005).
2. V. Banine, "Extreme ultraviolet sources for lithography applications," 2005 EUVL Symposium San Diego, CA, USA.

3. M. Corthout, J. Pankert, M. Loeken, and P. Zink, "The Philips Extreme UV Sn Source: on the way to an integrated system," SPIE Advanced Lithography 2007–6517-26, San Jose, CA, February–March 2007. See also: P. Zink, F. E. Zocchi, A. Mader, G. Bianucci, G. L. Cassol, J.-M. Gery, O. Franken, R. Apetz, K. Bergmann, and H. Scheuermann, "Thermal and Optical Characterization of an Integrated Alpha Level Source, Debris Mitigation and Collector System," 2007 International EUVL Symposium, Sapporo, Japan, 29–31 October 2007.
4. D. Attwood, *Soft X-Rays and Extreme Ultraviolet Radiation: Principles and Applications*, Cambridge University Press (2000).
5. E. Spiller, *Soft X-Ray Optics*, SPIE Press, Washington, 1994.
6. B. L. Henke, E. M. Gullikson, and J. C. Davis, "X-Ray Interactions: Photoabsorption, Scattering, Transmission and Reflection at $E = 50\text{--}30,000$ eV, $Z = 1\text{--}92$," *Atomic Data and Nuclear Data Tables* 54, p. 181 (1993); see also <http://www-cxro.lbl.gov/optical-constants>.
7. Media Lario Technologies, Private communication (2006).
8. H. Wolter, "Mirrors systems with glancing incidence as image producing optics for x-rays," *Ann. Phys.* **10**, 94–114 (1952).
9. P. Marczuk and W. Egle, "Grazing-Incidence EUV Collectors," in V. Bakshi Ed., *EUV Sources for Lithography*, Ch. 33. SPIE Press, Bellingham, Washington, USA (2005).
10. D. de Chambure, R. Lainé, K. V. Katwijk, J. V. Casteren, and P. Glaude, "The status of x-ray mirror production for the ESA XMM spacecraft," *SPIE Proc.* **2808**, 362–375 (1996).
11. R. Hudec, L. Pina, and A. Inneman, "Replicated grazing incidence x-ray optics: past, present, and future," *SPIE Proc.* **3766**, 62–71 (1999).
12. E. Buratti, V. Rigato, Fabio E. Zocchi, Hiroyuki Kondo, Hideki Komatsuda, J. Kleinschmidt, G. Schrieffer, and J. Brudermann, "Optimisation of optical design in grazing incidence collector for EUV lithography DPP sources," Fourth International EUVL Symposium, San Diego, CA, 7–9 November 2005.
13. F. E. Zocchi, E. Buratti, and V. Rigato, "Design and optimization of collectors for extreme ultra-violet lithography," *SPIE Proc.* **6151**, 61510T (2006).
14. V. Rigato, "Collecting the light," 3rd European EUVL Workshop, Vienna, 19 September 2005.
15. G. Bianucci, F. E. Zocchi, G. Pirovano, G. L. Cassol, F. Marioni, P. Binda, L. Porreca, I. Ahmad, D. Bolshukhin, and M. C. Schürmann, "Thermal management design and verification of collector optics into high power EUV source systems," *SPIE Proc.* **6517**, 63.
16. F. E. Zocchi, G. Bianucci, V. Rigato, G. Pirovano, G. L. Cassol, G. Salmaso, P. Binda, P. Zink, K. Bergmann, B. Nikolaus, and M. C. Schürmann, "Experimental validation of collector's thermo-optical design," EUVL Source Workshop, Barcelona, October 2006.
17. B. Nikolaus, J. Kleinschmidt, D. Bolshukhin, I. Ahmad, M. Schürmann, G. Schrieffer, G. Bianucci, G. L. Cassol, G. Pirovano, F. E. Zocchi, and A. Rit-

- ucci, "Collector optics integration into medium power EUV source systems," EUVL Symposium, Barcelona, October 2006.
18. E. Benedetti, P. Binda, F. Marioni, and F. E. Zocchi, "Optical characterisation under thermal load of collectors for extreme ultra-violet lithography," EUVL Source Workshop, Vancouver, May, 2006.
 19. V. Banine and R. Moors, "Extreme ultraviolet sources for lithography applications," *SPIE Proc.* **4343**, 203–214 (2001).
 20. V. Banine, "Next generation extreme ultraviolet sources for lithography applications," presented at the Fourth Sematech EUVL Symposium, San Diego, CA, 7–9 November 2005.
 21. F. E. Zocchi "High-efficiency collector design for extreme-ultraviolet and x-ray applications," *Applied Optics* **45**, N. 35, 8882.
 22. F. E. Zocchi and E. Benedetti, "Comparison of optical performances of alternative grazing incidence collector designs for EUV lithography," *SPIE Proc.* **6517**, 134.
 23. D. J. W. Klunder, M. M. J. W. van Harpen, V. Y. Banine, and K. Giellissen, "Debris mitigation and cleaning strategies for Sn-based sources for EUV lithography," *SPIE Proc.* **5751**, 943–951 (2005).
 24. J. Pankert, et. al., "Integrating Philips' extreme UV source in the alpha-tools," *SPIE Proc.* **5751**, 260–271 (2005).
 25. H. Meiling, V. Banine, N. Harned, B. Blum, P. Kurz, and H. Meijer, "Development of the ASML EUV alpha demo tool," *SPIE Proc.* **5751**, 90–101 (2005).
 26. H. Hassanein, et al., "Electrode and Condenser Materials for Plasma Pinch Sources," in V. Bakshi Ed., *EUV Sources for Lithography*, Ch. 35. SPIE Press, Bellingham, Washington, USA (2005).
 27. W. Eckstein, *Computer Simulation of Ion-Solid Interactions*, Springer-Verlag, Berlin-Heidelberg (1991).
 28. W. Möller and W. Eckstein, *Nucl. Instr. and Meth. in Phys. Res.* **B 2**, 814 (1984).
 29. W. Möller, W. Eckstein, and J. P. Biersack, *Comput. Phys. Commun.* **51**, 355 (1988).
 30. W. Möller and W. Eckstein, Report IPP 9/64, Max-Planck Institute of Plasma Physics, Garching (1988).
 31. W. Eckstein and J. P. Biersack, *Appl. Phys.* **A 37**, 95 (1985).
 32. R. Kelly, *Surf. Science* **100**, 85 (1980).
 33. J. Pankert, et al., "EUV sources for the alpha-tools," *SPIE Proc.* **6151** (2006).



Valentino Rigato has served as the Chief Scientist Officer of advanced thin films of Media Lario s.r.l. since 2005. He is responsible for the reflective coatings of EUV collectors and x-ray mirrors and leads thin films process engineering. He has been working for more than 15 years at the National Institute of Nuclear Physics–National Laboratories of Legnaro (INFN–LNL, Italy), responsible for many research projects

on advanced detectors materials as well as the coordination of the Van de Graaff AN2000 ion accelerator. His experience ranges from studies on plasma and ion surface interactions to thin film processes, particularly on the synthesis and characterization of nanostructured materials and multilayers.

Chapter 6C

Normal Incidence (Multilayer) Collector Contamination

David N. Ruzic and Shailendra N. Srivastava

Contents

6C.1 Introduction	285
6C.2 Overview of Normal-Incidence Collector Mirrors	287
6C.3 Collector Performance	290
6C.3.1 Erosion by fast ions and lifetime calculation	290
6C.3.2 Contamination and optics cleaning	301
6C.3.3 Thermal load and layer intermixing	305
6C.4 Summary	317
Acknowledgments	318
References	318

6C.1 Introduction

Current lithography using 193-nm light can be extended down to the 45-nm and even 32-nm nodes using various resolution enhancement techniques such as immersion and double patterning. However, to produce smaller and faster chips by the year 2010 or 2011 for the 22-nm mode, next-generation lithography (NGL) methods such as extreme ultraviolet lithography (EUVL) will be needed. EUVL requires EUV light from a plasma source to be collected using reflective mirror optics. The economic feasibility of EUVL commercialization will require these mirror components to have a longer lifetime because frequent replacement would lead to an unacceptable cost of ownership (CoO).

Before EUVL technology can be put into high-volume use, several critical issues must be solved. One challenging problem in moving EUVL from the drawing board to the manufacturing floor is the need to operate a high-power light source in conjunction with the collector optics for light capture. Currently, two prospects for EUV light sources are being considered. The first is a laser-produced plasma (LPP),^{1,2} which uses a pulsed laser to ablate fuel material (xenon [Xe], tin [Sn], or lithium [Li]) and create the high temperatures required for EUV light generation.

The second option is a discharge-produced plasma (DPP),¹ which uses some type of pinch (dense plasma focus, z-pinch, etc.) to compress plasmas to high temperatures, generating the ion species required for EUV light emission.

Both DPP- and LPP-based sources produce strong electric fields during plasma expansion that can accelerate the fuel ions to extremely high energies, on the order of 10 keV for Xe and perhaps 1 keV for lighter ions like Li. As a consequence, the mirror surfaces will be bombarded by a potentially large flux of energetic ions, eventually damaging the mirror surface. The mechanisms for mirror degradation could be surface erosion, roughening, deposition or implantation of impurities, and layer mixing. Ultimately, these debris mechanisms degrade mirror reflectivity, causing a loss of productivity in the manufacturing process. Characterization of the fast-ion debris is critical to creating an operational junction between the light source and the collector optics because of the mirror erosion that occurs as a result of heavy-ion impact. Low-energy sputtered debris can also cause reflectivity degradation through deposition and coating processes, but these effects are minimal compared to erosive fluxes encountered in the source chamber. Debris generation is an inherent problem in any source because expansion occurs during the post-emission time frame, accelerating the gases away from the pinch location.

The multilayer (ML) mirrors used in EUVL applications require not only high-normal-incidence reflectivity, but also long-term temporal and thermal stability at operating temperatures. This requirement is most important to the ML mirrors nearest to the EUV source—the collector optics—where the thermal load and reflectivity loss are dominant. Reflectivity from molybdenum-silicon (Mo/Si) ML mirrors is greatly affected by the interface structure, roughness, and layer intermixing.³ Multilayer reflectivity decreases significantly because of broadening of the interface due to the interdiffusion process. The interdiffusion process and compound formation are very likely at the interfaces in Mo and Si.⁴ Structural instability of Mo/Si interfaces under a high thermal load is more pronounced,⁵ which causes a significant drop in the reflectivity and other optical properties.

Several authors have reported on the thermal stability of Mo/Si MLs to be used in EUVL.^{6–26} Using diffusion barriers such as carbon, boron-carbide (B₄C), and silicon dioxide (SiO₂) (Refs. 24–28) or using a different ML pair can considerably improve the performance and thermal stability of a ML mirror. Multilayer mirrors with a high reflective quality have been made using several sputtering and deposition techniques.^{29–34} However, it is reported that the MLs produced with dc magnetron sputtering systems^{7,27} using an interdiffusion barrier layer have the highest reflectivities.

Currently the most important issue for commercial EUVL is the lifetime of the ML optics. Lifetime testing for the projection and illuminator optics is performed with Mo- and Si-capped layers in good vacuum conditions.^{35,36} If those conditions are maintained, the performance of the ML will not change significantly. However, EUVL will not be operated in an ideal vacuum condition, so it is important to test the optics' lifetime in a real environment^{37–40} that contains contamination. Ideally lifetime testing should be performed in commercial EUV sources, but EUV sources

are still in the development stage so an optimized source with reliable performance is not currently available. Thus, the experiments on lifetime are often performed with electron beams.⁴¹

For the projection and illuminator optics, two important problems are carbon contamination and oxidation. There are several ways to remove carbon contamination,^{41–44} but oxidation is viewed as the more serious problem. The secondary electrons that are produced at the top layer of a ML can have enough energy to break the water bonding and create free radicals, which interact with the top layer of the ML to form an oxide. This problem can be minimized by using protecting capping layers. Ruthenium (Ru) and carbon-capped MLs have been reported to exhibit an extended lifetime against oxidation.^{45–48}

Xe, Sn, and Li are candidate fuel materials for next-generation EUV technology. Sn is the preferred fuel in EUV sources due to its higher conversion efficiency (3%) compared to that (1%) of Xe and the highly reactive Li (2 to 3%). However, Sn has several critical challenges. Sn is a condensable fuel that deposits on nearby surfaces. In this technology the light is collected using reflective collector mirrors, which are placed near the plasma pinch area. The collection efficiency of these mirrors and their ability to direct EUV light to the intermediate focus (IF) depend heavily on the mirrors' reflectivities, which in turn depend on their surface morphology and composition. Sn contamination reduces the reflectivities of the mirror surfaces. High-energy Sn ions or neutrals contaminate the surfaces, making them rougher while also eroding them. Due to these effects, mirrors would need to be changed frequently, which would in turn increase the CoO.

The collector lifetime is a leading challenge to the successful implementation of HVM EUVL. This chapter addresses the contamination of normal-incidence collectors and potential solutions.

6C.2 Overview of Normal-Incidence Collector Mirrors

EUVL technology, which is based on reflective optics for 13.5 nm, is currently being developed using Mo/Si reflective coatings.⁴⁹ Mo/Si MLs also have been used for other spectroscopy applications.^{50–55} Mo/Si MLs are usually deposited as a periodic stack of alternating Mo and Si layers. In spite of the small reflection through individual layers, the reflections from all of the interfaces in a ML mirror can interfere constructively to yield a total reflectivity close to 70% at the 13.5 ± 0.2 wavelengths.^{32,56} To achieve the highest reflectivity from such interference-based mirrors, the bilayer period must be tuned to a particular wavelength.⁵⁷ To achieve near-normal-incidence reflectivity in the EUV range, the bilayer period must be approximately 6.9 nm. The highest reflectivity occurs when the Mo layer thickness is approximately 40% of the bilayer period. Bragg's law is then the necessary condition to achieve the maximum reflection efficiency in a ML mirror.^{58,59}

An optical path through the stacks of Mo and Si layers is schematically represented in Fig. 6C.1. The large number of periods will result in higher reflectivity because there is more constructive interference. However, since absorption is also

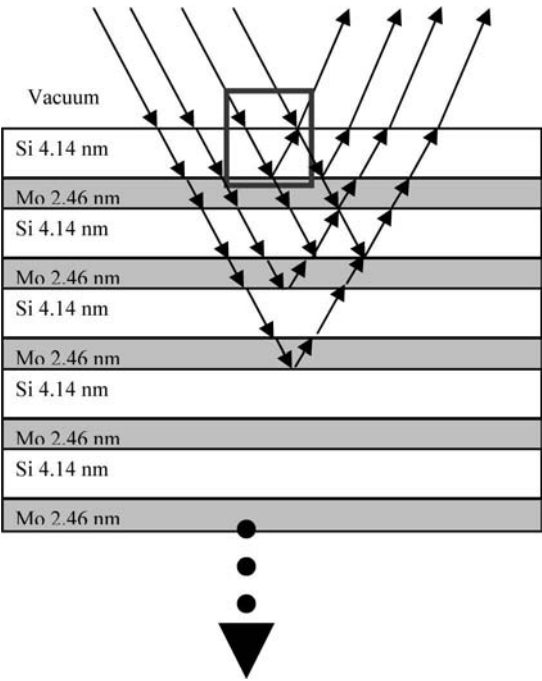


Figure 6C.1 Reflection from a ML mirror.

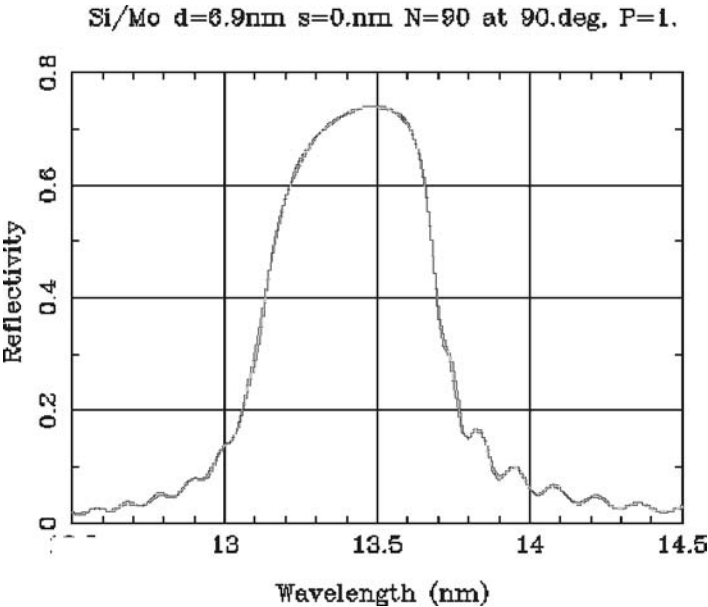


Figure 6C.2 Reflectivity variation as a function of wavelength for a Si/Mo ML. [Reprinted from the website of the National Institute of Standards and Technology (NIST).]

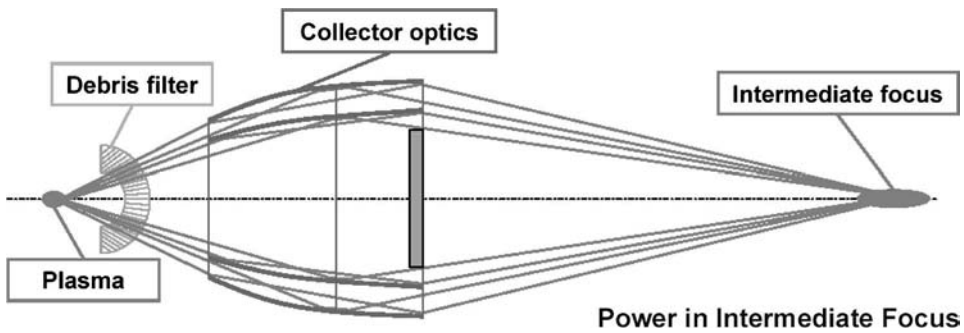


Figure 6C.3 DPP source-collector system.

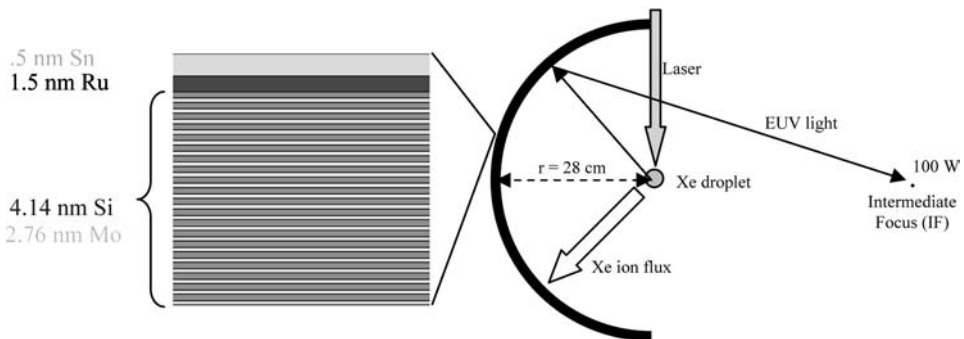


Figure 6C.4 LPP source-collector system.

present in the layers, the reflectivity will not increase continuously with the number of periods.

Reflectivity variation is shown against the wavelength for a ML mirror in Fig. 6C.2. Reflectivity is typically quoted as peak reflectivity.

The lifetime of a ML mirror depends greatly on the efficiency of the debris mitigation. EUV sources differ in which debris mitigation techniques they can use.

In a DPP source (Fig. 6C.3), the debris mitigation approaches have some advantages. Since the light needs to traverse only the space between the source and the collector optics in one direction, there is room for items that can extend the lifetime of the mirrors. In addition, grazing angle collectors can be used, as shown in Fig. 6C.3. These mirrors are not MLs and have a lower reflectivity as the angle of incidence becomes less grazing. LPP EUV sources (Fig. 6C.4) cannot use collimating debris filters because the light traverses the same region in multiple directions. However, the collectors for LPP sources, due to their larger solid angle of collection, allow a higher collection efficiency of EUV light than from the grazing angle collectors used in DPP EUV sources.

6C.3 Collector Performance

Given the challenges of using ML reflective optics in EUVL, the remainder of this chapter will focus on the specific problems and solutions concerning fast-ion damage, mirror surface contamination, optics cleaning, and thermal damage of ML mirrors. Ion debris data used in the following discussions are from measurements taken in a DPP EUV source, where the interaction of debris with ML mirrors was studied.

6C.3.1 Erosion by fast ions and lifetime calculation

It is desirable to know the lifetime limits of ML mirrors used as collector optics in EUV sources. Reflectivity degradation of the collector optics is an effect of debris interaction with the collector optics. Two kinds of mirrors are used in EUVL: normal-incidence mirrors (ML mirrors) and grazing-incidence mirrors. For grazing incidence mirrors, sputter-induced roughness and contamination are the main causes of reflectivity loss. For normal-incidence mirrors, erosion, in addition to roughness and contamination, plays a critical role in reflectivity degradation. The optimum number of bilayers for high reflectivity is about 50. However, to mitigate the erosion due to plasma debris in LPP sources, additional bilayers can be used on the ML collector optics to extend lifetime. The thicker stacks of MLs have enough bilayers to keep the reflectivity constant as layers are eroded away. However, more bilayers means an increased cost. A calculation in Fig. 6C.5 shows how the reflectivity changes with the number of bilayers eroded in a ML mirror. The highest theoretical reflectivity of a ML mirror is around 73% (Fig. 6C.5), though this reflectivity has yet to be achieved experimentally. When the reflectivity drops

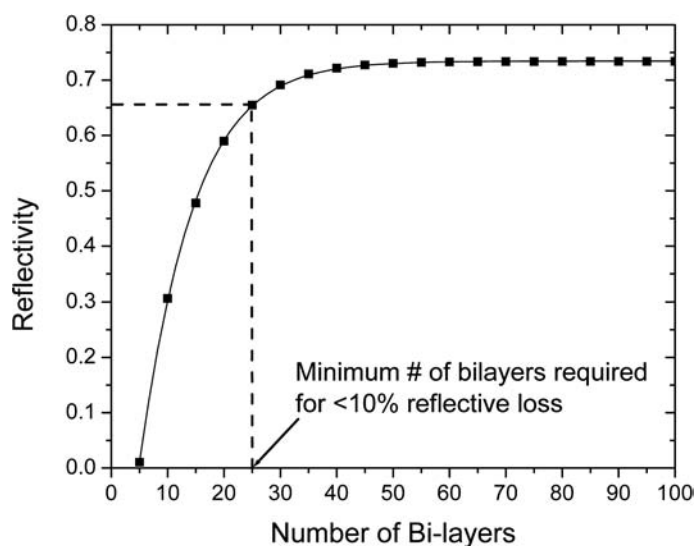


Figure 6C.5 Calculation showing the reflectivity from a ML versus the number of bilayers.

Table 6C.1 Basic material data for Ru, Si, and Mo.

MLM material	Standard thickness (nm)	Atomic mass (g)	Mass density (g/cc)
Ru	1.50	1.678×10^{-22}	12.3
Si	4.14	4.664×10^{-23}	2.32
Mo	2.76	1.593×10^{-22}	10.2

below 10% of the initial reflectivity, the mirrors must be changed in a high-volume-manufacturing (HVM) tool per lifetime criterion. Calculations show that, in order to reduce the reflectivity to 10% of the maximum value, a minimum of 50 bilayers is needed to achieve 73% reflectivity and the maximum tolerable erosion is 25 bilayers.

It is important for source and mirror suppliers to know the number of shots that will erode a given number of bilayers from a ML mirror. For the following calculations, we will choose 25 bilayers as a representative number. But first, a general understanding of debris and erosion problems and methods to mitigate them must be developed.

The first item is to determine the particle flux needed to remove a given thickness of a substrate (ML mirror). In the change of thickness equation [Eq. (6C.1)] below, ΔT , Γ , Y , t , m , and ρ denote, respectively, the change of surface thickness due to erosion, the particle flux, sputtering yield, time, substrate mass, and substrate density, and the subscripts ' i ' and ' n ' refer to ions and neutral particles:

$$\Delta T_E = \frac{\Gamma_i Y_i t m_s}{\rho_s} + \frac{\Gamma_n Y_n t m_s}{\rho_s}. \quad (6C.1)$$

Assuming that only physical sputtering is occurring due to the low charge states that reach the mirror surface, so that $Y_i = Y_n = Y$ and $\Gamma_i + \Gamma_n = \Gamma$, then the flux necessary to sputter away a layer of a given substrate is given by

$$\Gamma = \frac{\Delta T_E \rho_s}{Y t m_s}. \quad (6C.2)$$

Table 6C.1 shows the basic material data (thickness in a ML mirror with a 1.5-nm-thick capping layer of Ru, mass, and density) for Ru, Si, and Mo. Table 6C.2 shows the sputtering yield of Ru, Si, and Mo using Xe and Sn at an average energy of 6 keV calculated using SRIM software (<http://www.srim.org>).

Now, using Eq. (6C.2), one can calculate the Xe fluence needed to remove individual layers of Si and Mo. Thus, the fluence required to remove one layer of Si is 6.17×10^{15} particles/cm², and the fluence required to remove one layer of Mo is 1.06×10^{16} particles/cm². These values are tabulated in Table 6C.3.

Thus, the fluence required to remove one bilayer of Si/Mo is

$$6.17 \times 10^{15} + 1.06 \times 10^{16} = 1.677 \times 10^{16} \text{ particles/cm}^2. \quad (6C.3)$$

Table 6C.2 Sputtering yield calculation using SRIM from Ru, Si, and Mo.

MLM material	Xe (6 keV at 10 deg)	Sn (6 keV at 10 deg)
Ru	4.38	4.65
Si	2.87	2.99
Mo	1.94	1.93

Table 6C.3 Xe and Sn fluxes needed to erode one layer of Ru, Si, and Mo.

MLM material	Xe (6 keV at 10 deg)	Sn (6 keV at 10 deg)
Ru	2.34×10^{15}	2.20×10^{15}
Si	6.17×10^{15}	5.93×10^{15}
Mo	1.06×10^{16}	1.07×10^{16}

If we multiply the fluence by 25, theoretically we know the fluence tolerance for a 10% reflectivity loss. Now we need to know the actual debris flux in EUV sources, and depending on those values, we can estimate the mirror lifetimes.

This brings us to a point where the importance of debris measurement can be realized. Mirror degradation depends on the amount and energy values of plasma debris, which expand during the plasma expansion in the form of ions, neutrals, and accelerated electrode materials. If the absolute number and energy of ions and neutrals can be measured, the lifetime of the collector optics can be estimated. Different source suppliers around the world have different EUV sources, and the debris generated by each source varies. Thus, a standardized, calibrated debris diagnostic tool is needed to measure ions and estimate the collector lifetimes of different EUV sources. The Center for Plasma Material Interactions (CPMI) at the University of Illinois has developed a spherical energy sector analyzer (ESA) that measures ions based on their charge to mass ratio. This instrument, capable of recording ion peaks differential to their charge states, is calibrated with an ion gun and a Faraday cup (see Fig. 6C.6) to extract the absolute number of particles coming out of an EUV source. As shown in Fig. 6C.6, the ion gun signal is measured from both the ESA and Faraday cup by changing the ion gun position in the line of sight of either the ESA or Faraday cup, respectively.

Figure 6C.7 shows the experimental setup used at CPMI. The plasma source was XTREME Technologies' XTS 13-35 DPP source,¹ which is currently used in Exitech Ltd.'s microexposure tool (MET). This plasma source uses Xe gas to create 35 W of EUV light (2% bandwidth) in 2π sr with a conversion efficiency of 0.55%. The self-compression of the Xe gas column results in heating sufficient to generate Xe^{8+} to Xe^{12+} ions, which are necessary for the emission of EUV light at 13.5 nm and measured with a one-bounce photodiode (<http://www.ird-inc.com>). The ESA is fitted with a set of Burle⁶⁰ dual microchannel plates (MCP) to measure the flux of ion debris emitted by the plasma source.⁶¹ The ESA consists of two spherical segments that are charged to equal and opposite voltages to guide ions of a specific energy-to-charge ratio between them toward the MCPs. Ions with too

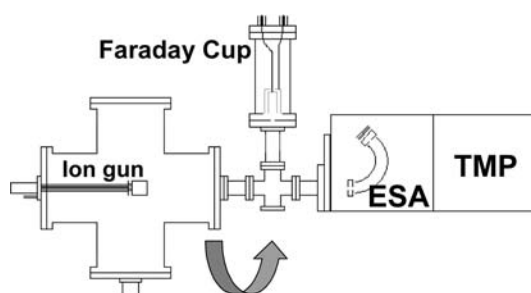


Figure 6C.6 Calibration setup for the ESA (the ion gun signal is measured with the ESA and Faraday cup).

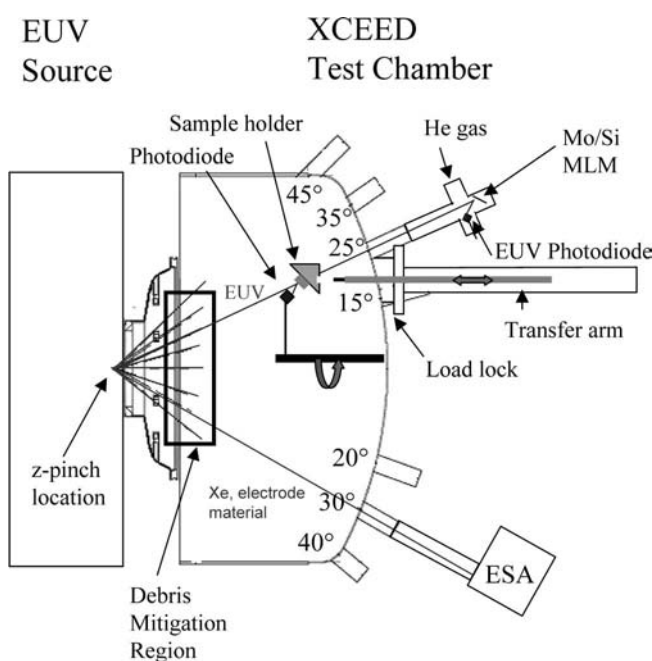


Figure 6C.7 XTREME Technologies' XTS 13-35 DPP EUV source at CPMI, University of Illinois.

much energy extinguish against the outer wall, while ions with too little energy extinguish against the inner wall. Neutrals and negatively charged particles are also unable to traverse the spherical path. Ions with different masses and charge states are distinguished by recording their time of arrival. Knowing the detector distance and ion energy enables us to theoretically calculate the time of arrival. Ions with different masses and charge states are then identified on the recorded time of flight spectra.

Ion spectra for Xe and Sn sources are measured and shown in Figs. 6C.8 and 6C.9, respectively. Figure 6C.8 shows the ion spectra from a Xe EUV source.

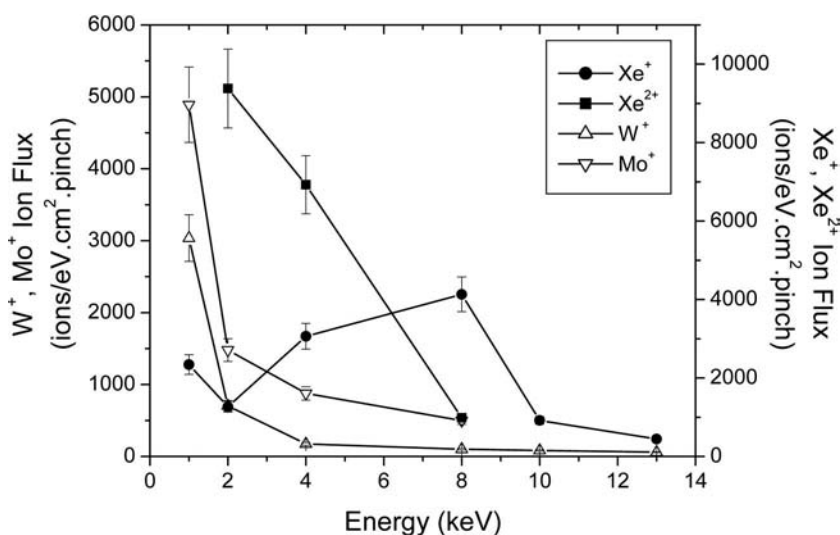


Figure 6C.8 Ion spectra of a Xe-fueled XTS source in absolute fluxes against the ion energies in keV measured at 157 cm. Individual error bars are shown; however, day-to-day reproducibility of a given spectra can vary from 10 to 20%.

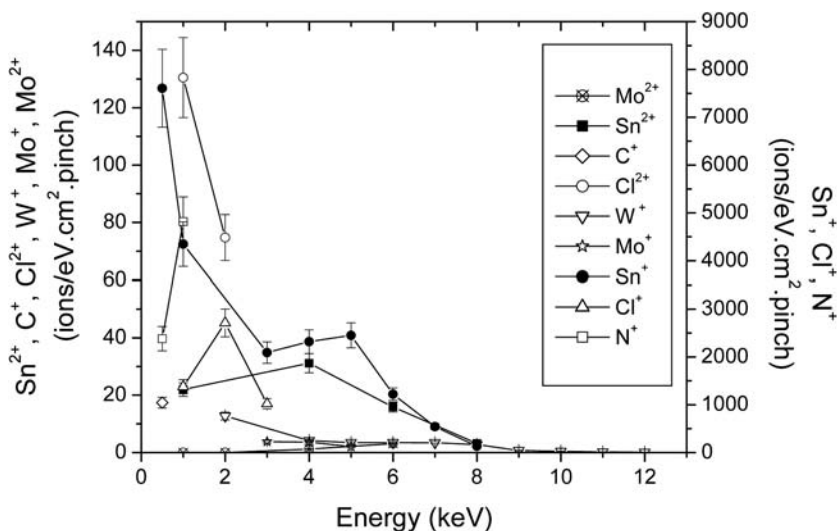


Figure 6C.9 Ion spectra of a Sn-fueled XTS source in absolute fluxes against the ion energies in keV measured at 157 cm. Individual error bars are shown; however, day-to-day reproducibility of a given spectra can vary from 10 to 20%.

Fluxes in absolute units are plotted on the y axis against the energies in keV on the x axis. Similar spectra are obtained from a Sn EUV source in Fig. 6C.9.

The ion spectra measured at the University of Illinois were tested and cross checked for reliability using the following steps. First, the erosion was predicted using the measured ion fluxes and SRIM code. Second, several samples, includ-

Table 6C.4 Measured and predicted erosion of several materials.

Material	Measured erosion (nm)	Predicted erosion (nm) (considering ions only)
C	< 3	1.1
Au	54	33
Mo	10	6.5
Si	< 3	5.8
Si/Mo MLM	13	8.5
Pd	20	18
Au/Mo	11	10

ing multilayer mirror (MLM) samples, were exposed to the plasma debris; after a certain number of shots, the material characterization was made for the eroded thickness. The measured and predicted erosions were in agreement within the error bars if neutral emission was also considered (see Fig. 6C.10).

The sputtering yield (Y_{sputt}), which is atoms eroded per ion, can be calculated using SRIM calculations:

$$Y_{\text{sputt}} = \frac{\text{atoms}}{\text{ion}}, \quad (6C.4)$$

$$N = \text{total atoms eroded} = Y_{\text{sputt}} \cdot \text{Ion}_{\text{flux}} \left(\frac{1}{\text{cm}^2 \text{ shots}} \right), \quad (6C.5)$$

$$\Delta T(\text{cm}) = \text{Erosion} = N \cdot \frac{m}{\rho} \left(\frac{1}{\text{cm}^2 \text{ shots}} \cdot \frac{\text{g}}{\text{g/cm}^3} \right) \cdot \text{shots}. \quad (6C.6)$$

To calculate the total atoms eroded, the sputtering yield is multiplied by the measured ion flux, as shown in Eq. (6C.5). Equation (6C.6) shows the calculation for eroded thickness from the substrate surface.

Table 6C.4 shows the measured and predicted erosion for several materials that were investigated. The measured and predicted values are close, with a slight under-prediction of the erosion. A clearer picture can be seen in Fig. 6C.10, where the predicted and measured erosion values are plotted and compared for all the materials.

This good agreement between predicted and measured erosion allows the life-time to be estimated for a given collector. As shown in Fig. 6C.10, the predicted erosions are generally less than the measured ones because the neutral particles are not taken into account in the ion fluxes used in Eq. (6C.5). There are fast neutrals present in the plasma due to charge exchange between the fast ions and the background gas. They are able to damage the collector optics as well.

After obtaining absolute ion flux data and testifying to their reliability, we can return to the question we started with: How many shots are needed to erode 25 bilayers? The experimental flux measured using ESA at the University of Illinois at 28 cm from the pinch location is 1.87×10^9 ions/cm² pinch, and the particle fluence required to erode one bilayer from the MLM is 1.677×10^{16} [see Eq.

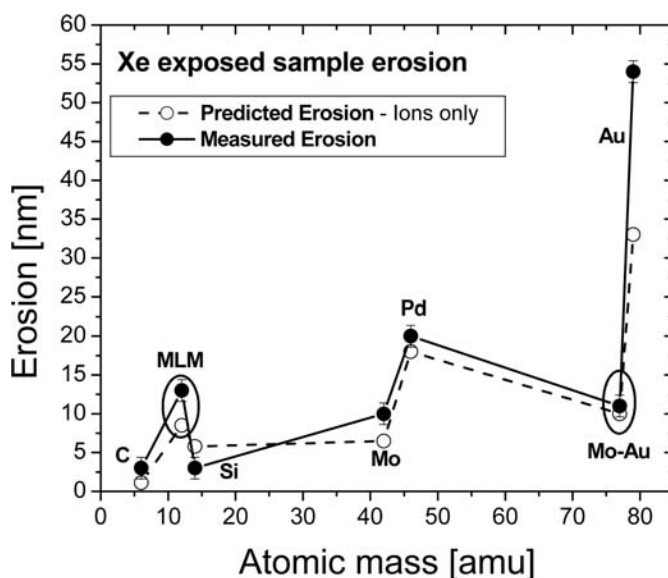


Figure 6C.10 Comparison of measured and predicted erosion for different materials.

(6C.3)]. Thus,

$$1.87 \times 10^9 \times \text{number of shots} = 1.677 \times 10^{16}. \quad (6C.7)$$

Therefore,

$$\text{number of shots} \sim 9 \times 10^6. \quad (6C.8)$$

Thus, the number of shots required to erode one bilayer is about 9 million, so $9 \times 25 = 225$ million shots can erode 25 bilayers, reducing the reflectivity to 10% of the original value.

Based on the above calculations, the lifetime of a ML collector mirror can be predicted. In HVM, if the source is operational at 10 kHz, the mirror lifetime based on the above calculations is expected to be six hours. This is clearly unacceptable and shows why debris mitigation systems are used in EUV sources. With a diagnostic tool such as ESA, one can keep track of debris system efficiency and therefore predict the lifetime of the collector optics.

Collector mirror lifetime and the investigation of the ML damage mechanism are important issues for EUV light source development. Hiroshi et al. characterized fast ions and studied their effects on Mo/Si MLs.⁶² They also reported a magnetic confinement scheme for fast-ion mitigation. Using a time-of-flight method, they measured kinetic energies of fast Xe ions produced in laser plasma and observed Xe^+ to Xe^{6+} ions with Xe^{2+} as the main charge state. While studying the ion damage mechanism, they also observed the missing ML boundary and increased surface roughness. They measured the reflectivity from a Mo/Si ML sample and

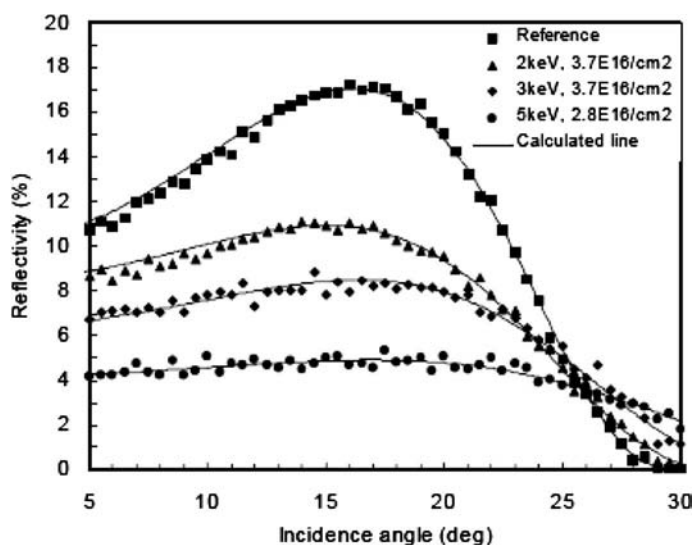


Figure 6C.11 Measured and calculated reflectivities of exposed Mo/Si ML samples. (Reprinted from Ref. 62.)

compared it with the calculated reflectivity as shown in Fig. 6C.11. It was found that the reflectivity decreased with increasing ion energy. They also showed that as the number of ML bilayers decreases, the interface and/or surface roughness increases with ion dose, which indicates that reflectivity goes down with increased interface roughness. They measured the ions with and without a magnetic field and demonstrated that a magnetic confinement scheme is effective for ion mitigation.

R. Anderson measured the erosion rates of a number of materials and proposed a mechanism for erosion of the condenser optics.⁶³ The material response of the ion interactions was calculated using the TRIM code. Figure 6C.12 shows the erosion of the Mo film. The erosion rate was found to increase monotonically with laser pulse energy. The angular dependence of the erosion rate with respect to the laser axis was measured and is shown in Fig. 6C.13. Anderson hypothesized that the measured erosion was due to Xe surface kinetic sputtering, and that the Xe flux was not isotropic.

Apart from damage due to sputtering from plasma debris viz. ions and neutrals, contamination also occurs from Sn deposition on surfaces when using a Sn source, which degrades the reflectivity. Figure 6C.14 shows the reflectivity degradation due to Sn deposition on the surface of a normal-incidence MLM.

These data show what happens when Sn is allowed to accumulate on the surface of a MLM. The calculations, performed using the programs available on the Center for X-ray Optics (CXRO) Web site (<http://www-cxro.lbl.gov/opticalconstants/>), assume a surface roughness of $1 + \sqrt{c}$ (thickness of Sn) nm surface roughness. As Sn deposits, the surface is likely to become rougher. Both the accumulation of Sn and the increasing roughness decrease reflectivity. Based on this calculation, no

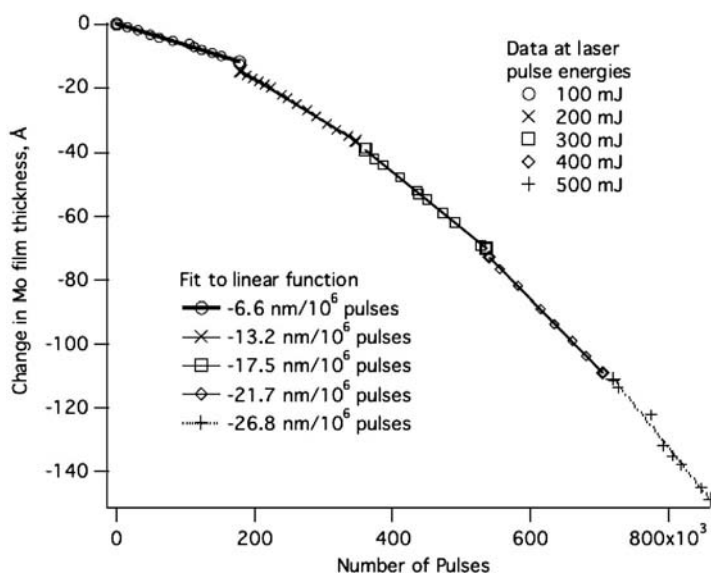


Figure 6C.12 Erosion of Mo film on a quartz crystal monitor at different laser pulse energies using a 30- μm filament jet target. The sample was 110 mm from the target, and the chamber pressure was 0.0036 torr. (Reprinted from Ref. 63.)

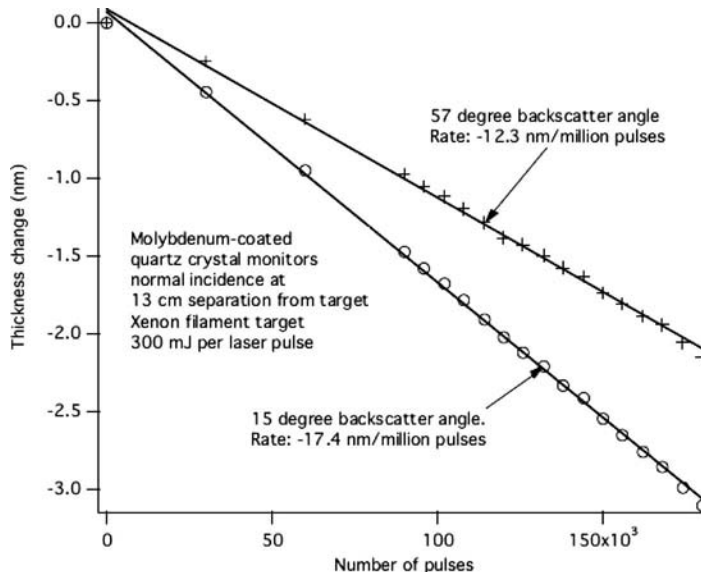


Figure 6C.13 Comparison of erosion rates taken simultaneously for Mo films at two scattering angles. (Reprinted from Ref. 63.)

more than 1 nm of Sn can be deposited onto the surface of a MLM before the overall reflectivity is reduced by 10%.

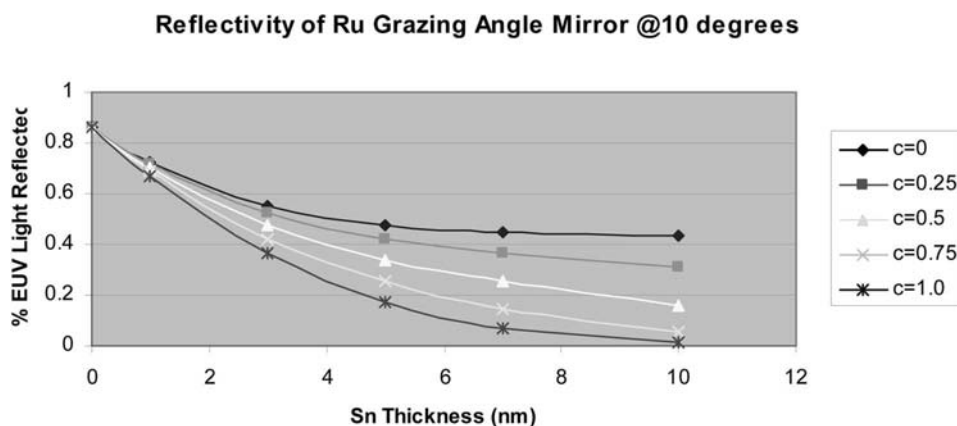


Figure 6C.14 Reflectivity of Ru at a 10 deg grazing incident angle for EUV light as a function of overlaying Sn thickness. “c” is a parameter denoting surface roughness. RMS surface roughness is equal to $1 + “c”$ times the Sn thickness. Thus, the line for $c = 0$ is for a RMS surface roughness of 1 nm. The line for $c = 1$ has roughness increasing as deposition increases.

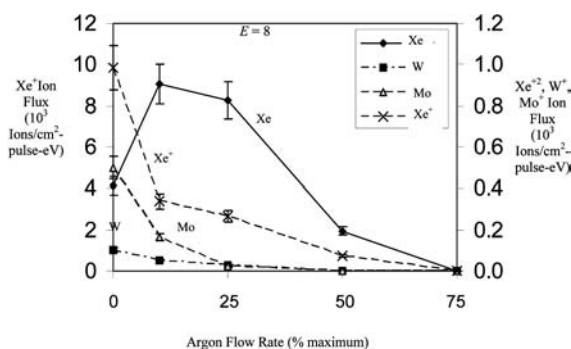


Figure 6C.15 Gas curtain mitigation: ion fluxes at different Ar gas flow rates.

These examples show that both debris generation and contamination can reduce the collector lifetime. Therefore, it is critical to reduce the debris generated and determine the efficiency of debris mitigation schemes. Standard mitigation schemes such as foil trap and gas flow, the Illinois ion energy reduction technique (INERT), and pulsed foil trap mitigation have already been tested at the University of Illinois with encouraging results.

Figure 6C.15 shows the reduction of ion fluxes at different gas flow rates through a foil trap debris mitigation tool. In the INERT technique shown in Fig. 6C.16, the inclusion of a light element gas in the input fuel can considerably reduce the ion fluxes.⁶⁴

Ion energy spectra under different gas fueling mixtures keep the partial pressures of all components equal in the analysis chamber. The EUV light output is the same in all three cases.

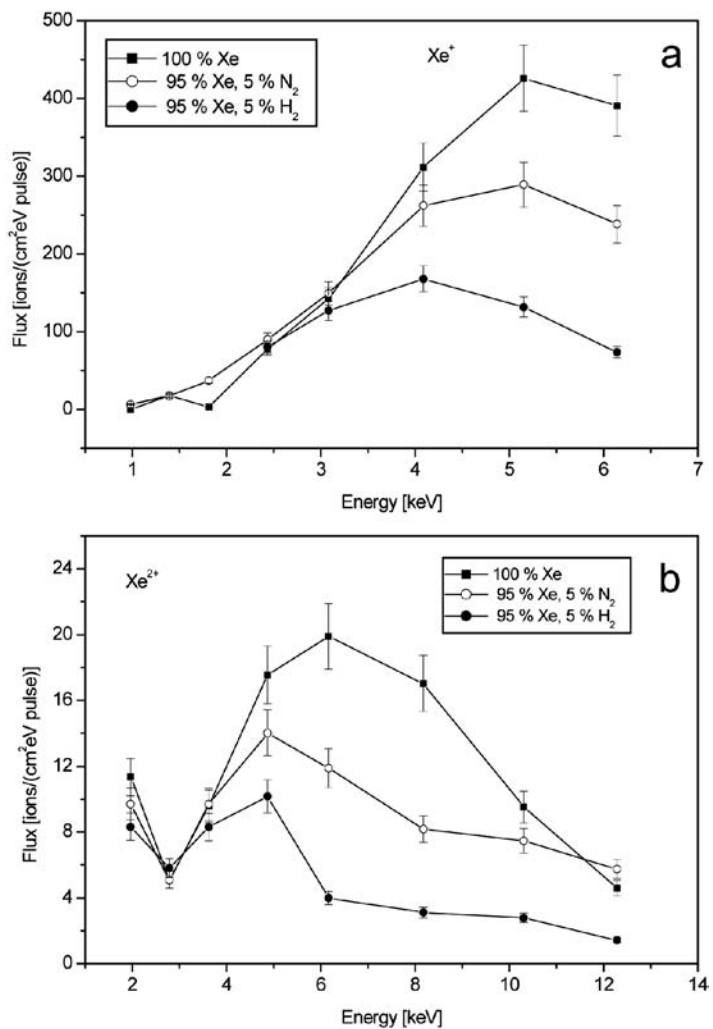


Figure 6C.16 Illinois ion energy reduction technique (INERT).

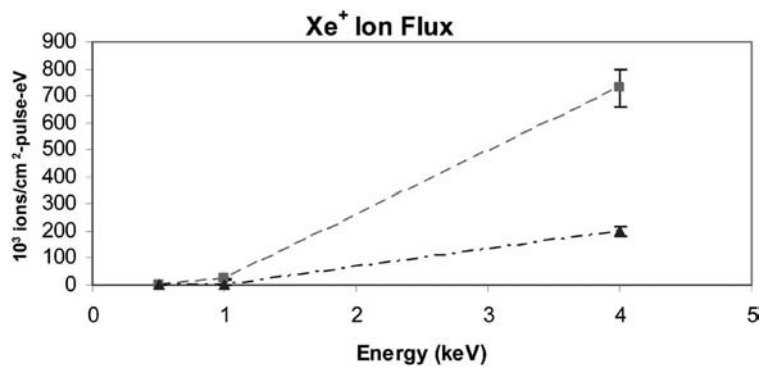


Figure 6C.17 Use of a pulsed foil trap mitigation technique to decrease by a factor of 3.75 for 4 keV Xe⁺ ions.

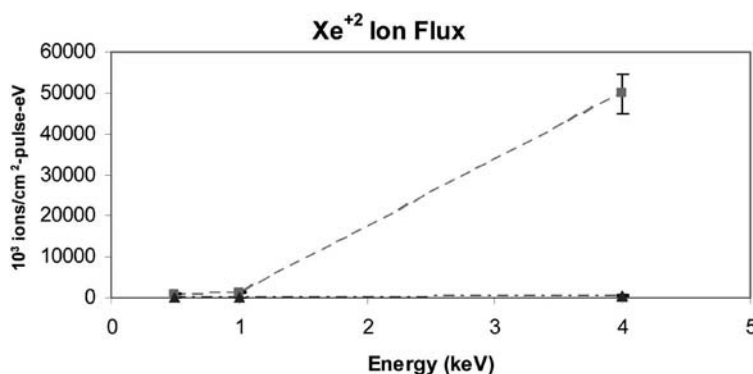


Figure 6C.18 Use of a pulsed foil trap mitigation technique to decrease by a factor of 88 for 4 keV Xe^{2+} ions.

Electric-field foil trap mitigation was tested with and without the electric field to investigate debris reduction. The results, shown in Figs. 6C.17 and 6C.18, showed a dramatic reduction by a factor of 3.75 for 4 keV Xe^+ ions and a factor of 88 for 4 keV Xe^{++} ions.

S. S. Harilal summarized various concepts to mitigate ion debris by using tape targets, ambient gas for moderating the species, foil traps, cavity confinement, electrostatic repeller fields, magnetic fields, and mass-limited targets.⁶⁵

6C.3.2 Contamination and optics cleaning

The previous section described how energetic ion debris can be measured as well as reduced. However, as the debris is deposited on the mirrors, cleaning methods must be developed and integrated into the HVM tool to enhance the collector mirror lifetime. For example, Fig. 6C.19 shows Sn contamination on a MLM sample after being exposed to a Sn DPP EUV source in which the mitigation systems were not activated.

To increase mirror lifetime, several groups are investigating debris mitigation techniques and cleaning methods based on the understanding of interactions between particles and mirrors. Atomic hydrogen cleaning methods for removing Sn as well as carbon showed the feasibility of cleaning EUV mirrors.^{66,67}

Reactive ion etching (RIE), also called ion-enhanced etching, of debris is another potential solution for effectively cleaning contaminated mirror surfaces. If a plasma can selectively etch debris on mirrors in certain conditions, even in-situ cleaning will be possible and save significant time and cost. The preliminary research has shown that RIE with Ar/Cl_2 can selectively etch Sn. Therefore, it may be possible to conduct RIE Sn cleaning without severe damage to the mirror.

In CPMI's investigations, the etch rates of Sn with Ar/Cl_2 plasma have been measured using a substrate RF bias as the primary independent variable. For the selectivity study, SiO_2 was chosen to compare the etch rates. Si or Ru was used for the capping layer of a Mo/Si ML EUV mirror, but a thin native oxide layer

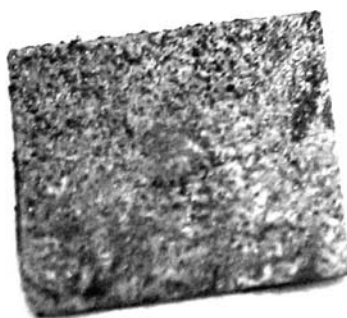


Figure 6C.19 MLM sample exposed to a Sn DPP EUV source showing massive Sn deposition on the surface.

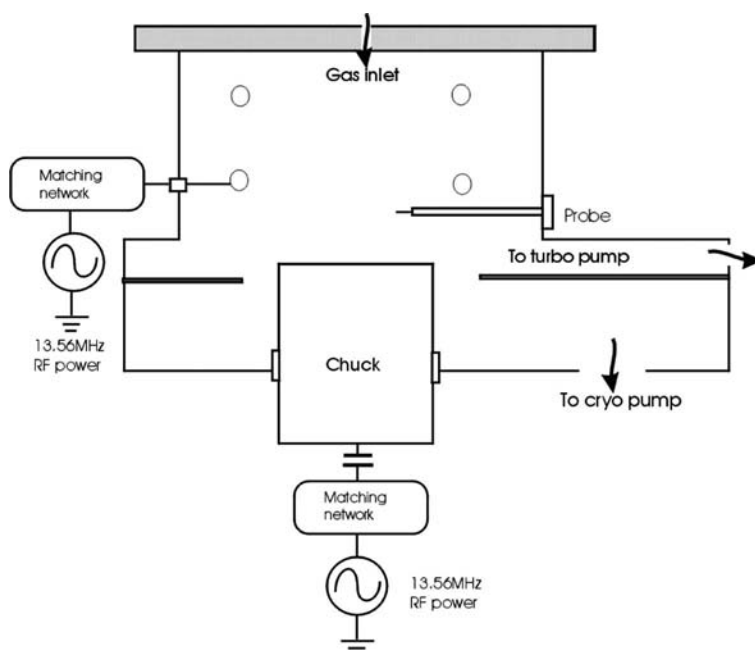


Figure 6C.20 RIE chamber.

exists on Si, whereas Ru has better resistance to oxidation. For this study, only a Si capping layer was considered.

Figure 6C.20 shows the experimental setup for the RIE system. The RIE chamber was equipped with a stainless-steel two-turn internal coil for an inductively coupled plasma source. It also included a MKS mass flow controller connected to a Java computer program controller, a 1200 l/s Ar speed Helix cryopump, a 500 l/s Ar speed Pfeiffer turbo pump, a Dryvac 100P dry pump to handle a corrosive gas, an ion gauge, convectron gauges, and an exhaust-handling system for corrosive gas. It used two 13.56-MHz RF power supplies, both of which were connected to RF matching networks to minimize the reflected power. A residual gas analyzer

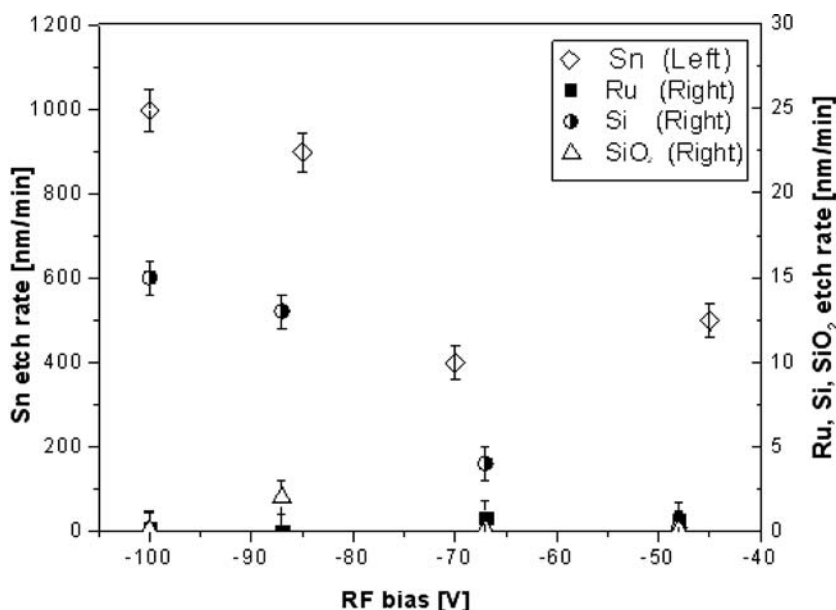


Figure 6C.21 Measured etch rates for Sn, Ru, Si, and SiO₂ samples along various RF biases to the chuck. The y axis on the left shows the Sn etch rate, and the y axis on the right shows other materials because substantial differences exist between their etch rates. The reading error of depth measurement with a profilometer was about ± 100 nm for Sn and ± 10 nm for other samples.

(RGA) and RF-compensated Langmuir probe were used for plasma diagnostics. Several cross checks and tests were performed to obtain more reliable and dependable data.

The etch rates of Sn, Ru, Si, and SiO₂ were measured as a function of increasing chuck bias voltage. Figure 6C.21 shows the etch rates of Sn, Ru, Si, and SiO₂ using Cl₂/Ar plasma as the etching recipe where etch rates (in nm/min) are plotted against DC bias voltage in volts. The figure shows that etching is a strong function of biasing, and the rate increases with increasing bias voltage in the case of Sn. The largest difference between the etch rates of Sn and other materials presents the possibility of cleaning only Sn off of other substrate materials that are not nearly as affected by the etchant.

After achieving a considerably high Sn etch rate, the same recipe was used to clean Sn off of a Ru surface. In this experiment, 100 nm of Sn were deposited on the Ru sample. Figure 6C.22(a) shows the Auger electron spectroscopy (AES) profile of Sn-deposited samples. As expected, the Sn concentration is highest. The Sn was cleaned using an Ar/Cl₂ mixture. Figure 6C.22(b) shows clearer evidence that Sn was completely removed.

We then measured the EUV reflectivity from a pure Ru sample before Sn deposition and after Sn cleaning. Figure 6C.23 shows that reflectivity is restored after Sn cleaning. The photodiode traces are nearly identical. Note that the difference between noise levels on the baseline is not related to the sample cleanliness.

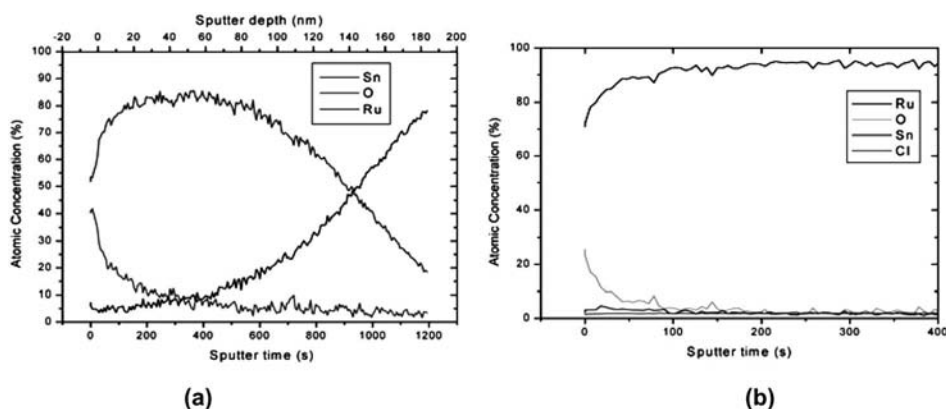


Figure 6C.22 AES profiles of a Ru sample (LHS) before Sn deposition, and (RHS) after Sn cleaning.

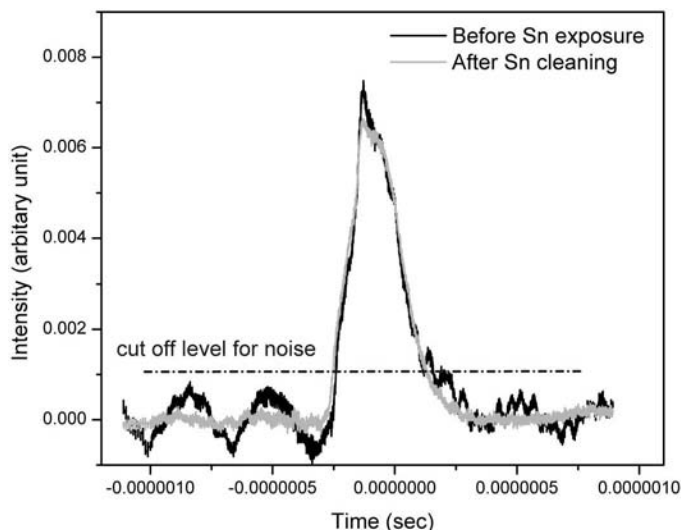


Figure 6C.23 Reflectivity measurement in an EUV source from a pure Ru sample and after cleaning Sn off of the Ru surface.

Another critical EUVL issue is carbon contamination of the collector and other MLM optics during EUV radiation exposure. Several methods have been investigated to remove carbon: RF discharge atomic hydrogen or oxygen,⁶⁸ EUV,⁶⁹ and SR.⁷⁰ Carbon removal using atomic hydrogen is especially promising.⁶⁷

H. Oizumi reported carbon contamination removal from an EUV ML using atomic hydrogen, which was produced by a heated catalyzer.⁷¹ Experimental arrangements are shown in Fig. 6C.24.

X-ray photoelectron spectroscopy (XPS) measurements show that carbon from the surface of a Si-capped Mo/Si ML could be completely removed. A marginal

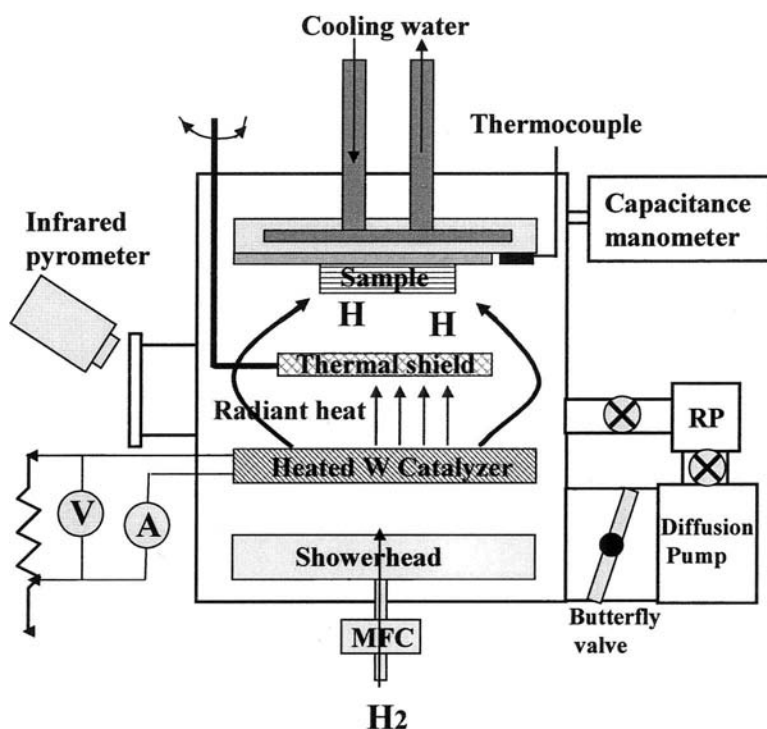


Figure 6C.24 Atomic hydrogen cleaning apparatus. (Reprinted from Ref. 71.)

change was noticed in EUV reflectivity and wavelength, which demonstrated the effectiveness of atomic H carbon removal without damaging the ML surface.

6C.3.3 Thermal load and layer intermixing

As described in the introductory section, the stability of EUV MLs under high thermal and radiation loads is a challenging issue for the commercialization of EUVL. Numerous authors have investigated and suggested solutions to this important problem. Giovanni showed that the steady-state operating temperature of a debris mitigation tool (DMT) could be as high as 700°C.⁷² A large fraction of this thermal load could be deposited on the collector mirror. Since no ML can function at such a high temperature, care must be taken to sufficiently cool the collector. Many cleaning schemes are temperature-dependent and could occur simultaneously with deposition. In those cases, one would not want to over-cool the collector. Since the best values of $T_{\max}$, the maximum temperature a ML mirror can handle without intermixing, is likely to be 200°C (without using a diffusion barrier), some effort should be made to quantify the temperature, T , of the collector optics.

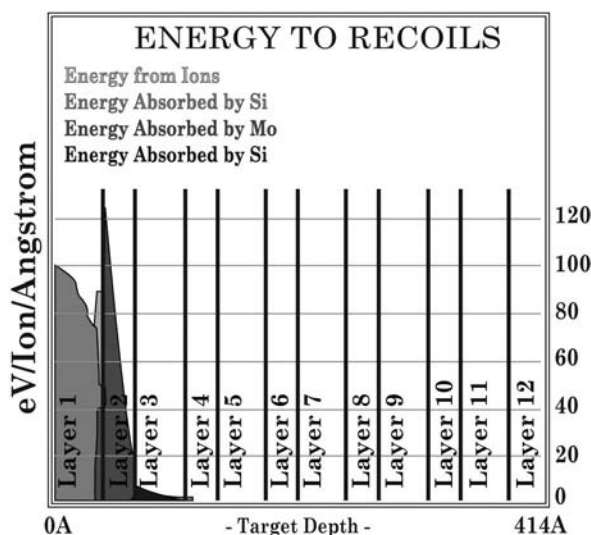


Figure 6C.25 Average energy imparted to recoiled atoms as a function of substrate thickness.

The steady-state temperature of a cooled collector mirror comes from the solution of the heat transfer equation:

$$q'' = mc_p \frac{dT}{dt} + hA(T - T_{\text{fluid}}), \quad (6C.9)$$

where m is the mass, c_p is the specific heat, h is the heat transfer coefficient, A is the collector area, and q'' is the power flux.

Therefore, to design the cooling system to maintain that steady-state temperature of the mirror at a given value but below T_{max} , all the parameters shown above in Eq. (6C.9) are needed. The only parameter unique to EUVL is the expected power flux, q'' . This next two pages will derive an estimate for that quantity while considering both radiation and ion impact. Also, transient effects are discussed, which can be important for intermixing of the uppermost layer.

To model the EUV source itself as a spherical plasma spark with a radius of 1 mm and an ion density of $1 \times 10^{18} \text{ cm}^{-3}$, a temperature of 30 eV and duration of 50 ns will be assumed, which are values typical of either DPP- or LPP-based EUV sources.

The average energy of the ions observed in an experiment using Xe is 6 keV, which will be used as a representative energy of all of the ions in this simple model. In addition to the many other quantities calculated by SRIM that have been featured in this chapter, the energy of the ions transferred to recoiled atoms also can be displayed as a function of substrate depth, as is shown in Fig. 6C.25.

The integration over each layer shown in Fig. 6C.25 can be done in a straightforward manner to yield Table 6C.5, where all of the results beyond layer 3 gave negligible energies and therefore were omitted.

Table 6C.5 Results of integration from Fig. 6C.25.

Layer	Composition	Thickness	Average energy per recoiled atom
1	Si	41.4 Å	3.7 keV/ion
2	Mo	27.6 Å	1.9 keV/ion
3	Si	41.4 Å	0.1 keV/ion

Table 6C.6 Average energies in each layer.

Layer	keV/cm ² pinch
1	6.9×10^9
2	2.3×10^9
3	1.9×10^8

Table 6C.7 Power deposition in each layer.

Layer	mW/cm ²
1	11
2	4
3	0.3

If the observed ion flux of 1.87×10^9 ions/cm² pinch is used, the average energies in each layer increase as shown in Table 6C.6.

If a repetition rate of 10 kHz is assumed, then average energy can easily be turned into power deposition per square centimeter as shown in Table 6C.7.

These values are clearly not a large amount of power deposition, but they should be noted for any transient effect because all of this energy is deposited in the first few nm.

The primary source of energy deposition into the collector mirror is from the radiation itself. To determine the amount of radiation that is coming off of this plasma, a simulation was carried out for the previously stated plasma conditions using PrismSPECT, which is a commercial spectral analysis software. It was found that in the whole spectrum, there was a large spike of radiation at 10 nm, whereas a very large amount of radiation was emitted in the broader spectrum. Integrating this spectrum yields 3.5 J, which is the total amount of energy that is lost to radiation from the plasma. Current EUV sources have an energy level on the order of 5 J per pulse. The simulation result shows that 70% of that energy is carried away in the form of radiation, as expected. The remaining energy is likely spent on heating the electrodes or background gas.

If the source is running at 10 kHz in HVM, 35 kW of power goes into radiation. Thus, a heat load of about 7 W/cm² is expected at the mirror surface, assuming it is 28 cm from the pinch location.

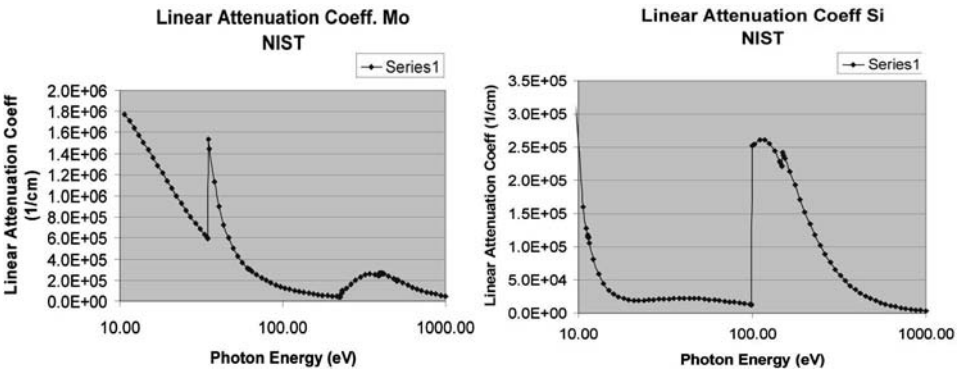


Figure 6C.26 Linear attenuation coefficients for Si and Mo for photon energies from 10 to 1000 eV.

Table 6C.8 Linear attenuation coefficients for Mo.

Photon energy (eV)	Linear attenuation coefficient (nm ⁻¹)
12	0.1643
90	0.0155

Since the energy is not only deposited on the surface of the collector but also penetrates into the surface, it could be beneficial to calculate the photon flux inside the mirror to be able to track transient heat loads that may initiate bilayer mixing.

The flux may be written in differential form as shown in Eq. (6C.10):

$$\frac{d}{dx}\phi(x) = -\mu\phi(x), \tag{6C.10}$$

where ϕ is the flux, and μ is the linear attenuation coefficient. This yields the well-known exponential flux relation:

$$\phi(x) = \phi_0 e^{-\mu x}. \tag{6C.11}$$

The attenuation coefficients for both Mo and Si are available as a function of photon energy from the NIST website (<http://physics.nist.gov/PhysRefData/FFast/html/form.html>). Plots of the linear attenuation coefficients for this energy range are shown in Fig. 6C.26.

The linear attenuation coefficients evaluated at 12 eV and 90 eV are summarized in Tables 6C.8 and 6C.9.

Figure 6C.27 is an evaluation of the intensity equation (6C.11) using the linear attenuation coefficients shown in Tables 6C.8 and 6C.9. As expected, the 8 to 18 nm (with an average of 90 eV) light that accounts for nearly two-thirds of the total radiation intensity incident upon the collector penetrates deep into the mirror and explains why many layers are required to reach the maximum reflectivity, due to

Table 6C.9 Linear attenuation coefficients for Si.

Photon energy (eV)	Linear attenuation coefficient (nm ⁻¹)
12	0.0081
90	0.0014

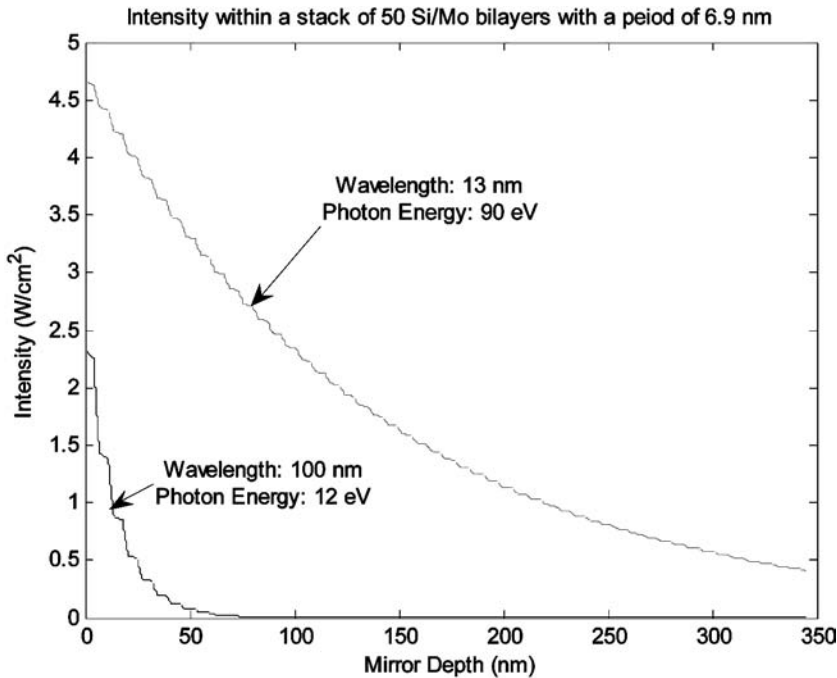


Figure 6C.27 Intensity distribution within the MLM due to linear attenuation for 12 and 90 eV light.

Bragg’s law. This radiation intensity is not absorbed power flux. Since the bilayer structure has a reflectivity around 65%, only about one-third of the intensity shown for the 90 eV light in Fig. 6C.27 is actually absorbed as heat. The 18 to 400 nm (12 eV weighted average) light that accounts for one-third of the total intensity of the incident light is attenuated much more quickly and is not greatly reflected, thus depositing most of its intensity as power near the surface of the mirror.

To further investigate the possibility of bilayer mixing, ion bombardment of the MLMs is studied using the Monte Carlo binary collision simulation (SRIM-2006). A flux of 8 keV Xe ions impacts a surface at an incidence angle of 10 deg from normal. The results of this simulation are depicted in Figs. 6C.28 and 6C.29. It was also determined that on average, four atoms are removed from the surface for every Xe ion that impacts the surface, and that 0.72% of the Xe ions are reflected. The fact that sputtering yield is greater than unity implies that the surface will be damaged by erosion, quickly rendering the capping layer irrelevant.

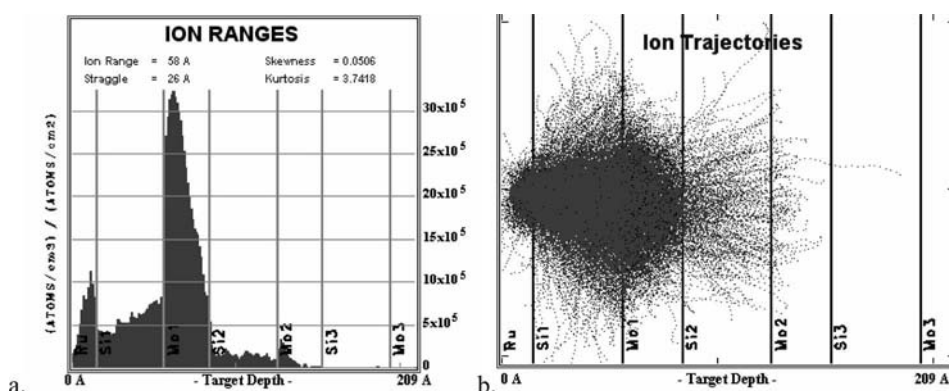


Figure 6C.28 (a) Relative number of ions stopped in a given depth within the MLM as a function of overall depth. (b) Trajectories traveled within the MLM as a function of depth.

Figure 6C.28, and in particular part (a), demonstrates a second danger that will threaten the longevity of a MLM. The majority of the Xe is stopped in the interface between the first Si and Mo layers, which could result in a buildup of Xe between layers and result in the delamination of the MLM. This would obviously drastically reduce the MLM's efficiency at reflecting EUV light. However, given the short distance to the surface, the Xe is likely to diffuse out of the material quickly—especially given the simultaneous erosion that is taking place.

Figure 6C.29 shows a more immediate threat. The large amount of mixing of the materials wipes out the clean separation between the layers upon which the Bragg interference depends. This could dramatically increase the roughness not of the top level surface, but of the interfaces between the two surfaces of the bilayer, and between one bilayer and the next.

High reflectivity from MLMs is the most important requirement for a collector optics system. Windt showed a maximum reflectivity of 75.5% at 13.4 nm.⁷³ He assumed an ideally flat surface, but due to an imperfection in the Mo/Si ML, the experimentally measured reflectivity was lower (68.7%). The intermixing zones are formed within the ML stacks, which is responsible for the lower reflectivity. Methods have been suggested to overcome this problem by introducing an interdiffusion barrier layer, which could prevent the layer intermixing and in turn the reflectivity loss. Braun et al. showed the electric field distribution within a ML, where the Bragg condition was fulfilled when the wavelength was equal to the period thickness.²⁷ This is shown in Fig. 6C.30, where the wave amplitude has node locations at the Mo-on-Si interface, which means that the EUV reflectivity will be weakly affected on these layers if an interdiffusion barrier layer is added at this location.

Braun et al. showed that if a thin layer is used as a barrier layer at the Mo-on-Si interface, an EUV reflectivity >75% can be obtained, regardless of the barrier material.²⁷ Both Bajt et al.⁷ and Braun et al.²⁷ have demonstrated that this approach really works. Figure 6C.31 clearly shows the reflectivities for different barrier layers of different thicknesses at the Mo-on-Si interface. It also shows that a silver

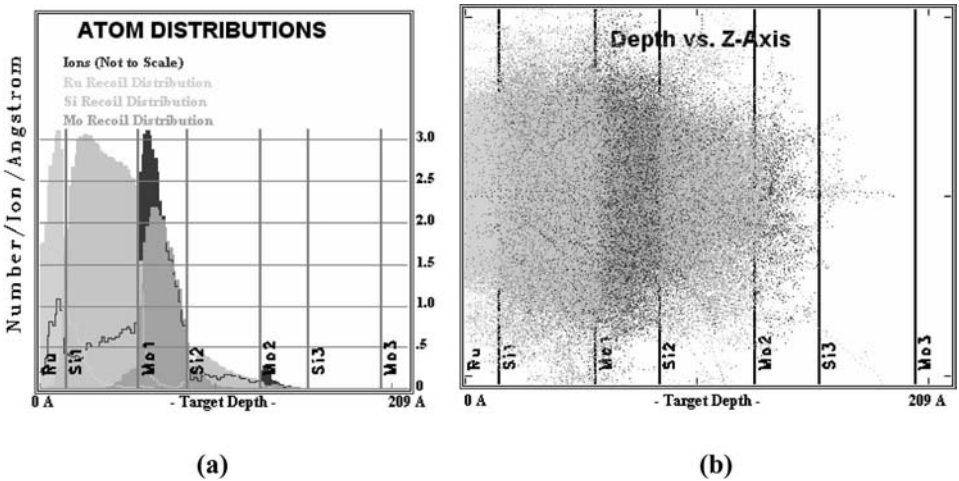


Figure 6C.29 (a) Relative numerical distribution of displaced atoms/ion stopping ranges as a function of MLM depth. (b) Trajectories of ions and atoms that are displaced within the MLM and their stopping positions as a function of MLM depth.

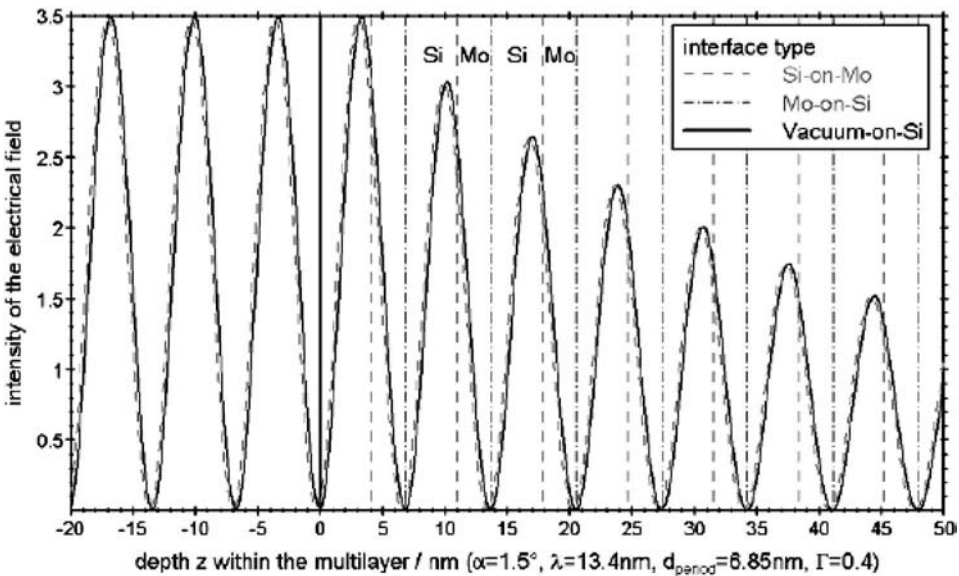


Figure 6C.30 Distribution of the electrical field intensity within a Mo/Si ML in the case of maximum reflectivity (Bragg condition fulfilled). The field strength is high at the Si-on-Mo interfaces and low at the Mo-on-Si interfaces. Therefore, at this interface a thin barrier layer, even one made of absorbing material, will not affect the field distribution and the EUV reflectivity. The dotted line shows the electrical field intensity in the case of a 0.5-nm-thick W barrier layer at the Mo-on-Si interface. (Reprinted from Ref. 27 with permission from the *Japanese Journal of Applied Physics*.)

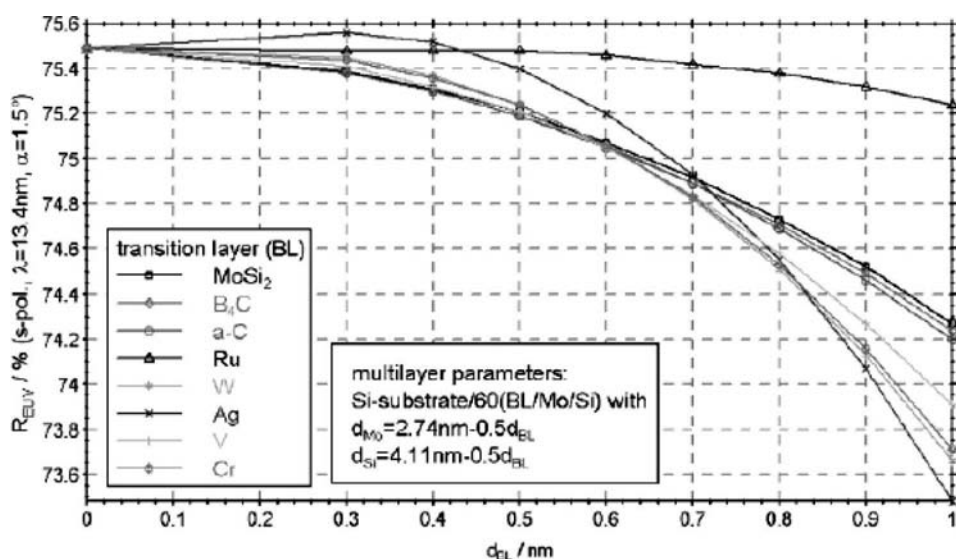


Figure 6C.31 Calculations of EUV reflectivity depending on the barrier-layer thicknesses of different materials at the Mo-on-Si interface. (Reprinted from Ref. 27 with permission from the *Japanese Journal of Applied Physics*.)

barrier layer gives reflectivity even higher than the ideal Mo/Si system. A 75.2% reflectivity is observed for Ru layers even at a 1-nm thickness.

For the Si-on-Mo interface, calculations from Braun et al.²⁷ show that even low EUV absorption materials (such as B₄C or carbon) as a barrier layer can degrade the reflectivity to a great extent (Fig. 6C.32). This figure shows the reflectivity depending on the thickness of the B₄C or carbon barrier layers compared with MoSi₂ transition layers. Braun et al. reported that the MoSi₂ transition layer thickness is about 0.7 nm at the Si-on-Mo interface. Thus, to obtain higher reflectivity, the barrier layers should be thin (B₄C < 0.5 nm and carbon < 0.3 nm).

Many researchers have addressed the problem of interface stabilization in Mo/Si MLs and the effect of annealing at elevated temperatures on the interdiffusion layers.^{74,75} Feigl et al. reported the thermal stability of several materials, annealed in the temperature range 100°C–500°C.²¹ A comparison of reflectivity from annealed Mo/Si and Mo₂C/Si layers are presented in Fig. 6C.33. The measurement shows the reflectivity change after annealing for 2 hours.

Figure 6C.34 shows the change in peak wavelength and in peak reflectivity versus annealing temperature. The general decrease in both of these parameters is known because of the silicide formation at the interfaces and the interdiffusion. Feigl et al. measured the reflectivities after deposition for both Mo/Si and Mo₂C/Si ML systems, and the measured reflectivities were 68.4% and 66.8%, respectively.²¹ For $T > 300^\circ\text{C}$, they found that $R_{\text{Mo}_2\text{C/Si}} > R_{\text{Mo/Si}}$. They also revealed that interdiffusion due to the thermal load is hindered by the presence of carbon, which gives a higher thermal stability for Mo₂C/Si MLs than Mo/Si.

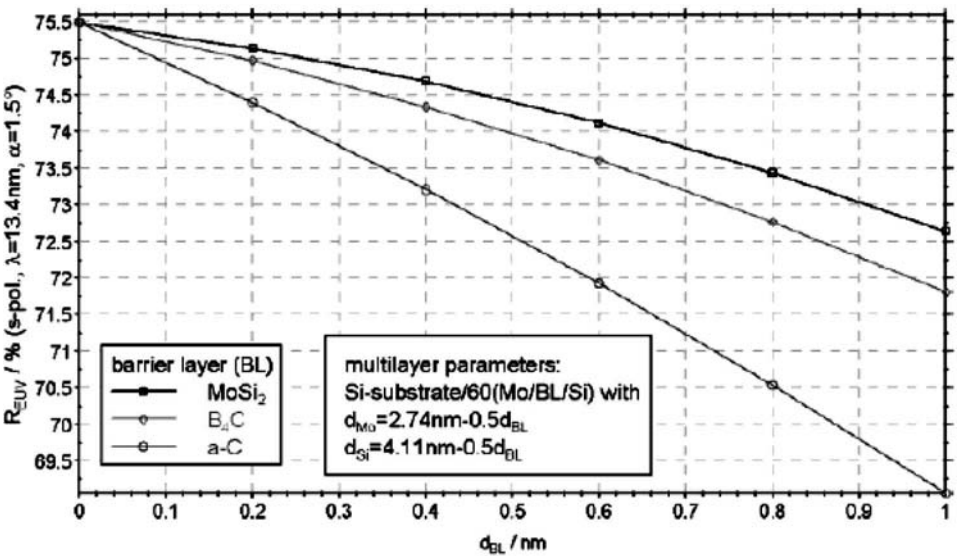


Figure 6C.32 Calculations of EUV reflectivity depending on the thicknesses of B_4C and carbon barrier layers in comparison to MoSi_2 transition layers at the Si-on-Mo interface. (Reprinted from Ref. 27 with permission from the *Japanese Journal of Applied Physics*.)

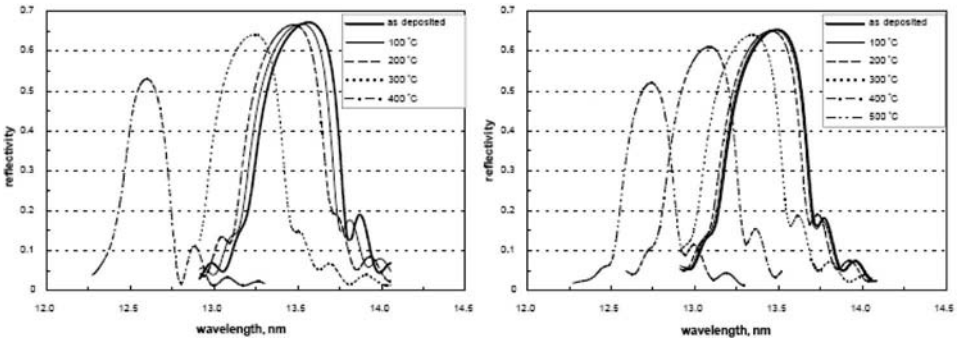


Figure 6C.33 Measured Mo/Si (left) and $\text{Mo}_2\text{C}/\text{Si}$ (right) ML reflectances after 2 hours of annealing at $T = 100^\circ\text{C}$ – 500°C . (Reprinted from Ref. 21 with permission from the *Japanese Journal of Applied Physics*.)

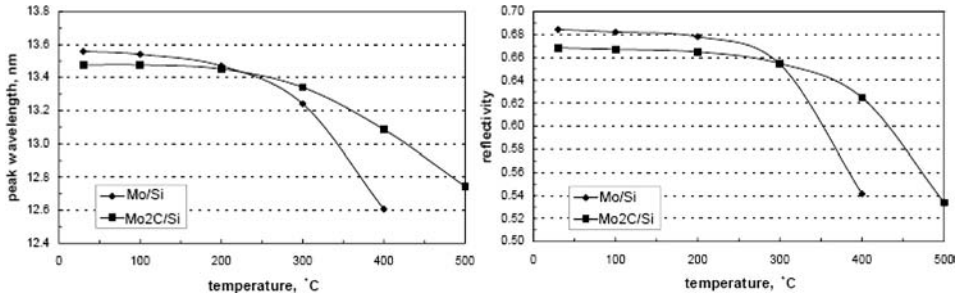


Figure 6C.34 Change in the peak reflectivity (left) and the peak wavelength (right) versus annealing temperature. (Reprinted from Ref. 21 with permission from the *Japanese Journal of Applied Physics*.)

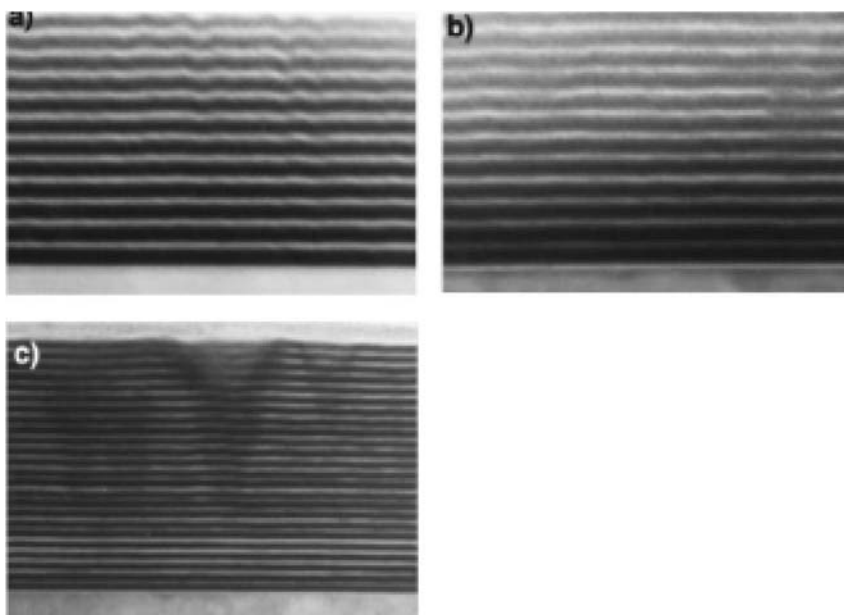


Figure 6C.35 TEM picture of Mo/Si MLs produced at different temperatures: (a) 388 K, (b) 478 K, and (c) 511 K. (Reprinted from Ref. 17 with permission from the American Institute of Physics.)

Voorma et al. studied the performance of Mo/Si MLs at elevated temperatures.¹⁷ Three samples were produced in an e-beam coating at three different temperatures (388 K, 478 K, and 511 K) and analyzed with TEM as shown in Fig. 6C.35, where the light and dark areas represent Si and Mo, respectively.

They observed three types of interface roughness: ripples, V-shaped, and intermixing. Ripple formations are known and have been reported elsewhere.⁷⁶ In Fig. 6C.35, a strong correlation between the surfaces can be seen at 388 K, where the ripples have the same structure. An increase in the temperature essentially smoothes the layer structure. Voorma et al. also observed the V-shaped structure at high temperatures, which is a known phenomenon that occurs in MLs at high temperatures. Their results show that the optimum interface roughness is at 488 K.

Benoit et al. reported radiation stability by irradiating samples with a Xe gas discharge source, pulsed at 50 Hz. Mo/Si mirrors were irradiated up to 8 hours, without a mitigation system, and placed at 140 mm from the source at normal incidence.⁷⁷

Benoit et al. also showed a peak reflectivity of 68.5% from a Mo/Si ML after deposition, whereas the reflectivity after 8 hours of radiation exposure was 50%. The Si top layer underwent complete oxidation, and the Mo top layer underwent partial oxidation based on the XPS results. They then investigated the reflectivity change from a MoSi₂/Si ML system upon thermal treatment. Figure 6C.36 shows a comparison of EUV reflectivity in the as-deposited state and after annealing at 500°C for the MoSi₂/Si system. Long-term annealing up to 650°C was also

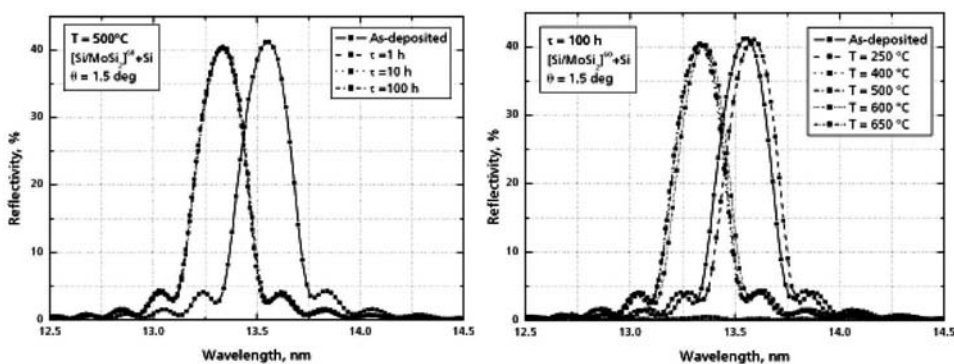


Figure 6C.36 Comparison of the EUV reflectivity curves measured for MoSi_2/Si MLMs in an as-deposited state and after annealing at $T = 500^\circ\text{C}$; and the evolution of EUV properties of such mirrors after long-term annealing up to 650°C . (Reprinted from Ref. 77.)

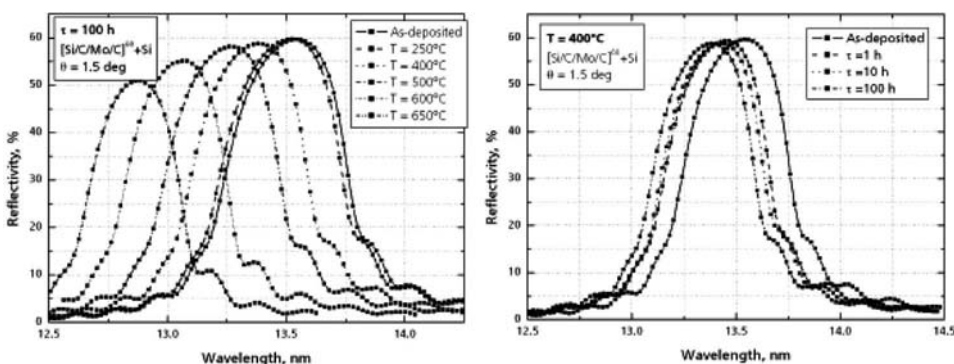


Figure 6C.37 Comparison of the EUV reflectivity curves measured for Mo/C/Si/C MLMs in the as-deposited state and after annealing at $T = 400^\circ\text{C}$. The evolution of the EUV properties of such mirrors after long-term annealing at temperatures up to 650°C is also shown. (Reprinted from Ref. 77.)

performed, as shown in Fig. 6C.36. A shift in the center wavelength as well as a reflectivity drop was observed. Benoit et al. suggested inserting a carbon layer between the Mo-Si and Si-Mo interfaces and investigated thermal treatments. EUV reflectivity was measured in the as-deposited state as well as after annealing at 400°C , as shown in Fig. 6C.37. Thermal-induced changes were observed for both the annealing time and the temperature treatments.

The change in the center wavelength with an annealing temperature of 400°C can be explained as the change in interdiffusion at the Mo/C/Si/C interfaces. The wavelength shifts at different annealing temperatures should also be noted. The formation of a new compound, SiC, was confirmed using large-angle x-ray diffraction, which was the result of inter-diffusion after sample annealing at 400°C for 100 hours.

Takenaka et al. investigated the effect of heating on the layer structure of Mo/Si and two Mo-silicide/Si (MoSi_2/Si and $\text{Mo}_5\text{Si}_3/\text{Si}$) MLs.⁷⁸ As shown in Fig. 6C.38,

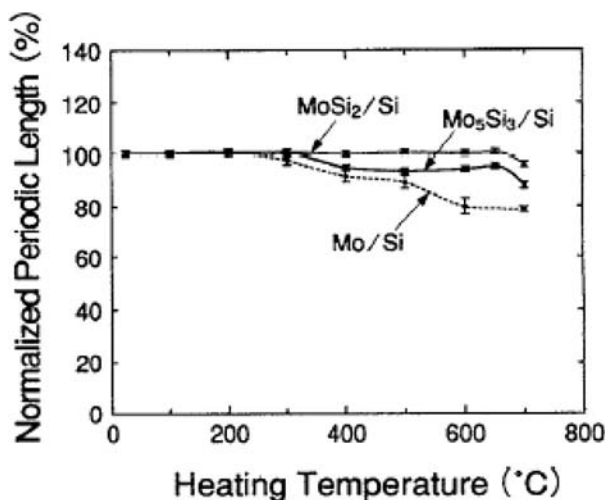


Figure 6C.38 Relationship between the normalized periodic length of Mo/Si, MoSi₂/Si, and Mo₅Si₃/Si MLs and heating temperature. (Reprinted from Ref. 78 with permission from the American Institute of Physics.)

the periodic length decreases with increasing temperature. The maximum change is observed in Mo/Si, whereas MoSi₂/Si showed a constant periodic length up to 600°C. The changes noted in Mo₅Si₃/Si were between the other two MLs.

Takenaka et al. also performed TEM characterization for as-deposited, 600°C and 700°C MLs (Fig. 6C.39) to reveal thermally induced deterioration in all three ML structures. Mo/Si MLs clearly showed inter-diffusion layers in the as-deposited state, but as the temperature increased, they showed larger inter-diffusion layers. The MoSi₂/Si ML showed a well-defined structure even at elevated temperatures [Figs. 6C.39B(a) and 6C.39B(b)], and they have almost the same structure as Mo₅Si₃/Si MLs [Figs. 6C.39C(a) and 6C.39C(b)]. At 700°C, the Mo₅Si₃/Si ML showed a structure similar to Mo/Si, while the MoSi₂/Si ML showed small agglomerations [Figs. 6C.39B(c) and 39C(c)]. The results suggest that MoSi₂/Si MLs are thermally more stable than other ML structures.

To improve the heat stability of MLs, Ishino et al. inserted SiO₂ layers into the interfaces of Mo/Si MLs.²⁸ They revealed that the Mo/Si MLs inserted with SiO₂ layers are thermally more stable than conventional Mo/Si MLs.

Numerous designs are being tested against the thermal load on normal-incidence collector optics. In one such design suggested by Sagem Défense Sécurité (SAFRAN Group), the collectors were at a greater distance from the source to avoid radiation and thermal damage. While this design required two reflections to reach the intermediate focus, a larger solid collection angle is possible than in a grazing-incidence collector, and the area near the pinch is still available for a foil trap debris mitigation system since the light rays traverse that region in only one direction.

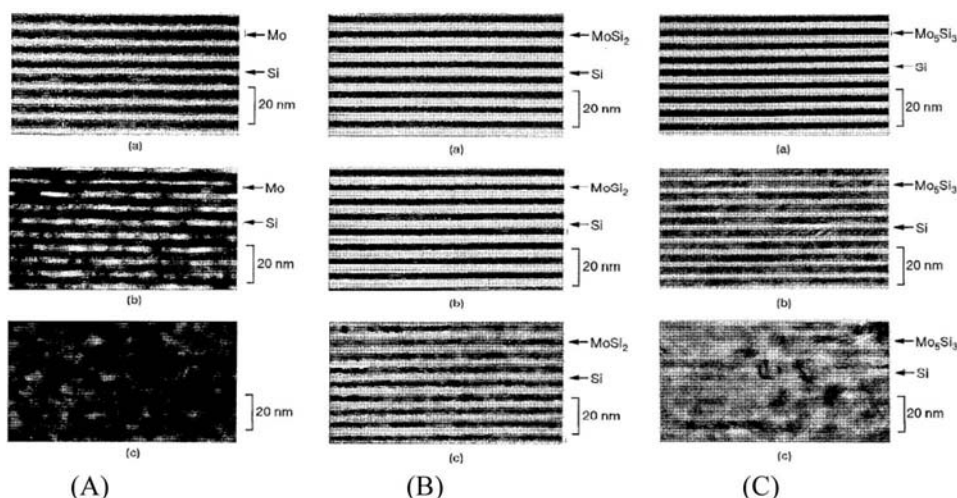


Figure 6C.39 (A) TEM cross-section for (a) as-deposited, (b) 600°C heated, and (c) 700°C heated Mo/Si MLs. (B) TEM cross-section for (a) as-deposited, (b) 600°C heated, and (c) 700°C heated MoSi₂/Si MLs. (C) TEM cross-section for (a) as-deposited, (b) 600°C heated, and (c) 700°C heated Mo₅Si₃/Si MLs. (Reprinted from Ref. 78 with permission from the *Japanese Journal of Applied Physics*.)

6C.4 Summary

EUVL is the leading NGL candidate for producing feature sizes below 32 nm in the HVM of chips. One main difference between EUVL and other lithography techniques is that EUVL requires reflective optics because sufficient transmission at the EUV wavelength does not exist. For normal-incidence collector optics, a Mo-Si MLM is designed to reflect light at 13.5 nm. This normal-incidence collector mirror is exposed to plasma, either in DPP or LPP EUV sources. The optics surface is subjected to harsh plasma debris in the form of fast ions, neutrals, radiation, and thermal load, which results in reflectivity loss. Reflectivity is also greatly affected by oxidation and carbon deposition on the mirror surfaces.

Ion damage of mirror surfaces, which degrades the reflectivity to a great extent, has been investigated by several groups, and progress toward measuring and characterization of the ion debris has been reported. High-energy ions are responsible for surface erosion, roughness, and ion implantation. Debris mitigation schemes have been developed to improve the mirror lifetime, and a quantitative estimate of mirror surface erosion and lifetime has been developed. Mitigation schemes are an absolute necessity to prevent the destruction of reflective mirror surfaces by plasma debris. An advanced fuel such as Sn has the advantage of providing greater conversion efficiency; it is condensable and deposits on the mirror surface, which in turn degrades the reflectivity. Several cleaning techniques have been developed to remove contaminants from normal-incidence mirror surfaces, and the EUV reflectivity can be restored after cleaning. Thermal load on the microstructure of Mo-Si MLs have been investigated in great detail. Reflectivity loss due to layer

intermixing could be a significant obstacle to using MLs in a HVM fab, especially if cleaning techniques require the operation of collector optics at higher temperatures. To optimize the performance of mirrors, several researchers have worked on interlayer diffusion barriers to avoid layer intermixing. Results so far are encouraging, though advancements in current technologies are still needed for successful implementation of EUVL in HVM.

Acknowledgments

We would like to express special thanks to graduate students Keith C. Thompson, Hyungjoo Shin, Huatan Qiu, and Josh B. Spencer for their pioneering work to study and investigate the source-collector problem at the Center for Plasma Material Interactions (CPMI). We also thank Drs. Erik L. Antonsen and Brian E. Jurczyk for their devotion to this project. The results could not have been achieved without the help of undergraduate students John Sporre, David Papke, and Bob Lofgren. We also acknowledge INTEL, XTREME, CYMER, ENERGETIQ, SEMATECH, ASML, UCD, and Starfire Industries for general funding of EUV efforts at CPMI.

References

1. U. Stamm, J. Kleinschmidt, K. Gabel, et al., "EUV source power and lifetime: the most critical issues for EUV lithography," *Proc. SPIE* **5374**, 133–144 (2004).
2. M. Richardson, C.-S. Koay, K. Takenoshita, et al., "Laser plasma EUVL sources—progress and challenges," *Proc. SPIE* **5374**, 447–453 (2004).
3. D. Windt, R. Hull, and K. Waskiewicz, "Interface imperfections in metal/Si multilayers," *J. Appl. Phys.* **71**, 2675–2678 (1992).
4. M. Slaughter, P. Kearney, D. Schulze, et al., "Interfaces in Mo/Si multilayers," *Proc. SPIE* **1343**, 73–82 (1990).
5. R. Rosen, D. Stearns, M. Viliardos, et al., "Silicide layer growth rates in Mo/Si multilayers," *Appl. Opt.* **34**, 6975–6980 (1993).
6. H. Takenaka and T. Lawamura, "Thermal stability of Mo/C/Si/C multilayer soft x-ray mirrors," *J. of Elec. Spec. and Rel. Phenom.* **80**, 381–384 (1996).
7. S. Bajt, J. B. Alameda, T. W. Barbee Jr., et al., "Improved reflectance and stability of Mo-Si multilayers," *Opt. Eng.* **41**, 1797 (2002).
8. R. R. Kola, D. L. Windt, W. K. Waskiewicz, et al., "Stress relaxation in Mo/Si multilayer structures," *Appl. Phys. Lett.* **60**, 3120–3122 (1992).
9. H. Azuma, A. Takeichi, I. Konomi, Y. Watanabe, and S. Noda, "Thermally induced structural modification of nanometer-order Mo/Si multilayers by the spectral reflectance of laser-plasma soft x-rays," *Jpn. J. Appl. Phys.* **43**, 2078–2082 (1993).
10. D. L. Windt, "Stress, microstructure, and stability of Mo/Si, W/Si, and Mo/C multilayer films," *J. Vac. Sci. Technol. A* **18**, 980–991 (2000).

11. Z. Jiang, X. Jiang, W. Liu, and Z. Wu, "Thermal stability of multilayer films Pt/Si, Mo/Si, and W/Si," *J. Appl. Phys.* **65**, 196–200 (1989).
12. R. S. Rosen, D. G. Stearns, M. A. Villiardos, M. E. Kassner, S. P. Vernon, and Y. Cheng, "Silicide layer growth rates in Mo/Si multilayers," *Appl. Opt.* **32**, 6975–6980 (1993).
13. Kloidt, K. Nolting, U. Kleineberg, et al., "Enhancement of the reflectivity of Mo/Si multilayer mirrors by thermal treatment," *Appl. Phys.* **58**, 2601–2603 (1991).
14. Montcalm, "Reduction of residual stress in extreme ultraviolet Mo/Si multilayer mirrors with post deposition thermal treatments," *Opt. Eng.* **40**, 469–477 (2001).
15. L. Windt, S. Donguy, J. Seely, and B. Kijornrattanawanich, "Experimental comparison of extreme-ultraviolet multilayers for solar physics," *Appl. Opt.* **43**, 1835–1848 (2004).
16. J. M. Liang and L. J. Chen, "Interfacial reactions and thermal stability of ultrahigh vacuum deposited multilayered Mo/Si structures," *J. Appl. Phys.* **79**, 4072–4077 (1996).
17. T. Feigl, S. Yulin, T. Kuhlmann, and N. Kaiser, "Damage resistant and low stress EUV multilayer mirrors," *Jpn. J. Appl. Phys.* **41**, 4082–4085 (2002).
18. Y. Ijdiyaou, M. Azizan, E. L. Ameziane, M. Brunel, and T. A. N. Tan, "On the formation of molybdenum silicides in Mo-Si multilayers: The effect of Mo thickness and annealing temperature," *Appl. Surf. Sci.* **55**, 165–171 (1992).
19. V. V. Kontradenko, Yu. P. Pershin, O. V. Poltseva, et al., "Thermal stability of soft x-ray Mo-Si and MoSi₂-Si multilayer mirrors," *Appl. Opt.* **32**, 1811–1816 (1993).
20. H.-J. Voorma, E. Louis, N. B. Koster, and F. Bijkerk, "Temperature induced diffusion in Mo/Si multilayer mirrors," *J. Appl. Phys.* **83**, 4700–4708 (1998).
21. T. Leisegang, D. C. Meyer, A. A. Levin, S. Braun, and P. Paufler, "On the interplay of internal/external stress and thermal stability of Mo/Si multilayers," *Appl. Phys. A* **77**, 965–972 (2003).
22. T. Feigl, H. Lauth, S. Yulin, and N. Kaiser, "Heat resistance of EUV multilayer mirrors for long-time applications," *Microelectr. Eng.* **57–58**, 3–8 (2001).
23. E. Ziegler, "Multilayers for high heat load synchrotron applications," *Opt. Eng.* **34**, 445–452 (1995).
24. T. Böttger, D. C. Meyer, P. Paufler, et al., "Thermal stability of Mo/Si multilayers with boron carbide interlayers," *Thin Solid Films* **444**, 165–173 (2003).
25. H. Takenaka, H. Io, T. Haga, and T. Kawamura, "Design and fabrication of highly heat resistant Mo/Si multilayer soft x-ray mirrors with interleaved barrier layers," *J. Synchrotron Rad.* **5**, 708–710 (1998).
26. S. Bajt, "High-reflectance interface-engineered multilayers," invited talk at PXRMS'02, Chamonix, France, <http://cletus.phys.columbia.edu/~pxrms/archives/pxrms02/index.html> (2002).
27. S. Braun, H. Mai, M. Moss, R. Scholz, and A. Leson, "Mo/Si multilayers with different barrier layers for applications as extreme ultraviolet mirrors," *Jpn. J. Appl. Phys.* **41**, 4074–4081 (2002).

28. M. Ishino, O. Yoda, H. Takenaka, K. Sano, and M. Koike, "Heat stability of Mo/Si multilayers inserted with compound layers," *Surf. Coat. Technol.* **169–170**, 628 (2003).
29. J. A. Folta, S. Bajt, T. W. Barbee, Jr., et al., "Advances in multilayer reflective coatings for extreme-ultraviolet lithography," *Proc. SPIE* **3676**, 702–709 (1999).
30. M. Putero-Vuaroqueaux and B. Vidal, "Extreme-ultraviolet multilayer mirrors deposited using radio-frequency magnetron sputtering: the influence of self-bias voltage on reflectivity and roughness," *J. Phys. Condens. Matter* **13**, 3969–3976 (2001).
31. E. Spiller, S. Baker, P. A. Mirkarimi, et al., "High performance Mo₂/Si multilayer coatings for EUV lithography using ion beam deposition," *Appl. Opt.* **42**, 4049–4058 (2003).
32. E. Louis, A. E. Yakshin, P. C. Görts, et al., "Progress in Mo/Si multilayer coating technology for EUVL optics," *Proc. SPIE* **3997**, 406–411 (2000).
33. St. Braun, R. Dietsch, M. Haidl, et al., "Mo/Si multilayers for EUV applications prepared by pulsed laser deposition (PLD)," *Microelectron. Eng.* **57–58**, 9–15 (2001).
34. M. Shiraishi, N. Kandaka, and K. Murakami, "Mo/Si multilayers deposited by low-pressure rotary magnet cathode sputtering for extreme ultraviolet lithography," *Proc. SPIE* **5037**, 249–256 (2003).
35. J. H. Underwood, E. M. Gullikson, and K. Nguyen, "Tarnishing of Mo/Si multilayer x-ray mirrors," *Appl. Opt.* **32**, 6985–6990 (1993).
36. D. P. Gaines, R. C. Spitzer, N. M. Ceglio, M. Krumrey, and G. Ulm, "Radiation hardness of molybdenum silicon multilayers designed for use in a soft-x-ray projection lithography system," *Appl. Opt.* **32**, 6991–6998 (1993).
37. L. E. Klebanoff, W. M. Clift, M. E. Malinowski, et al., "Radiation-induced protective carbon coating for extreme ultraviolet optics," *J. Vac. Sci. Technol. B* **20**, 696–703 (2002).
38. L. E. Klebanoff, M. E. Malinowski, P. Grunow, et al., "First environmental data from the EUV engineering test stand," *Proc. SPIE* **4343**, 342–346 (2001).
39. S. Oestreich, R. Klein, F. Scholze, et al., "Multilayer reflectance during exposure to EUV radiation," *Proc. SPIE* **4146**, 64–71 (2000).
40. M. Wedowski, S. Bajt, J. A. Folta, et al., "Lifetime studies of Mo/Si and Mo/Be multilayer coatings for extreme ultraviolet lithography," *Proc. SPIE* **3767**, 217–224 (1999).
41. N. Koster, B. Mertens, R. Jansen, et al., "Molecular contamination mitigation in EUVL by environmental control," *Microelectron. Eng.* **61–62**, 65–76 (2002).
42. B. M. Mertens, B. van der Zwan, P. W. H. de Jager, et al., "Mitigation of surface contamination from resists outgassing in EUV lithography," *Microelectron. Eng.* **53**, 659–662 (2000).
43. S. Graham, C. Steinhaus, M. Clift, and L. Klebanoff, "Radiofrequency discharge cleaning of silicon-capped Mo/Si multilayer extreme ultraviolet optics," *J. Vac. Sci. Technol. B* **20**, 2393–2400 (2002).

44. K. Hamamoto, T. Tanaka, T. Watanabe, et al., "Cleaning of extreme ultraviolet lithography optics and masks using 13.5 nm and 172 nm radiation," *J. Vac. Sci. Technol. B* **23**, 247–251 (2005).
45. S. Bajt, H. N. Chapman, N. Nguyen, et al., "Design and performance of capping layers for EUV multilayer mirrors," *Proc. SPIE* **5037**, 236–248 (2003).
46. S. Bajt, H. N. Chapman, N. Nguyen, et al., "Design and performance of capping layers for extreme-ultraviolet multilayer mirrors," *Appl. Opt.* **42**, 5750–5758 (2003).
47. B. M. Mertens, N. Koster, R. Jansen, et al., ASET/SEMATECH Workshop on EUV Lithography, Matsue, pp. O4–5, SEMATECH (2001).
48. E. Yakshin, E. Louis, E. L. G. Maas, et al., "Protection of Mo/Si multilayers with carbon capping layer," ASET/SEMATECH Workshop on EUV Lithography, Matsue, pp. P6–6, SEMATECH (2001).
49. W. Gwyn, R. Stulen, D. Sweeney, and D. Attwood, "Extreme ultraviolet lithography," *J. Vac. Sci. Technol. B* **16**, 3142 (1998).
50. R. B. Hoover, D. L. Shealy, B. R. Brinkley, et al., "Development of the water window imaging x-ray microscope utilizing normal incidence multilayer optics," *Opt. Eng.* **30**, 1086 (1991).
51. N. M. Ceglio, D. G. Stearns, D. P. Gaines, A. W. Hawryluk, and J. E. Trebes, "Multipass amplification of soft x rays in a laser cavity," *Opt. Lett.* **13**, 108 (1988).
52. M. Finkenthal, A. P. Zwicker, S. P. Regan, H. W. Moos, and D. Stutman, "Near normal incidence spectroscopy of a penning ionization discharge in the 110–180 Å range with flat multilayer mirrors," *Appl. Opt.* **29**, 3467 (1990).
53. T. W. Barbee, et al., "Multi-spectral solar telescope array II. Soft x-ray/EUV reflectivity of the multilayer mirrors," *Opt. Eng.* **30**, 1067 (1991).
54. D. S. Martinez-Galarce, A. B. C. Walker, D. B. Gore, et al., "High resolution imaging with multilayer telescopes: resolution performance of the MSSTA II telescopes," *Opt. Eng.* **39**, 1063 (2000).
55. M. Toyoda, Y. Shitami, M. Yanagihara, et al., "A soft-x-ray imaging microscope with a multilayer-coated Schwarzschild objective: Imaging tests," *Jpn. J. Appl. Phys. Part 1*(39), 1926 (2000).
56. J. A. Folta, S. Bajt, T. W. Barbee, et al., "Advances in multilayer reflective coatings for extreme-ultraviolet lithography," *Proc. SPIE* **3676**, 702 (1999).
57. E. Spiller, *Soft X-ray Optics*, SPIE Press, Bellingham, WA (1994).
58. J. R. Meyer-Arendt, *Introduction to Classical and Modern Optics*, xv, 4314th ed., Prentice Hall, Englewood Cliffs, NJ (1995).
59. D. T. Attwood, *Soft X-Rays and Extreme Ultraviolet Radiation: Principles and Applications*, Vol. xvi, p. 470, Cambridge University Press, Cambridge, New York (2000).
60. Burle Electro-Optics, www.burle.com, Sturbridge, MA.
61. E. Antonsen, K. C. Thompson, M. R. Hendricks, et al., "Ion debris characterization from a Z-pinch extreme ultraviolet light source," *J. Appl. Physics* **99**, 063301 (2006).

62. H. Komori, G. Soumagne, H. Hoshino, et al., "Ion damage analysis on EUV collector mirrors," *Proc. SPIE* **5374**, 839–846 (2004).
63. R. J. Anderson, D. A. Buchenauer, K. A. Williams, et al., "Investigation of plasma-induced erosion of multilayer condenser optics," *Proc. SPIE* **5751**, 128–139 (2005).
64. D. N. Ruzic, K. C. Thompson, B. E. Jurczyk, et al., "Reduction of ion energies from a multi-component z-pinch plasma," *IEEE Transactions on Plasma Science* **35**, 606–613 (2007).
65. S. S. Harilal, M. S. Tillack, Y. Tao, et al., "Extreme ultraviolet spectral purity and magnetic ion debris mitigation with low density tin targets," *Opt. Lett.* **31**, 1549 (2006).
66. D. J. W. Klunder, M. M. J. W. van Herpen, V. Y. Banine, and K. Gielissen, "Debris mitigation and cleaning strategies for Sn-based sources for EUV lithography," *Proc. SPIE* **5751**, 943–951 (2005).
67. S. Graham, C. Steinhaus, M. Clift, L. Klebanoff, and S. Bajt, "Atomic hydrogen cleaning of EUV multilayer optics," *Proc. SPIE* **5037**, 460–469 (2003).
68. S. Graham, et al., "Studies of EUV contamination mitigation," *Proc. SPIE* **4688**, 431 (2002).
69. M. Malinowski, et al., "Use of molecular oxygen to reduce EUV-induced carbon contamination of optics," *Proc. SPIE* **4343**, 347 (2001).
70. K. Hamamoto, et al., "Investigation of contamination removal from finished EUVL mask," *J. Photopolym. Sci. Technol.* **16**, 395 (2003).
71. H. Oizumi, H. Yamanashi, I. Nishiyama, et al., "Contamination removal from EUV multilayer using atomic hydrogen generated by heated catalyzer," *Proc. SPIE* **5751**, 1147–1154 (2005).
72. G. Bianucci, F. E. Zocchi, G. Pirovano, et al., "Thermal management design and verification of collector optics into high power EUV source systems," *Proc. SPIE* **6517**, 65171S-1–65171S-12 (2007).
73. D. L. Windt, "IMD-software for modelling the optical properties of multilayer films," *Comput. Phys.* **12**, 360–370 (1998).
74. K. Holloway, K. B. Do, and R. Sinclair, "Interfacial reactions on annealing molybdenum-silicon multilayers," *J. Appl. Phys.* **65**, 474 (1989).
75. D. G. Stearns, M. B. Stearns, Y. Cheng, J. H. Smith, and N. M. Ceglio, "Thermally induced structural modification of Mo-Si multilayers," *J. Appl. Phys.* **67**, 2415 (1990).
76. M. Niibe, M. Haysashida, T. Iizuka, et al., "Suppression of columnar structure formation in Mo-Si layered synthesis microstructure," *Proc. SPIE* **1343**, 2 (1990).
77. N. Benoit, S. Yulin, T. Feigl, and N. Kaiser, "EUV multilayer mirrors with enhanced stability," *Proc. SPIE* **6317** (2006).
78. H. Takenaka, T. Kawamura, Y. Ishii, S. A. Nishi-shinjuku, and Shinjuku-ku, "Heat resistance of MoBi, MoSiSi, and Mo/Si multilayer soft x-ray mirrors," *J. Appl. Phys.* **78**, 9 (1995).



David N. Ruzic is a professor in the Department of Nuclear, Plasma and Radiological Engineering at the University of Illinois at Urbana-Champaign. He joined the faculty in 1984 after receiving his PhD in Physics from Princeton University and doing post-doctoral work at Princeton Plasma Physics Laboratory. His research centers on the interaction of plasmas with materials; applications include magnetic fusion energy as well as microelectronic processing. Professor Ruzic

has a passion for teaching, particularly about energy sources, because he gets to blow something up in almost every class.



Shailendra Srivastava is a post-doctoral fellow in the Department of Nuclear, Plasma and Radiological Engineering at the University of Illinois at Urbana-Champaign. Dr. Srivastava obtained his PhD degree from Technische Universitaet Kaiserslautern, Germany, in experimental physics, where he worked extensively on laser-produced plasmas. His current research interests are plasma material interactions, advanced debris mitigation techniques for Sn- and Xe-fueled

EUV sources, and contamination studies from collector optics and the methods to remove them.

Chapter 7

EUV Mask and Mask Metrology

Han-Ku Cho and Jinho Ahn

Contents

7.1	Introduction	326
7.2	EUV Mask Structure and Process Flow	327
7.3	Mask Substrate	328
7.3.1	Mechanical property requirements	329
7.3.2	Surface figure requirements	330
7.3.3	Defect requirements	332
7.4	Mask Blank Fabrication	332
7.4.1	Multilayer deposition process	332
7.4.2	Multilayer characterization	335
7.4.3	Multilayer performance improvement techniques and defect mitigation	337
7.4.4	Multilayer defect inspection	342
7.4.5	Multilayer defect repair	345
7.4.6	Multilayer defect compensation	347
7.5	Absorber Stack and Backside Conductive Coating	349
7.5.1	Absorber layer	349
7.5.2	Buffer layer	349
7.5.3	Antireflection coating	350
7.5.4	Shadowing effect	351
7.5.5	Bossung curve asymmetry and focus shift	352
7.5.6	Backside conductive coating and mask handling	353
7.6	Mask Patterning	355
7.6.1	E-beam writing	355
7.6.2	Absorber stack etch	355
7.6.3	Absorber defect inspection	357
7.6.4	Absorber defect repair	357
7.6.5	Buffer layer etch	360
7.6.6	Buffer layer defect inspection and repair	360
7.7	Mask Cleaning	361
7.8	Advanced Mask Structure	363
7.8.1	Etched binary mask	364
7.8.2	Attenuated phase shift mask	366
7.8.3	Alternating phase shift mask	371

7.8.4 Modified alternating phase shift mask	372
7.9 Summary and Future Outlook	372
Acknowledgments	373
References	373

7.1 Introduction

For the successful implementation of extreme ultraviolet lithography (EUVL) technology for the future semiconductor fabrication process, EUV mask technology is considered to be one of the most critical issues. Since EUV light is strongly absorbed by most materials, reflective optics is applied to all the optical components, including the mask. As a result, the EUV mask structure, based on the mirror-type mask blank, is radically different from that of conventional optical lithography. All the mask components must be prepared with great care to consider the 13.5-nm reflection, which requires nano-scale thin-film technologies. The *International Technology Road Map for Semiconductors* (ITRS) forecasted that the target technology node for EUVL implementation would be 32 nm and below; today, mask defects are the leading challenge for EUV masks.

The reflection of a 13.5-nm wavelength requires a multilayer (ML) structure consisting of many alternating layers of materials having dissimilar EUV optical constants. The Bragg reflection—constructive interference of the partially reflected beam at several interfaces—is the only principle to have EUV reflection, and its efficiency is determined by the structural factor (e.g., the thickness of each layer and their ratios) as well as optical properties (refractive index and extinction coefficient). To produce optical contrast for imaging, the patterns with high EUV absorbance should be formed on the top of this ML mirror. An oblique incident light angle, which is inevitable during image transfer with an EUVL system and causes a shadowing effect, imposes a unique restriction for the EUV mask structure. The ML and absorber specifications are specified in the standard SEMI P38-1103.

The mask format specified by SEMI P37-1102 is $152\text{ mm} \pm 0.1\text{ mm}^2$ with a thickness of $6.35\text{ mm} \pm 0.1\text{ mm}$, which is consistent with the current optical mask format. This same form factor allows us to use the current mask fabrication infrastructure with minimum modification. However, special considerations are required for the tools in order to meet the mask requirements for sub-32-nm pattern transfer. One consideration is defect mitigation to minimize fabrication-induced mask defects. The other consideration is the mask inspection issue caused by the wavelength-dependent defectivity. EUV-specific metrology tools will be discussed in the following sections. Also, mask chucking to minimize the mask distortion due to mask nonflatness should be matched among the metrology tools, the e-beam writer, and the EUV stepper.

Table 7.1 shows SEMATECH's commercial EUV blank requirements needed for 32-nm half-pitch production through the program evaluations by year-end 2006. During the past few years, a lot of progress has been made in EUV mask fabrication processes. However, to meet all the requirements for the application to

Table 7.1 SEMATECH's commercial EUV blank requirements needed for 32-nm half-pitch assessed production through the program evaluations by year-end 2006.¹

December 2006 status	Parameter	Requirements
Substrate Material	Mean CTE ($\pm$ ppb/K)	± 5
	CTE Spatial Var. ($\pm$ ppb/K)	6
	Flatness Front (nm) (P-V)	32
	Flatness Back (nm) (P-V)	32
Substrate Finish	MSFR (nm rms)	N/A
	HSFR (nm rms)	<0.15
	High Local Slope front sur. (mrad 3s)	<1.8
Substrate Defects	Substrate Defects Density (def/cm ²)	0.003
	Cut-off size (PSL equivalent, nm)	30
Total Blank Defects	Total ML Defects Density (def/cm ²)	0.003
	Cut-off size (PSL equivalent, nm)	25
Multilayer Performance	Peak Reflectivity (%)	>67
	Peak Reflectivity Unif. (%P-V) Abs.	0.33
	Median central λ of Reflectivity (nm)	TBD
	Median central λ Offset (nm)	< ± 0.06
	Median Reflected λ Unif. (nm P-V)	0.05

sub-32-nm technology nodes, further improvements in a wide range of mask components are required. The following sections will address the status of the mask fabrication processes and their future prospects.

7.2 EUV Mask Structure and Process Flow

An EUV mask fabrication process consists of two steps: mask blank fabrication, and mask patterning. A high-precision EUV mask requires low thermal expansion material (LTEM) as a starting substrate. On this substrate, EUV-reflective ML coating is performed, which should be covered by a capping layer to prevent any unexpected oxidation. An absorber layer coating followed by an antireflective coating as well as a backside conductive layer coating will complete the mask blank fabrication process. Before the absorber layer coating, a buffer layer can be deposited (if needed) to protect the ML structure during absorber etching or repair. The mask patterning, which consists of e-beam writing and dry etching, is similar to the current optical mask process. The typical EUV mask fabrication process flow is shown in Fig. 7.1.

An EUV mask consists of several layers that have unique mechanical, chemical, and optical functions. The mask substrate maintains the rigidity of the mask with minimum distortion. It should have a flat and smooth surface with zero defects as well as a low coefficient of thermal expansion (CTE). The ML is one of the key components to determine mask efficiency; if its reflectivity is below 100%, the mask will cause an optical power loss. One of the greatest risks for EUV mask viability is maintaining ML performance over a reasonably long operation time. The ML's capping layer protects masks from degradation. The absorber layer in an EUV mask has a similar purpose to the chrome layer of a deep ultraviolet (DUV)

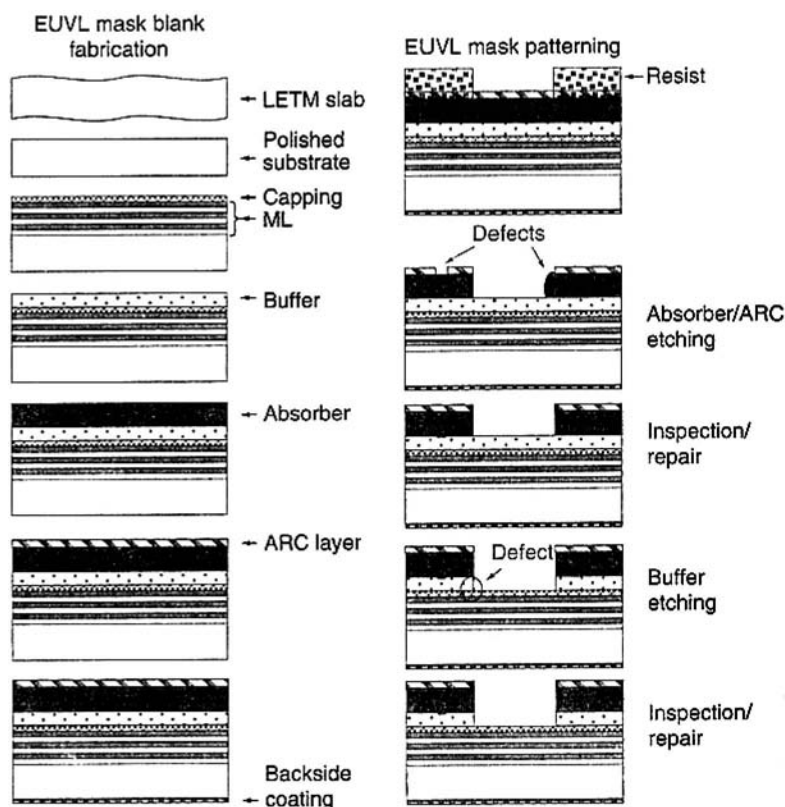


Figure 7.1 Schematics of EUV mask fabrication process flow. (Reprinted from Ref. 2 with permission from CRC Press.)

binary mask in terms of the pattern-forming function. Due to the reflective nature of the EUV mask structure, the absorber material can secure the pattern image contrast against the ML through absorption with minimum reflection. However, most of the metallic absorber materials show high DUV reflectivity, which can cause a problem in mask inspection efficiency using a DUV wavelength. To attain sufficient DUV contrast, an antireflective coating (ARC) can be applied on top of the absorber layer. The backside conductive layer is for electrostatic chucking, which might be required in various process tools as well as in the exposure tool. The key properties of an EUV mask are the peak wavelength (or centroid wavelength), which will be discussed in Sec. 7.4.1, and the peak reflectivity.

7.3 Mask Substrate

The substrate is the starting material for EUV mask fabrication, and its quality assurance is necessary even though it is not a condition for successful mask fabrication. The SEMI P37-1102 standard, which was approved in 2002, specifies substrate requirements: average and spatial variation in thermal expansion, surface

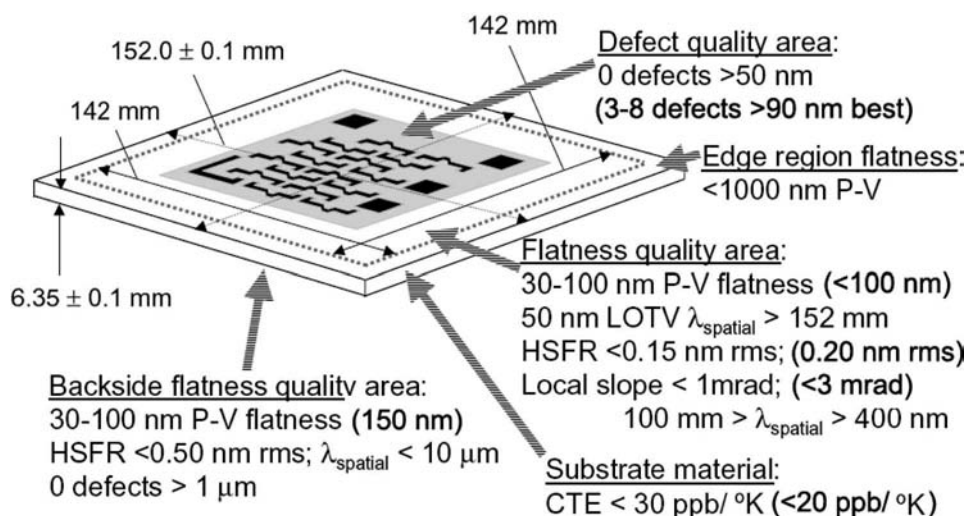


Figure 7.2 SEMI P37-1102 substrate requirements. (Reprinted from Ref. 3 with permission from SEMATECH.)

flatness, and defect level (Fig. 7.2). These requirements stem from EUV-specific issues as well as general nano-scale patterning applications.

7.3.1 Mechanical property requirements

The mask substrate should have low CTE. Ultra-low-expansion (ULE) glass from Corning and ZERODUR from Schott Glass are commercially available EUV mask substrates that exhibit low average values and low spatial variation in thermal expansion. ULE glass is an amorphous silica containing ~ 7.5 mol% titania (TiO_2). The TiO_2 concentration in the glass is an important parameter in determining the properties of the glass. Recent improvements to ULE glass have reduced inclusions and striae.⁴⁻⁶ Inclusions are small imperfections, either solid or gaseous, in the material. Striae is a layer-type inhomogeneity that contributes to mid-spatial-frequency roughness (MSFR) during the polishing process. Commercially available ULE material has an average CTE in the ± 10 ppb/K range. ZERODUR is a glass-ceramic material based on the $\text{Li}_2\text{O}/\text{Al}_2\text{O}_3/\text{SiO}_2$ (LAS) compositional system. This system consists of two main phases: a high-quartz solid-solution crystalline phase with negative CTE, and a glass phase with positive CTE. The fractional volumes of both phases are adjusted so the total CTE is close to zero in the desired temperature range. ZERODUR is designed for application in the temperature interval from -50°C to $+100^{\circ}\text{C}$. A laboratory sample of ZERODUR with a CTE as low as 5 ppb/K has been reported.⁷ The mask substrate standard SEMI P37-1102 requires a CTE in the range from 0 ± 5 ppb/K with a 6 ppb/K total spatial variation to 0 ± 30 ppb/K with a 10 ppb/K total spatial variation, according to the four different classes of materials.

Since no commercial dilatometer meets EUVL requirements (measurement resolution of 1 ppb/K), a new technique to measure the absolute CTE with high accuracy and reproducibility is required. Recently, an optical heterodyne interferometer using a helium-neon (He/Ne) laser was proposed, and the results show reproducibility less than 1 ppb/K with handling capability for a wide variety of materials and a CTE ranging from ppm/K to ppb/K (see Refs. 8 and 9).

7.3.2 Surface figure requirements

The ML is coated onto the substrate of an EUV mask to attain high reflectivity at the 13.5-nm wavelength. The EUV reflectivity is degraded by the roughness of the substrate surface, especially by the high spatial frequency roughness (HSFR). As can be seen in Fig. 7.3(a), HSFR causes large-angle scattering and loss of EUV light from the projection lens. The roughness scattering light within the projection lens (MSFR) is shown in Fig. 7.3(b).

Mask MSFR (also referred to as slope error) is not a source of flare as that in optics, but rather leads to intensity variation in the image plane and becomes a source of line edge roughness (LER) or image placement error.¹¹ It was proposed that for a 0.25-NA optical system, the frequency range for MSFR and HSFR should be $10\text{--}6/\text{nm} < f < 0.004/\text{nm}$ and $0.004/\text{nm} < f < 0.02/\text{nm}$, respectively. The ML smoothing deposition technique can reduce the mask HSFR, but it is not effective for MSFR. The SEMI P37 standard specifies a HSFR of $<0.15\text{-nm rms}$, and a local slope angle of the front surface $<1.0\text{ mrad}$. The mask flatness issue stems from the unique EUVL imaging system design, which is a nontelecentric illumination system. Any height variation of the patterned mask surface (e.g., the nonflatness) causes an image placement error (or overlay error) on the wafer. According to Eq.

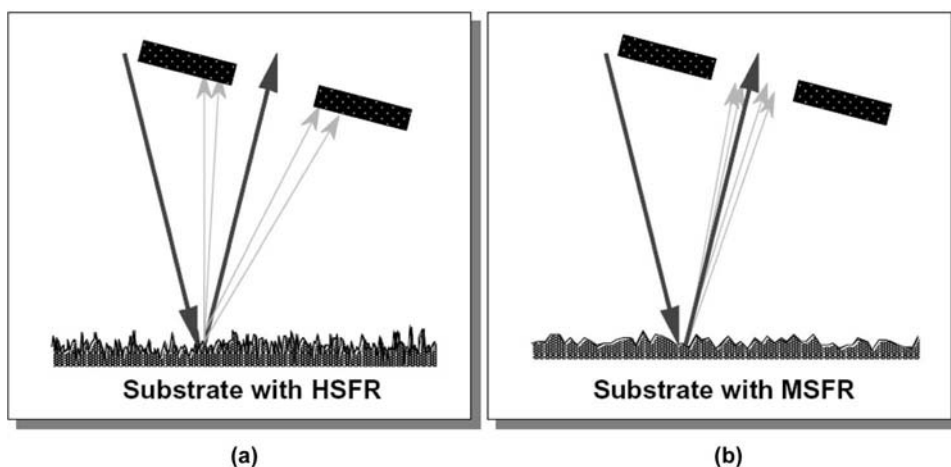


Figure 7.3 Schematics of (a) HSFR, and (b) MSFR. HSFR leads to scattering outside the exit pupil, which causes loss of light throughput. MSFR leads to small-angle scattering, which causes wavefront error and speckle. (Reprinted from Ref. 10 with permission from SEMATECH.)

(7.1), the image placement error on the wafer (Δx) is about 1/40 of the nonflatness of the mounted mask (Δz) at the nominal 5-deg illumination angle, θ (see also Fig. 7.4):

$$\Delta x = \frac{\Delta z \times \tan(\theta)}{M}. \quad (7.1)$$

The front surface flatness of an as-mounted mask is partially influenced by the freestanding flatness of the substrate. The backside flatness of the mask also contributes since a flat-faced electrostatic chuck is the designated method of mounting a mask in an exposure tool. The SEMI P37 standard specifies the front (freestanding) and backside flatness values less than 50-nm peak to valley (PV). Flatness correction techniques for EUV mask substrates, including magnetorheological finishing (MRF) and ion beam figuring (IBF) techniques, have been suggested.¹³ The advantage of MRF is that prepolished substrates can be used since this process is independent of the polished state of the substrate. Even though the process time is acceptable, it requires an additional polishing step to reduce defects and to attain reasonable roughness. The IBF technique has the advantage of achieving roughness as well as flatness during process and thus does not need an additional polishing step. However, the substrate should be completely polished beforehand, because existing defects can be decorated. Also, the process is lengthy, requiring several hours.

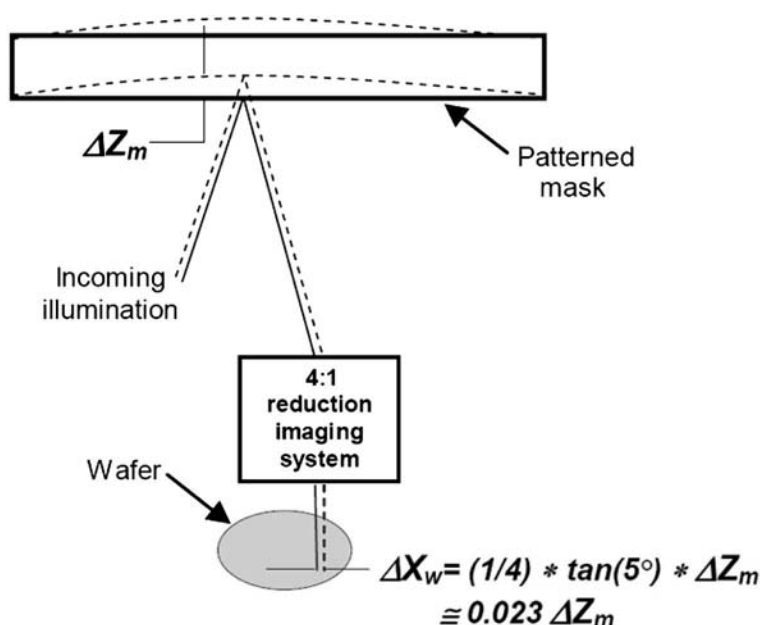


Figure 7.4 Image placement error at the wafer resulting from the mask nonflatness in the nontelecentric illumination system. (Reprinted from Ref. 12.)

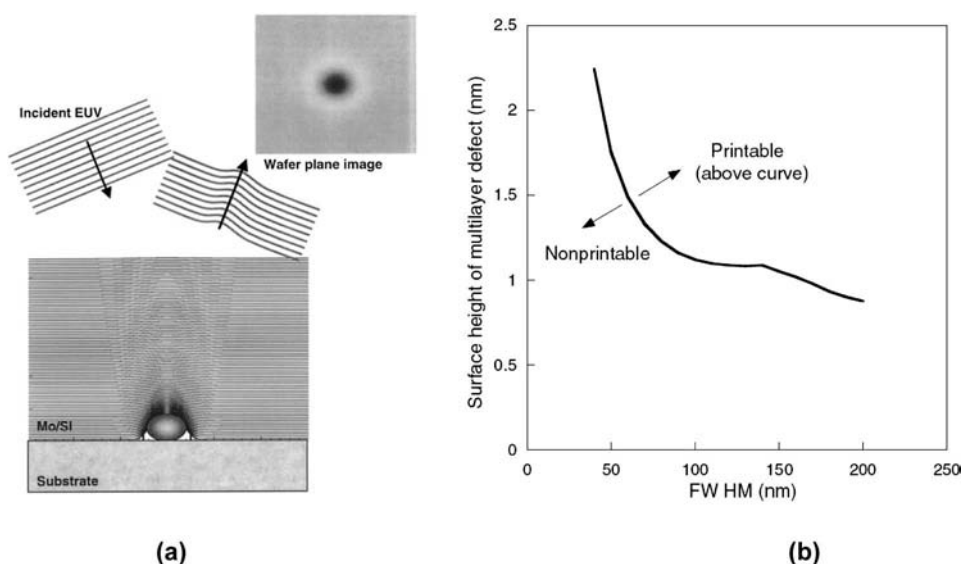


Figure 7.5 (a) Schematic illustration of defect propagation due to a substrate particle during ML deposition. (Reprinted from Ref. 16.) (b) Theoretical curve for the printability of a molybdenum-silicon (Mo/Si) ML defect as a function of the defect height and full width at half maximum (FWHM). (Reprinted from Ref. 15 with permission from Thomson Scientific.) The printability curve was generated for defects in proximity to 25-nm lines assuming a 0.25 NA and a 20% critical dimension (CD) variation criterium.^{15,17}

7.3.3 Defect requirements

A substrate surface defect tends to propagate through the ML coating. Depending on the deposition process and condition, the substrate defect can be magnified or de-magnified.¹⁴ As shown in Fig. 7.5, if the propagated mask surface defect is greater than a threshold value (diameter and height), it can be printed as a defect at the wafer.¹⁵ This causes perturbation of the reflected wavefront; this propagated mask surface defect is called a phase defect.¹⁶ The SEMI P37 standard specifies that the substrate front surface defect requirement in the defect quality area is $142 \times 142 \text{ nm}^2$, which is a zero defect greater than the 50-nm polystyrene latex PSL equivalent size.

7.4 Mask Blank Fabrication

7.4.1 Multilayer deposition process

At the EUV wavelength, every material has a refractive index close to 1 and a transmittance and reflectivity of almost zero. Thus, EUVL optics are required to be all reflective, and a ML-coated mirror consisting of a large number of alternating material layers having dissimilar EUV optical constants is the solution to achieve high reflectance by interfering EUV light. According to the Fresnel equation, the reflectivity at the boundary is proportional to the square of the difference

in the indices of refraction. Typically, two different layers for the ML have high and low atomic numbers, respectively, to maximize the difference in electron density. These materials also should have low EUV light absorption, which is determined by the imaginary part of the refractive index (extinction coefficient). By considering process capability as well as optical performance, Mo/Si MLs are known to be among the best choices from the several material combinations for high reflectivity at a wavelength around 13.5 nm, and are essential components for EUV exposure optics as well as for EUV masks.^{18,19} The Si layer has a low EUV absorption and works as a spacer for periodic structure. The Mo layer scatters the light even though it shows a high absorption characteristic. The thickness of the Mo/Si pair (d spacing) and the ratio of the Mo thickness to the bilayer period (γ ratio) are designed to exhibit maximum reflection but minimum absorption. The period of the ML pairs should satisfy the modified Bragg's law to produce maximum reflectance at the EUV wavelength:

$$n\lambda = 2d \cos \theta \sqrt{1 - \frac{2\delta}{1 - \cos^2 \theta}}, \quad (7.2)$$

where n is an integer, d is the period of the ML pairs (d spacing), λ is the EUV wavelength, θ is the light incident angle to the mask normal (usually 5 deg), and δ is the bilayer-weighted δn . δn is defined as $1 - n$, where n is the real part of the refractive index.

A Mo/Si ML stack for an EUV mask blank typically consists of 80 thin-film layers, or 40 pairs of Mo/Si bilayers. The d spacing (thickness of one period of bilayer) is ~ 6.9 nm, with a Mo thickness of ~ 2.8 nm and a Si thickness of ~ 4.1 nm (Fig. 7.6). Considering the defect repair process, ML pairs higher than 40 period might be necessary, namely about 50 pairs, which can result in only about an additional 1% peak reflectivity but can minimize the reflectivity loss by the repair process. The theoretical value of the peak reflectivity is about 75%, but the practical value is several percentage points lower (Fig. 7.7).²⁰ The primary factor for the reflectivity loss is the intermixing of Mo and Si at the interface. The extent of interdiffusion is more serious at the Mo-on-Si interface compared to the Si-on-Mo interface. Interface engineering by a third layer (see Sec. 7.4.3) inserted at the Mo/Si interfaces improves reflectance by realizing sharper and smoother interfaces.^{21–23} The currently available peak reflectance at 13.5 nm is about 70%.²⁴

The biggest challenge for the EUV mask blank is defect reduction. Defects on the substrate before ML deposition or defects generated inside the ML during the deposition process have the potential to cause printable defects during the lithography process. Printability is determined by the defect location in the ML stack and its size.¹⁷

The ion beam sputter deposition (IBD) tool equipped with a full standard mechanical interface (SMIF) has been developed for defect-free ML deposition (Fig. 7.8).^{16,27–30} Major system improvements have been made in the following components: a substrate robotic handling system, a low particulate ion source, and clean deposition-chamber shielding, which resists flaking and particulation.

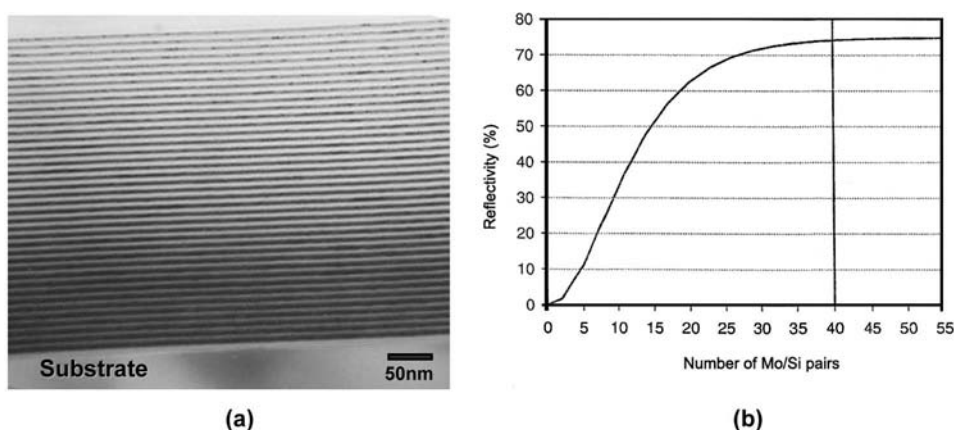


Figure 7.6 (a) Cross-sectional transmission electron microscope (TEM) image. (Reprinted from Ref. 25 with permission from the *Japanese Journal of Applied Physics*.) (b) Calculated peak reflectivity of the Mo/Si ML coating at normal incidence as a function of the number of period. (Reprinted from Ref. 26 with permission from CRC Press.)

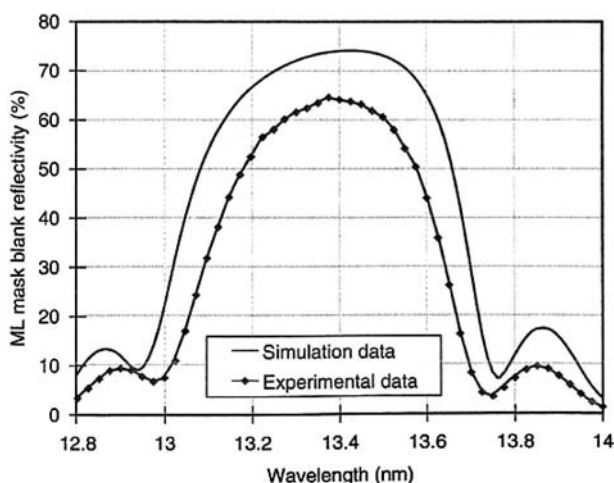


Figure 7.7 Theoretical and experimental EUV reflectance spectra of a 40-pair Mo/Si ML. (Reprinted from Ref. 20 with permission from CRC Press.)

Recently, the mean ML-coating-added defect density was significantly reduced to ~ 0.055 defects/cm² for particles larger than 80 nm in size (PSL equivalent) through compositional analysis of the particles followed by tool and procedural upgrades.³¹ More recently, defect inspection sensitivity was reduced to 53-nm PSL sensitivity using a new inspection tool.¹ Further improvements in blank defect levels require much more sensitive inspection platforms. Greater defect reduction will be possible by moving toward tools with greater inspection sensitivity. Magnetron sputtering is another technique for ML deposition and has been widely used for EUV optics deposition.³² It yields a higher throughput than an IBD system,

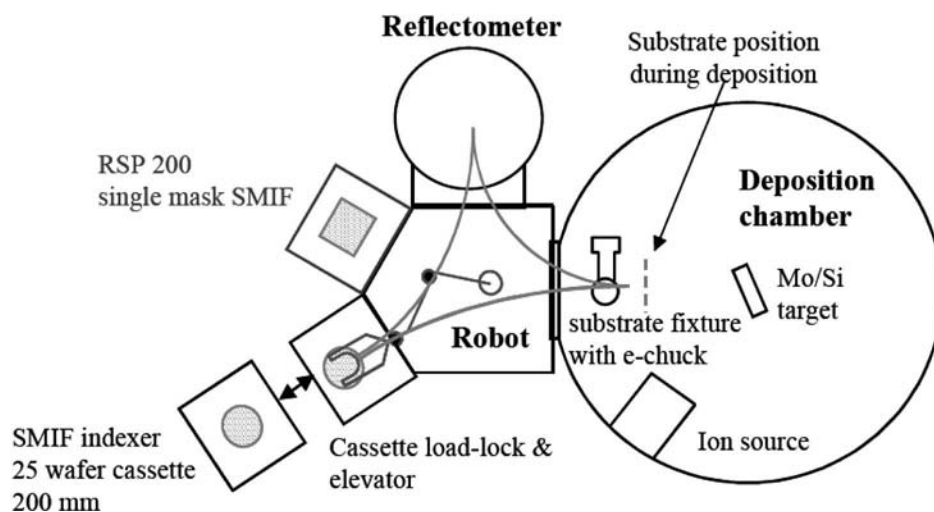


Figure 7.8 Plane view of a low-defect IBD system with reticle SMIF pod (RSP 200) robotics for coating standard-format mask blanks. (Reprinted from Ref. 28.)

exhibits good film thickness control, and has high EUV reflectance. An EUV reflectivity as high as 71% has been reported with low-pressure rotary magnet cathode sputtering using xenon (Xe) gas, but the stress-controlled doubly stacked Mo/Si ML (a 50-pair compressive ML with γ ratio of 0.35 stacked upon a 30-pair tensile ML with γ ratio of 0.7) showed 63% reflectivity due to surface roughness.³³ However, the defect level of magnetron sputtering is relatively high since little effort has been applied to defect reduction of magnetron sputtering tools. The primary reason for this low effort is because EUV optics are less sensitive to defects, since the defects will be imaged out of focus. The defects on the mask, however, are in focus during the lithographic imaging process.

Another parameter of interest is the centroid wavelength at which a ML's reflectivity is measured. The centroid wavelength is the median wavelength of the reflectance after fitting to the centroid; it is usually very close but slightly offset from the reflectance peak. The centroid wavelength of interest is 13.5 nm. During the IBD process, uniformity is a strong function of the substrate angle normal to the direction of the deposition flux and a weaker function of the target's angular orientation. A high substrate angle close to 55 deg results in good uniformity but a high defect density. Normal-incidence deposition results in poor uniformity. A deposition flux angle of 26 deg has been reported to yield good uniformity as well as low defect density.³¹

7.4.2 Multilayer characterization

To confirm the layered structure of the ML, cross-sectional TEM is a powerful tool (Fig. 7.9). The specimens for TEM are prepared following the procedure described by Bravman and Sinclair.³⁴ Careful calibration of the image scale is needed to

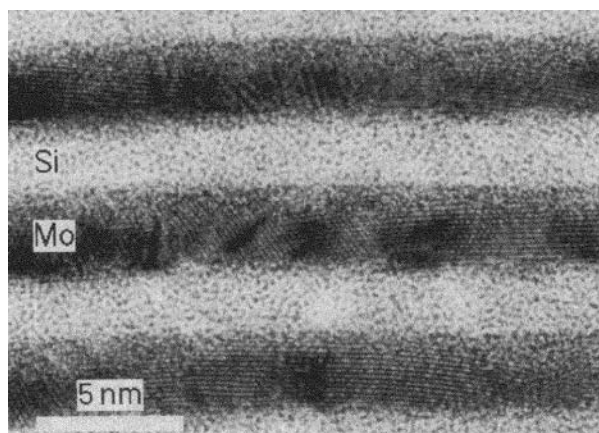


Figure 7.9 High-resolution TEM of a Mo/Si ML. Layer thickness as well as microcrystalline structure (amorphous Si and polycrystalline Mo) can be clearly observed. (Reprinted from Ref. 32 with permission from AVS—The Science & Technology Society.)

obtain precise thickness values of the nanometer-scale layers. If the specimen is thin enough and the defocus is small, the appearance of the resulting images is almost entirely due to amplitude contrast, with Si layers appearing light and Mo layers dark. Micrographs convey the detailed structural information of each layer as well as the general quality of the ML. From the geometrical data, the general optical behavior of the ML (e.g., peak wavelength) can be deduced.

However, cross-sectional TEM is a destructive technology requiring long sample preparation time. Low-angle x-ray diffraction (XRD) is a nondestructive analytical technique that can extract structural information of the ML.^{19,35} The ML period can be calculated from the low-angle peak positions by applying the Bragg equation, modified for refraction:

$$\sin^2 \theta \cong \left(\frac{m\lambda}{2d} \right) + 2\delta, \quad (7.3)$$

where d is the period, m is the integer reflection order number, and δ is the average deviation of the index from unity. When the experimentally determined peak positions are fitted to Eq. (7.3), it yields δ with moderate accuracy and d to an accuracy of approximately $\pm 0.1\%$. To obtain more structural information from the low-angle spectra, they can be fit using the Fresnel-type optical model.³⁶ These fits can be used to extract layer thickness and interface roughness parameters. Careful modeling for the practical layered structure considering interdiffusion can result in an accurate analysis (Fig. 7.10).

EUV reflectometry is an important tool for mask quality assurance. A synchrotron is a high-quality EUV source that is ideal for scientific research but is not suitable for in-house applications. Well-stabilized high-accuracy EUV reflectometers are available at several synchrotron facilities around the world. In-house, at-wavelength metrology requires compact and easy-to-operate systems, and they

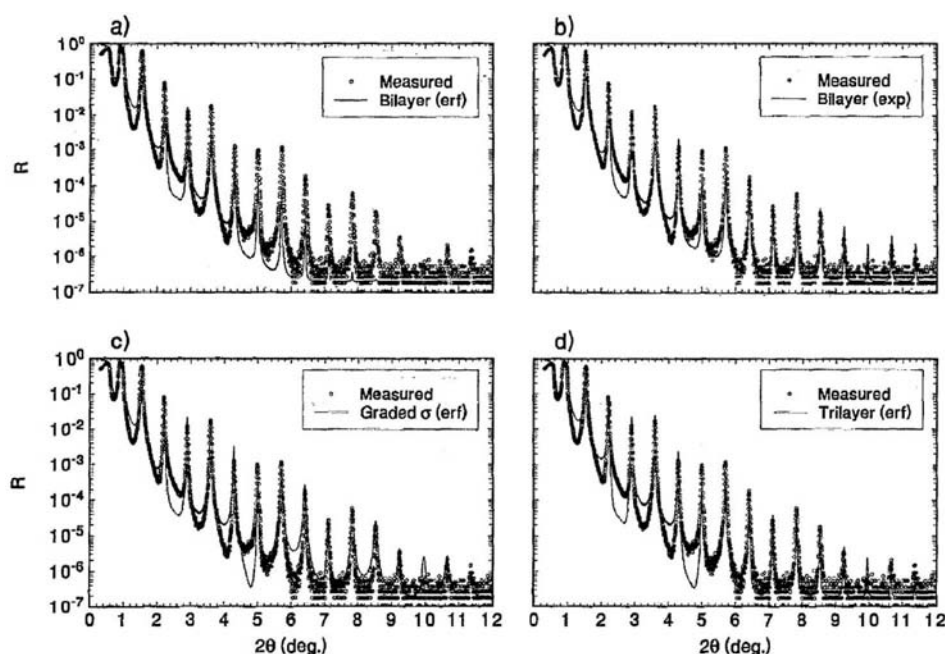


Figure 7.10 Example of low-angle XRD data and the fit for a Mo/Si ML. (Reprinted from Ref. 19 with permission from the American Institute of Physics.)

are based on laser- or discharge-produced plasma. Table-top EUV reflectometers with precise computer-controlled positioning units are available that allow complex surface scan and angle variation.^{37–39}

7.4.3 Multilayer performance improvement techniques and defect mitigation

During the past few years a lot of effort has been given to optimizing the deposition condition to maximize the reflectance of Mo/Si MLs. By optimizing the γ ratio and increasing the number of bilayers over 40, reflectance can be improved up to about 69%. However, further improvement requires a major change in the ML design.

One of the imperfections in MLs that reduces reflectance is the formation of surface oxide. Typical Mo/Si MLs are terminated with Si, but their reflectance tends to decrease in the presence of EUV light and water vapor due to growth of the silicon oxide (SiO) layer. It is believed that EUV irradiation creates low-energy secondary electrons that promote surface oxidation.²⁴ Thus, a new capping layer material that acts as an effective oxidation barrier is required. Ruthenium (Ru) is one of the strongest candidates for the capping layer due to its oxidation resistance as well as high initial reflectance.^{40,41} Some studies have pointed out the long-term lifetime of Ru capping in projection optics mirrors,^{42–45} and Ru's high etch selectivity against absorber material is an additional benefit. This allows the user to eliminate the buffer layer in the patterning process, which can greatly

simplify the EUV mask patterning process. The elimination of the buffer layer can also decrease the thickness of the absorber stack, which minimizes the shadow effect.^{41,46} Another capping layer, iridium (Ir), has been proposed to capitalize on its inertness in a harsh environment of oxygen and acids.⁴⁷

Another source of imperfection is silicide formation between Mo and Si layers. Silicide formation results in reflectance degradation as well as ML period contraction. Interestingly, the silicide layer thickness is interface-dependent; the silicide thickness of the Mo-on-Si layer is about two times thicker than that of the Si-on-Mo interface. A reduction of interdiffusion can be accomplished by introducing thin diffusion barriers between the Mo and Si layers, which leads to a transition from the traditional Mo/Si bilayer structure to an interface-engineered triple or quadruple structure (Fig. 7.11). Some examples of diffusion barrier material are boron carbide (B₄C), carbon (C), silicon carbide (SiC), and Ru; peak reflectivity as high as 70% was obtained.^{23,24} Another benefit from this interface engineering is the long-term thermal stability, which includes two aspects: (1) reflectivity loss, and (2) the centroid wavelength shift toward the shorter wavelength. Volume contraction occurs when the Mo and Si react with each other and form molybdenum silicide (MoSi₂), causing a decrease in d spacing and a centroid shift. The centroid shift is a more serious problem than the peak reflectivity loss, since the drop in reflectivity at the desired wavelength (13.5 nm) can become drastic with the spectral band shift. In the case of Mo/Si ML, silicide formation can occur at temperatures as low as 150°C, and the silicidation becomes more active at higher temperatures. At temperatures as high as 400°C, complete silicidation of the ML can happen within a short period of heating time.⁴⁸

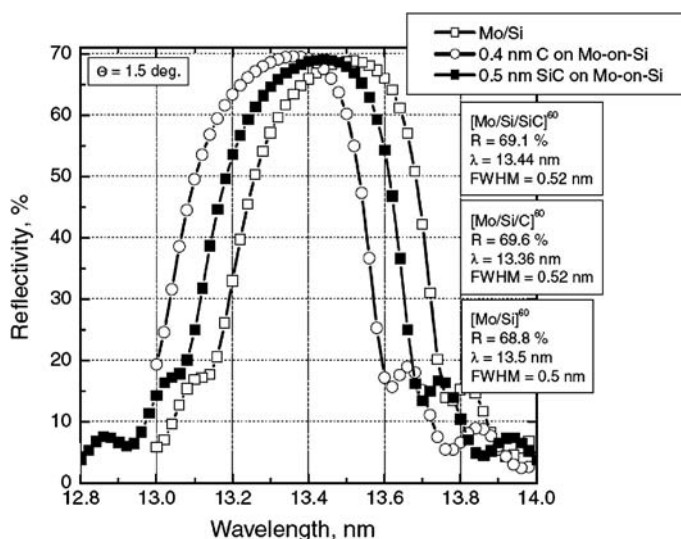


Figure 7.11 Measured reflectivity of standard Mo/Si, interface-engineered Mo/Si/C, and Mo/Si/SiC ML mirrors. (Reprinted from Ref. 23 with permission from Elsevier.)

Roughness of interfaces is another imperfection that lowers ML reflectance. A previous study identified a critical Mo thickness where the roughness increases dramatically due to amorphous-to-crystalline transition.⁴⁹ Fortunately, in an optimized ML for an EUV mask, the typical Mo thickness is well below that critical value. Using ML smoothing techniques during the deposition process can effectively reduce roughness problems caused by small substrate surface defects and substrate surface roughness. The propagation of substrate imperfections is strongly dependent on the substrate imperfection type, the deposition tool, and the deposition process conditions. In a typical IBD process, the ion beam energy and incident angle of deposition are the main process variations. Higher ion beam energy can enhance the smoothing by increasing the mobility of adatoms on the surface so the atoms can move around after attachment to the substrate. However, higher ion energy promotes the intermixing of Mo and Si layers during ML deposition, resulting in a reflectivity loss. The ion beam incident angle also results in conflicting effects on reflectivity uniformity and defect smoothing. Deposition with a non-normal angle usually produces a better deposition uniformity. However, the shadowing at the defect results in a less effective substrate bump smoothing. Ion polishing using a secondary ion source has been proposed for defect smoothing. Ion polishing is most effective if it is performed only on the Si layers after the deposition of each Si layer (Fig. 7.12). This planarization process for smoothing substrate particles using a secondary ion source has been reported to smooth ~ 80 -nm-diameter particles on the substrate to a height of ~ 0.5 nm, which would render them noncritical in an EUVL printing process (Fig. 7.13).¹⁵ Recently, about 50-nm-diameter particles have been reported to smooth to 0.2 nm in height.⁵⁰ However, a small peak reflectivity loss associated with the smoothing process has been found. EUV absorption by implanted argon (Ar) atoms or interfacial layer mixing due to a secondary ion

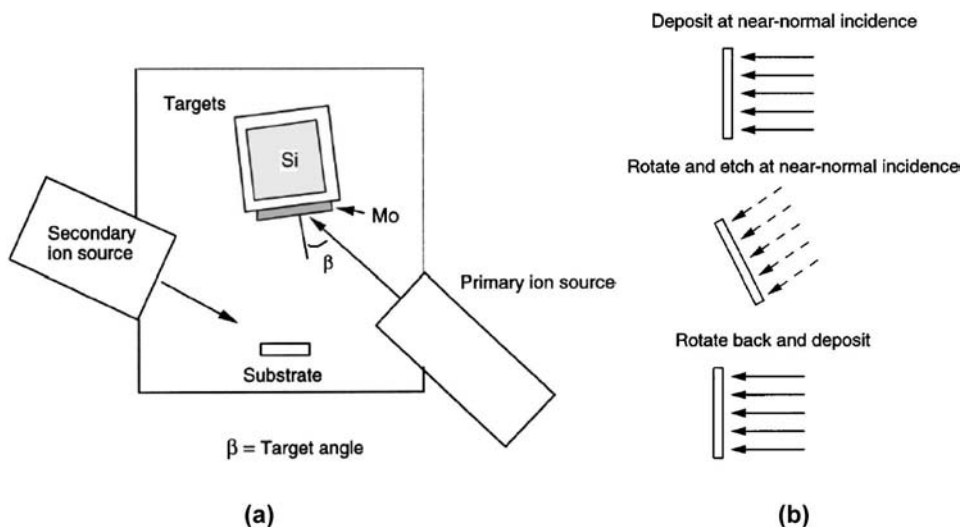


Figure 7.12 (a) Schematic diagram of the IBD tool. (b) Illustration of the ion-assisted procedure using a secondary ion source. (Reprinted from Ref. 16.)

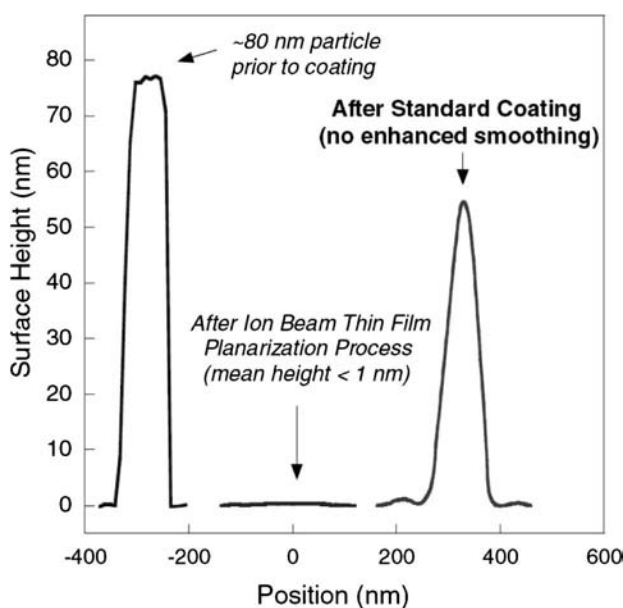


Figure 7.13 Cross-sectional surface profile as measured by atomic force microscopy (AFM) for 80-nm-diameter substrate particles before and after smoothing. (Reprinted from Ref. 15 with permission from Elsevier.)

source is speculated to be the source of reflectivity loss.³⁰ Another concern is pits, another type of defect in the EUV substrate.⁵¹ Pits can be smoothed by using more glancing angles for etch flux while substrate particles can be smoothed using normal angle etching.^{52–55} To smooth particles and pits simultaneously, a multistep process uses two different etch angles, the first focusing on pits, the second on particles, since the optimal etch angle of each is different. For ion beam sputtering, using 600-eV ion energy (Ar) and a medium incident angle of 30 deg is suggested as an optimum process condition combined with secondary ion beam polishing of 250-eV Ar.

Figure 7.14 shows the defect density reduction progress for EUV mask blanks from the beginning. Results are shown for defects added due to the second ML, denoted as “ML adders,” and defects due to both ML depositions plus defects on the incoming substrates, denoted as “total defects.” The industry defect goal for total mask blank defects of a pilot line by 2007 was 0.01 defect/cm² at 40 nm, and the long-term high volume manufacturing (HVM) goal for 2009 is 0.003 defect/cm² at 25 nm. A significant amount of work still must be done to achieve the specification of zero added defects for particles ≥ 25 nm (PSL equivalent).

The flatness requirement of the mask brings up the stress issue of all the layers used in EUV mask fabrication, which include the ML, buffer, absorber, and back-side conductive layers. Out-of-plane distortion (OPD) caused by the film stress eventually induces a pattern placement error of the patterned mask. The typical high-reflectance Mo/Si ML exhibits residual stress close to -400 MPa (compressive), which results from the combined effect of tensile (~ 300 MPa) Mo layers and

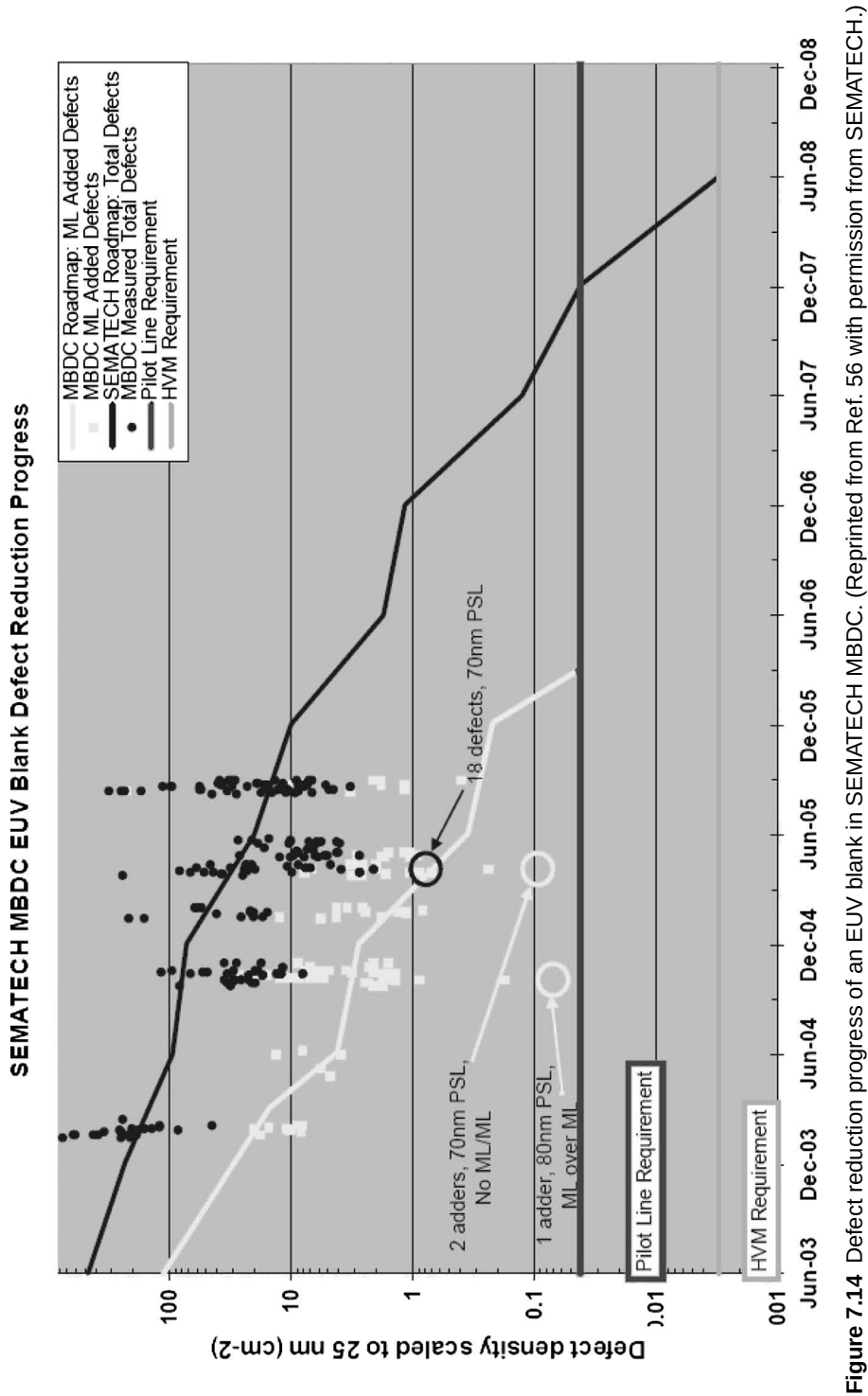


Figure 7.14 Defect reduction progress of an EUV blank in SEMATECH MBDC. (Reprinted from Ref. 56 with permission from SEMATECH.)

compressive (~ -1300 MPa) Si layers.⁵⁷ Most of the stress reduction approaches such as layer thickness adjustment, deposition condition variation, post-deposition annealing, and spacer layer compensation result in a loss of reflectivity. Since many other layers than the ML are involved in the mask structure and some of them are locally etched away, the best approach for mask flatness is to attain near-zero stress in each and every layer of the mask structure. By doing so, the nonuniform stress release causing local mask distortion can be minimized.

7.4.4 Multilayer defect inspection

To ensure a reliable supply of defect-free mask blanks, it is necessary to develop techniques to detect defects on mask blanks reliably and accurately prior to patterning. A ML defect can be generated from a substrate defect or from a particle during ML deposition. The ML defects can be classified into two types, one of which is an amplitude defect and the other a phase defect.⁵⁸ Figure 7.15 shows that these defects directly absorb EUV light and disrupt the constructive interference of the reflections off of each ML interface due to phase difference, respectively. Amplitude defects are either particles near the top of the ML stack or flaws in the ML. On the other hand, phase defects are swellings or depressions on the surface of the ML.

It is anticipated that high-throughput visible light inspection tools will be used in a production environment. However, to have confidence in the visible light inspection strategy, it will be necessary to confirm whether there are any defects visible by EUV that are not being detected by the visible light inspection tool. The mask inspection system should be able to capture all classes of printable mask defects. But there are still discrepancies between actinic (at-wavelength) and non-actinic inspection results, and their correlation is under study. Inspection systems using DUV wavelength (e.g., 199, 248, 257, and 266 nm) were developed, and some of them are used in the mask manufacturing industry.^{59–62} These systems can produce a contrasted image of the absorber patterns and defects present on top of the mask blank. At present, none of the metrology tools meet the requirements imposed by the EUVL production process, and there is a special difficulty in detecting buried defects by non-actinic defect inspection tools.

When actinic inspection using dark-field microscopy was studied, it resulted in a high sensitivity. Researchers using scanning dark-field microscopy reported the detection of phase defects as small as 60 nm in width and 3 nm in height.^{63,64} More recently, full-field imaging in a dark-field mode using 20 $\times$ Schwarzschild optics with a NA of 0.2 successfully detected a 75-nm width, 1.5-nm height, and 150-nm length programmed defect; and 26 $\times$ Schwarzschild optics detected a 55- to 67-nm width and 1.2-nm height programmed defect.^{65,66} International SEMATECH developed a similar inspection system that can detect a bright-field and a dark-field signal at the same time.^{67,68} The highest sensitivity for EUV defect detection has been obtained in dark-field scanning mode where only the light scattered out of the entrance pupil is detected. It could also observe a bright-field image from the mask with a zone plate. The recently developed inspection system is operated in

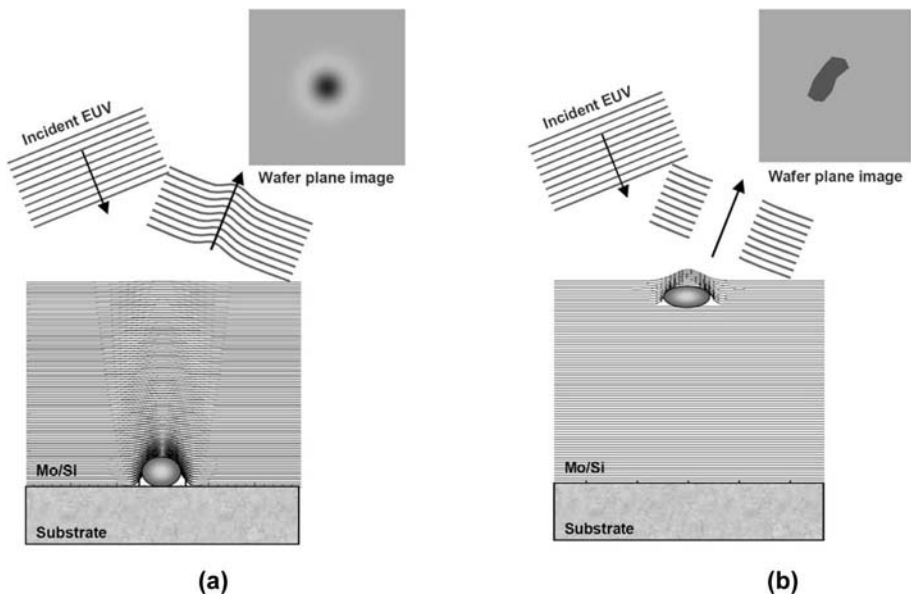


Figure 7.15 Classification of ML defects: (a) phase defect, and (b) amplitude defect. (Reprinted from Ref. 58.)

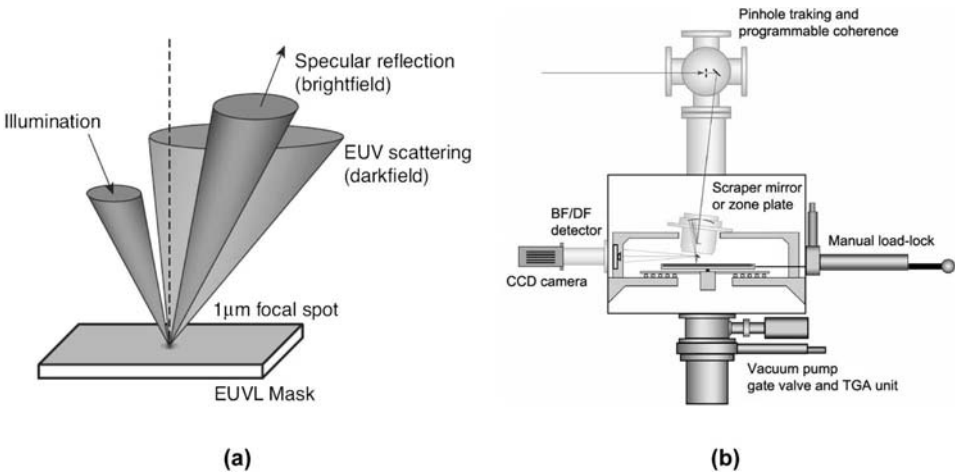


Figure 7.16 (a) Bright-field and dark-field signals from a mask used for defect inspection. (b) Conceptual layout of a dual-mode actinic defect inspection system. The scraper mirror is used for scanning mode and the reflective zone plate lens is used for high-resolution imaging mode. (Reprinted from Ref. 68.)

two modes; one is the EUV dark-field scanning mode, and the other is the aerial image monitoring mode (Fig. 7.16). These two modes can be combined to provide the capability of determining the coordinates of defects with high efficiency.^{67,68} First, whole mask blanks are scanned in high-speed inspection (scanning) mode to identify and map all locations on the mask that scatter a significant amount of EUV

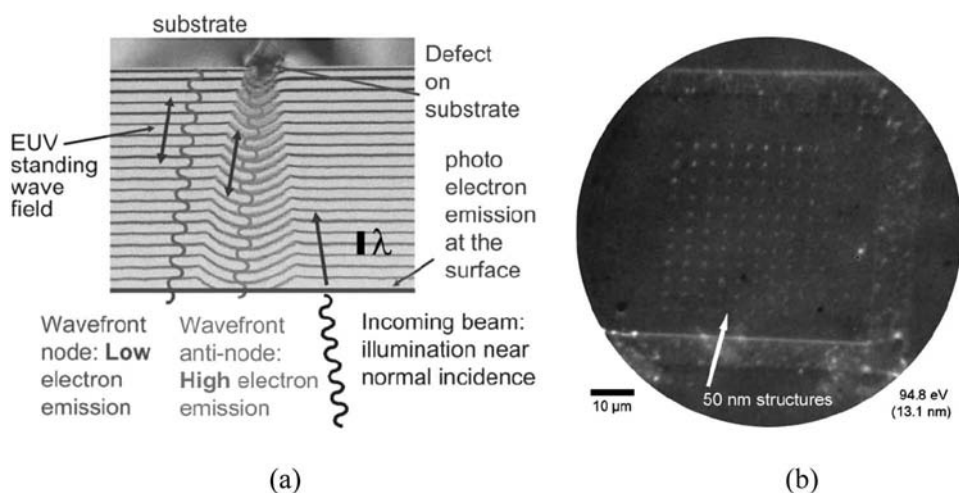


Figure 7.17 (a) Principle of contrast generation arising from the differences in photoelectron generation depending on the phase condition of the standing wavefront. (b) PEEM image of programmed defects buried approximately 350 nm deep under a 50-period Mo/Si ML stack. Structures with a lateral size of 50 nm can be seen in a rather large 110- μm field of view. (Reprinted from Ref. 73 with permission from the American Institute of Physics.)

light. In imaging mode (defect review mode), a zone plate is placed in the reflected beam path to image a region of interest onto a CCD detector with an effective resolution. An EUV microscope using an x-ray zooming tube also successfully observed the phase defect due to a programmed bump defect 90-nm wide and a programmed pit defect 100-nm wide.^{69,70} An EUV imaging tool developed by Exitech observed a defect by converting a 10 $\times$ magnified EUV image into a visible light image using a cesium-YAG scintillator.⁷¹

Recently, at-wavelength inspection using photoelectron emission microscopy (PEEM) with a near-normal incident standing wave has been proposed (Fig. 7.17).^{72,73} This technique is especially suitable for the inspection of defects buried inside the ML stack due to the phase distortion of the reflective wave in the vicinity of a buried defect. The PEEM technique detected 50-nm defects in a programmed-defect EUV mask blank in a rather large field of view (around 100 μm), and substrate defects with a step height of only 6 nm were clearly observed on a ML phase grating test sample. The PEEM image contrast shows a strong wavelength dependence, resulting in a contrast reversal between 13.10 and 13.55 nm. By observing the wavelength dependence of the contrast of a defect, one can distinguish a phase defect underneath the ML from an amplitude defect at the ML surface.

Confocal microscopy is an efficient defect inspection tool used in mask manufacturing due to its superior resolution and fast scanning speed, and has potential as a non-actinic defect inspection technology for an EUV mask [Fig. 7.18(a)]. A multibeam confocal microscopy system with 0.95 NA and 488-nm wavelength is already commercially available that has a capture rate sensitivity of 60-nm PSL

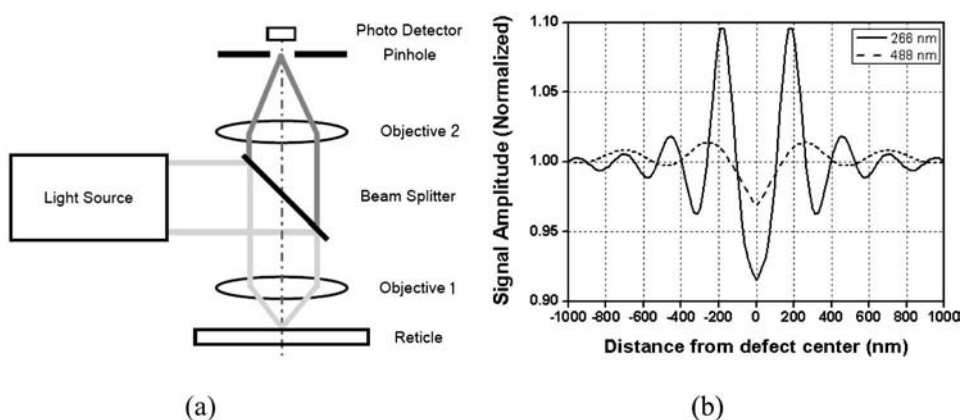


Figure 7.18 (a) Schematic diagram of a confocal microscopy system. (b) Confocal microscopy signal at 488-nm and 266-nm wavelengths. (Reprinted from Ref. 75.)

equivalent for the low-aspect-ratio defects.⁷⁴ Reduction of wavelength from 488 to 266 nm is under development, and enhancement of contrast is expected [Fig. 7.18(b)].

7.4.5 Multilayer defect repair

The amplitude defect repair method restores the local reflectivity by removing the particle or any damaged regions of the ML coating. The repair process must satisfy the following conditions: (1) a sufficient number of MLs must remain after repair for the reflectivity degradation to be negligible, (2) any phase shifts introduced by removing a small region of the reflective surface must be sufficiently small that the crater itself does not introduce a phase defect into the printed image, (3) the underlying layers of the ML stack should remain undamaged so they still reflect sufficient EUV light, and (4) there should be no particle deposition elsewhere on the mask blank resulting from the repair process.⁵⁸

A focused ion beam (FIB) is now widely used in nanotechnology for local deposition and etching due to its high spatial resolution. Multilayer repair also can be done by physically removing the particle using FIB [Fig. 7.19(a)]. This process leaves behind a shallow crater in the ML, but if the profile is carefully controlled to have very small slope, the repaired region can be restored to a nearly defect-free level. The reflectivity drop due to layer removal can be controlled since the ML reflectivity is a direct function of the number of bilayers in the ML stack. It has been shown that removing 20 pairs from a ML consisting of 50 to 60 bilayers will reduce the reflectivity by about 1%.⁵⁸ However, an additional effect from exposing the Mo and Si boundaries results in oxidation and thus a reflectivity drop in the repaired region. To prevent oxidation after repair, in-situ local IBD of a capping layer has been proposed [Fig. 7.19(b)].⁵⁸

Since phase defects originate from the bottom of the ML stack, the standard mask repair technology is incompatible. A new high-resolution electron beam

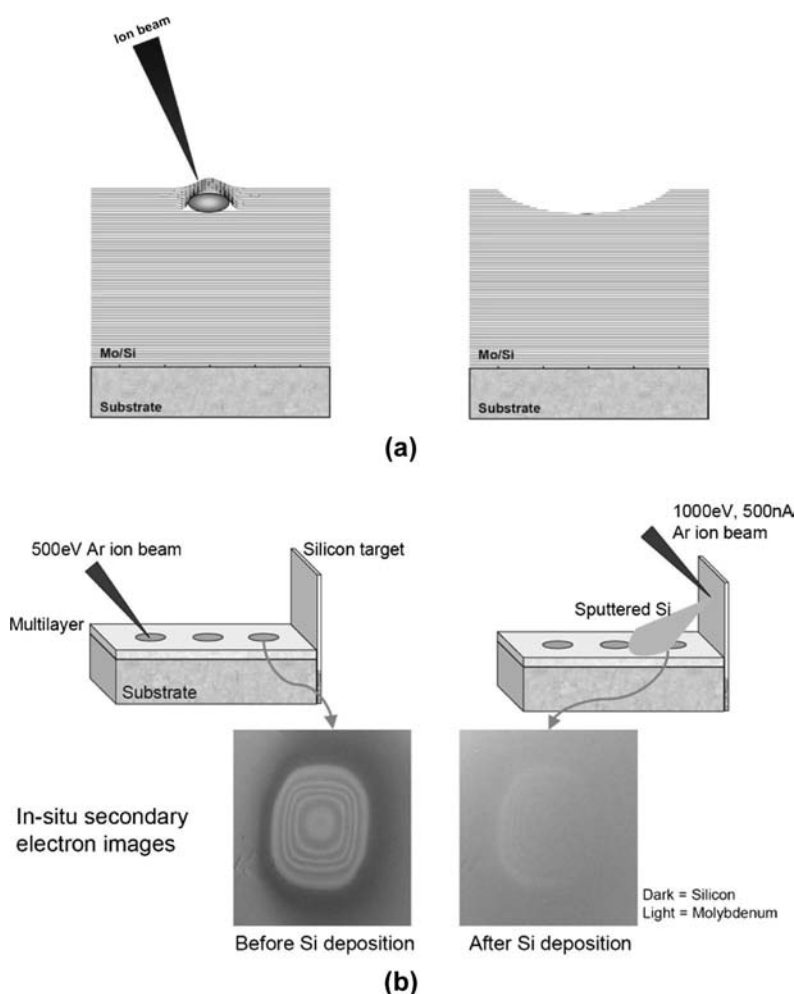


Figure 7.19 (a) Concept of amplitude defect repair using a FIB. (b) In-situ IBD for localized capping of the repaired region. (Reprinted from Ref. 58.)

repair technique should be able to correct the local deformation of the layers within the film. The proposed technique heats the ML to activate silicide formation followed by local contraction of the layer structure (Fig. 7.20). The nature of the electron beam heating mechanism permits users to perfectly repair (flatten) the structure at only one depth (called the repair depth) below the ML surface. To meet the goal of minimizing the phase shift from the repaired defect, the previous simulation study chose the repair depth value that divides the amplitude into two equal parts. The half of the reflected field coming from the layers below the repair depth has an increased phase due to the residual bump, and the half of the reflected field coming from the layers above the repair depth have a decreased phase due to the residual depression. These contributions tend to cancel out so that the total reflected field has a minimum phase shift. The repair depth is determined by considering the

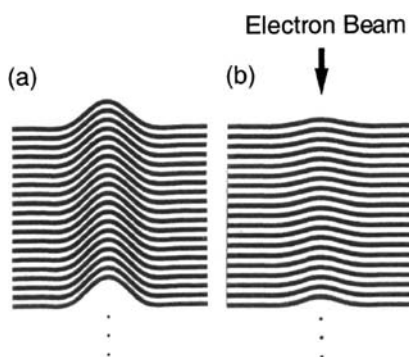


Figure 7.20 Schematic illustration of the phase defect repair concept. (Reprinted from Ref. 76 with permission from the American Institute of Physics.)

number of layers required to obtain half of the reflected amplitude, or one quarter of the reflected intensity of the entire ML coating. The optimum repair depth was calculated as the 7th period (~ 49 nm) from the top surface, and the repair process converted the original phase defect into a pure amplitude defect that decreases the reflectance by 6%.⁷⁶ Another consideration is the shift of the centroid wavelength, which is expected by the following equation using a simplifying assumption:

$$\Delta\lambda = 0.874(2\Delta d), \quad (7.4)$$

where Δd is the contraction of a single period. An interferometer surface scan and cross-sectional TEM micrograph confirmed the feasibility of this technique (Fig. 7.21).^{76,77} However, the height of a defect that may be repaired with this technique is limited; if the defect is too large, then after repair, the ML Bragg peak will be shifted outside the bandpass of the optical system and the phase defect will be turned into an amplitude defect.

This limitation is expected to be a several-nm-high Gaussian defect. Furthermore, to realize phase defect repair for an EUV mask blank, the depression diameter must be considered. S. P. Hau-Riege et al. reported that deformations were due primarily to the compaction of the substrate and not the ML, which inevitably led to depression diameters larger than 20 times electron-beam diameters of 20 nm or less.⁷⁸ To achieve surface depressions of smaller diameters, it is desirable to prevent substrate compaction by using a lower-energy electron beam, a thicker ML, an underlayer between the ML and substrate that absorbs the beam spillover, or a different substrate material.

7.4.6 Multilayer defect compensation

The ML defect compensation scheme can be divided into two approaches: (1) optical proximity correction (OPC), and (2) direct cover with absorber pattern. The efficiency of these two methods depends on the location of the defects and the type of mask (clear field or dark field). The OPC approach on an EUV mask is similar to

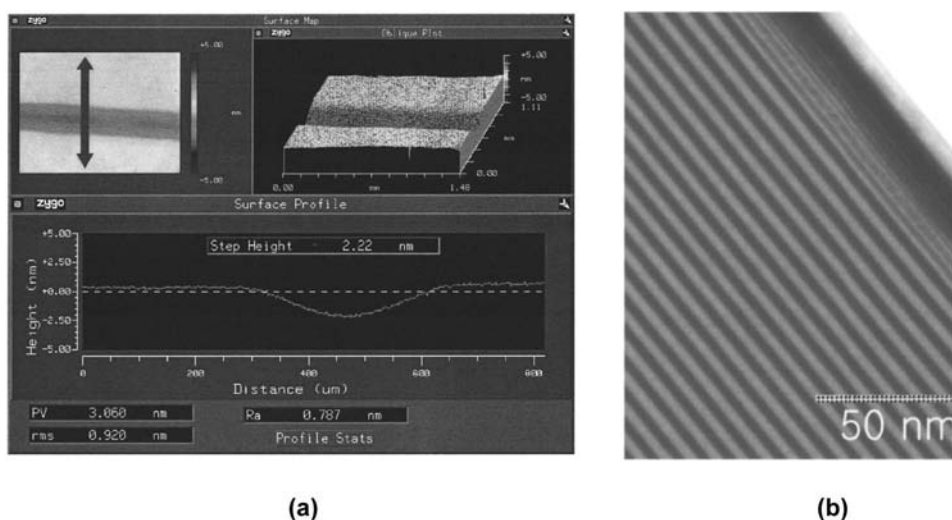


Figure 7.21 (a) Interferometer scan of a depression in a ML induced by an electron beam. (Reprinted from Ref. 76 with permission from the American Institute of Physics.) (b) Cross-sectional TEM micrograph for the top portion of a ML after e-beam heating. (Reprinted from Ref. 77 with permission from AVS—The Science & Technology Society.)

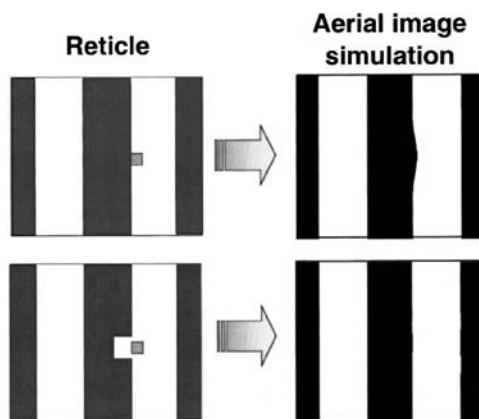


Figure 7.22 Aerial image simulation of an 80×80 nm π -phase edge defect without and with compensation. (Reprinted from Ref. 79 with permission from AVS—The Science & Technology Society.)

that on an optical mask. When a defect causes a printed pattern distortion, the absorber pattern near the defect is trimmed (Fig. 7.22). By doing so, the final printed image will be compensated with the proximity effect between the trimmed pattern and the defect, yielding the original designed pattern.⁷⁹ Also, the absorber pattern can cover the ML defect directly. This is especially attractive in the case of a dark-field mask such as a contact layer mask where most of the mask areas are covered by the absorber patterns. The defect compensation techniques require several steps: (1) fiducial alignment mark on the ML, (2) defect identification (size and location)

from the ML inspection tool, (3) mask pattern data matching with ML defect locations so that a maximum number of ML defects are covered by the absorber with an appropriate corrective mask pattern translation, and (4) electron-beam writing with compensated data.

7.5 Absorber Stack and Backside Conductive Coating

An EUV mask requires two or three films, called the absorber stack, which is on top of the ML. The absorber stack consists of a buffer layer, an absorber layer, and an ARC. The buffer layer protects the ML during absorber etch and repair, and the ARC secures the efficiency of optical inspection. The backside metal coating enhances the chucking force with the electrostatic-chuck (e-chuck). Detailed specifications will be explained separately.

7.5.1 Absorber layer

The absorber layer must exhibit several characteristics, including high EUV absorption, stability under EUV radiation, high image contrast during inspection, conductivity, high etch selectivity to buffer, and low DUV reflectivity to afford optical surface defect inspection. Several candidate materials, including tantalum (Ta), tantalum nitride (TaN), titanium (Ti), titanium nitride (TiN), aluminum copper (AlCu), chromium (Cr), and tungsten (W) have been proposed.^{80–84} Among them, Cr and TaN have been identified as the top contenders. Cr, currently used in conventional optical masks, can be deposited with low defect density and low stress. The Cr etch process, however, generally induces a large negative etch bias on the order of -50 to -80 nm.⁸⁵ Ta-based materials, which also have been developed for x-ray masks can be easily etched with Cl_2 -based chemistry and yield very little etch bias. Its performance in EUV mask fabrication and printing has been found compatible.⁸⁶ Aerial image contrast depends on the absorber material (higher with TaN and Cr) as well as the absorber thickness (higher with a thicker absorber). However, a low-refractive-index (n) material like TaN can act as an attenuated phase shift mask (PSM), resulting in an even higher contrast at low thickness (~ 45 nm in the case of TaN) (Fig. 7.23).⁸⁷ Chemical cleaning compatibility as well as the defect level of the TaN absorber layer is now comparable with high-end Cr material.⁸⁸

7.5.2 Buffer layer

Because the buffer layer must be able to protect the ML during absorber etch and absorber pattern repair, it should have the following characteristics: (1) low pinhole defectivity, (2) high etch selectivity to the absorber layer during absorber etch and repair, (3) high etch selectivity to ML capping during the buffer layer removal, (4) low EUV absorption such that a buffer defect can be tolerated without repair, and (5) stability during chemical cleaning. Various materials have been investigated

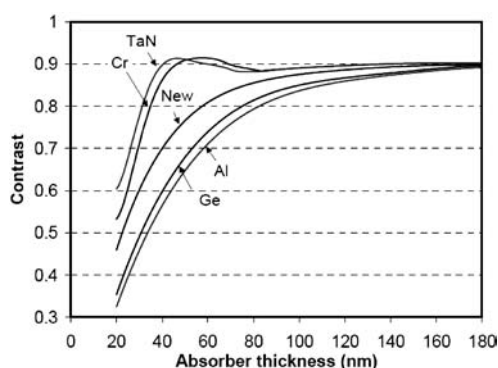


Figure 7.23 Wafer plane aerial image contrast as a function of absorber height for various absorbers with no buffer. (Reprinted from Ref. 87.)

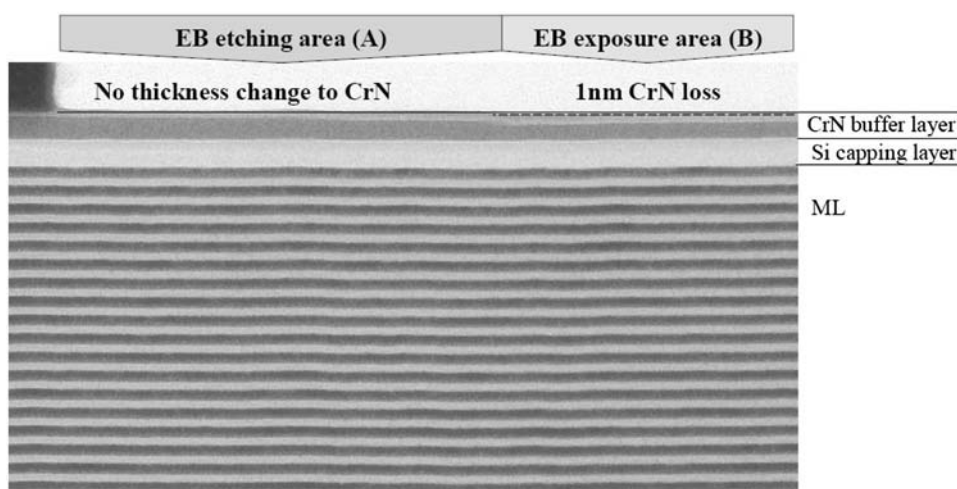


Figure 7.24 Cross-sectional TEM image near the repaired pattern. The repaired region shows no thickness change, while the CrN buffer layer without the absorber shows a thickness loss of around 1 nm. (Reprinted from Ref. 91.)

as a buffer layer, including silicon dioxide (SiO_2), silicon oxynitride (SiON), Ru, C, Cr, and chromium nitride (CrN).^{89–92} The effects on optical performance (the shadowing effect as well as focus shift that will be discussed later) also should be considered when selecting the buffer layer material. If the capping layer has high selectivity to the absorber layer during absorber patterning and repair, a buffer layer can be eliminated (Fig. 7.24).^{91,93}

7.5.3 Antireflection coating

A traditional optical mask can be inspected using transmission, reflection, or a combination of the two methods. However, the EUV mask can only be inspected using reflection mode. The image contrast depends on the reflectivity difference

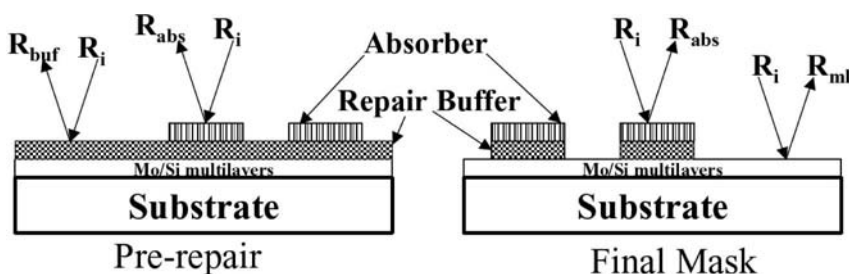


Figure 7.25 Reflectivity of the patterned and unpatterned areas used to determine the inspection image contrast. (Reprinted from Ref. 94.)

between the reflector region (ML or repair buffer) and the absorber region. The image contrast is defined as

$$\text{Image contrast} = \frac{(R_{\text{ml}} \text{ or } R_{\text{buf}}) - R_{\text{abs}}}{(R_{\text{ml}} \text{ or } R_{\text{buf}}) + R_{\text{abs}}} \times 100\%, \quad (7.5)$$

where R_{ml} , R_{buf} , and R_{abs} are reflectivities measured on the ML, buffer, and absorber, respectively, as shown in Fig. 7.25.

Since any metal layer (with TaN and Cr being the strongest candidates for the absorber layer) would reflect too much of the DUV light, an ARC is needed for DUV inspection to reduce this reflection as much as possible. The EUV light reflection at the absorber can be decreased easily by adjusting the thickness, as well as by selecting a material so that ARC is not needed for actinic inspection. Coupled with the typical ML reflectivity of 55 to 60% at the DUV wavelength, the considerable reflection on top of the absorber layer requires the AR function of the ARC layer to reduce the light reflection from the top of the absorber. Image contrasts of 75% and 88% were reported with 33-nm SiON-ARC on TaSiN and 20-nm Al_2O_3 -ARC on TaN, respectively.^{93,94} In addition to the low reflectivity at the inspection wavelength, the ARC application has these requirements: (1) easy to etch with zero etch bias, (2) high etch resistance during buffer etch, (3) common etch chemistry with absorber etch (preferably), and (4) good chemical cleaning durability.

7.5.4 Shadowing effect

The mask shadowing effect is a unique problem caused by the combination of oblique illumination and mask topography. Due to this effect, a printed CD bias and position shift will occur. The shadowing effect is schematically shown in Fig. 7.26. Compared to the designed mask CD, the mask space features will print smaller and the line features will print larger. This effect is exaggerated with increasing thickness of the absorber stack:

$$\text{Space CD (printed)} = \text{CD (designed)} - (2d \times \tan \theta) \times M \quad (7.6)$$

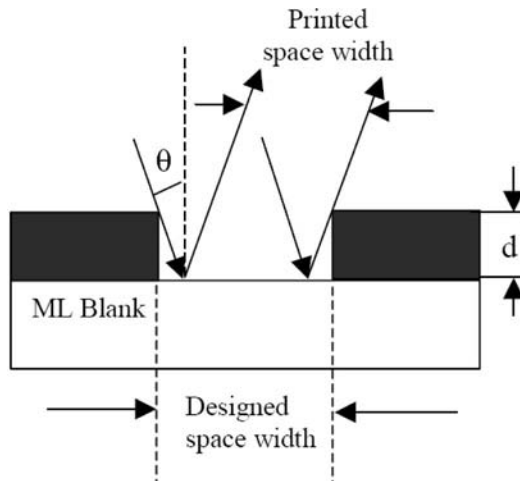


Figure 7.26 Geometrical optics illustration of the EUV mask shadowing effect. (Reprinted from Ref. 87.)

and

$$\text{Line CD (printed)} = \text{CD (designed)} + (2d \times \tan \theta) \times M, \quad (7.7)$$

where CD is measured at the wafer plane, M is the EUV scanner reduction factor, and θ is the light incident angle to the mask.

When the effect of near-field diffraction is considered, the electrical field in the dark region near the absorber edge is no longer completely dark. The light extends to the dark region at the edge and gradually reaches to zero intensity at a distance extended to the inside of the absorber. The electrical field that is diffracted at the mask edge will also interfere with the light reflected back from the ML. As a result, the light diffraction depends upon both the geometrical structure and the optical properties (index of refraction) of the material. According to the simulation, the use of TaN and Cr, which have a larger Δn (the difference between the real part of the refractive index and that of the vacuum), results in a larger shadowing effect compared to other materials like Al and germanium (Ge).⁸⁷ As the absorber thickness increases, the difference in CD for different materials decreases (Fig. 7.27). However, the buffer layer as well as the ARC should be considered if adopted in the mask structure. It should also be noted that the difference caused by the shadowing effect can be compensated via mask biasing. To obtain high image contrast, the absorber thickness must be sufficient so the leakage light is close to zero.

7.5.5 Bossung curve asymmetry and focus shift

Bossung curve asymmetry and the focus shift effect in EUVL have been discussed in previous publications.⁹⁵ When an EUV mask with a given topography is considered, the Bossung curve of a line at a large pitch is tilted and the best focus is

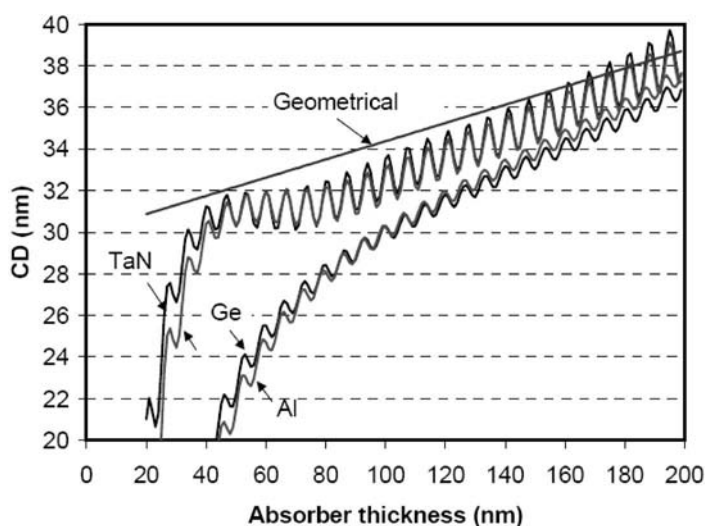


Figure 7.27 Printed CD as a function of absorber height based on geometrical optics calculations for a $4\times$ reduction exposure system. (Reprinted from Ref. 87.)

shifted. This focus shift is pitch-dependent. From the periodic lines to the isolated lines, the focus shift increases as the pitch increases. Figure 7.28 shows plots of Bossung curves for dense and isolated 30-nm lines for a 100-nm-thick TaN absorber. A small focus shift exists, even for the periodic lines. The maximum focus-shift difference between dense and isolated lines for the TaN case is as large as 40 nm. When the focus shifts are different between different pitches, the scanner focus adjustment cannot compensate for the focus shift of all the lines with different pitches. Since the total depth of focus (DOF) is only about 100 nm in EUVL, a 40-nm focus mismatch between the dense and isolated lines has a big impact on the total lithographic process window. Like the shadowing effect, this focus shift depends on the buffer and absorber materials' n and k values. But the thickness of the absorber material, as long as it allows sufficient EUV light absorption (residual reflectivity $<1\%$), plays a relatively small role in the focus shift effect. When a buffer layer is applied, the focus shift and the Bossung curve tilt effect will be modulated by the optical properties of the buffer layer material. When a buffer layer with a relatively large Δn is used, the focus shift and the Bossung curve tilt effect will increase regardless of the optical properties of the absorber material.⁹⁵

7.5.6 Backside conductive coating and mask handling

Since the EUV mask is a reflective mask, it is possible to chuck the mask from its backside to flatten the mask. The traditional vacuum chuck will not work in an EUV exposure tool, since the wafer exposure is performed in high vacuum. One possible way is to use an e-chuck, but a conductive mask backside coating is required. As a result, the SEMI P38-1103 standard requires a backside conductive coating for the EUV mask blank, and the SEMI P40-1103 standard sets

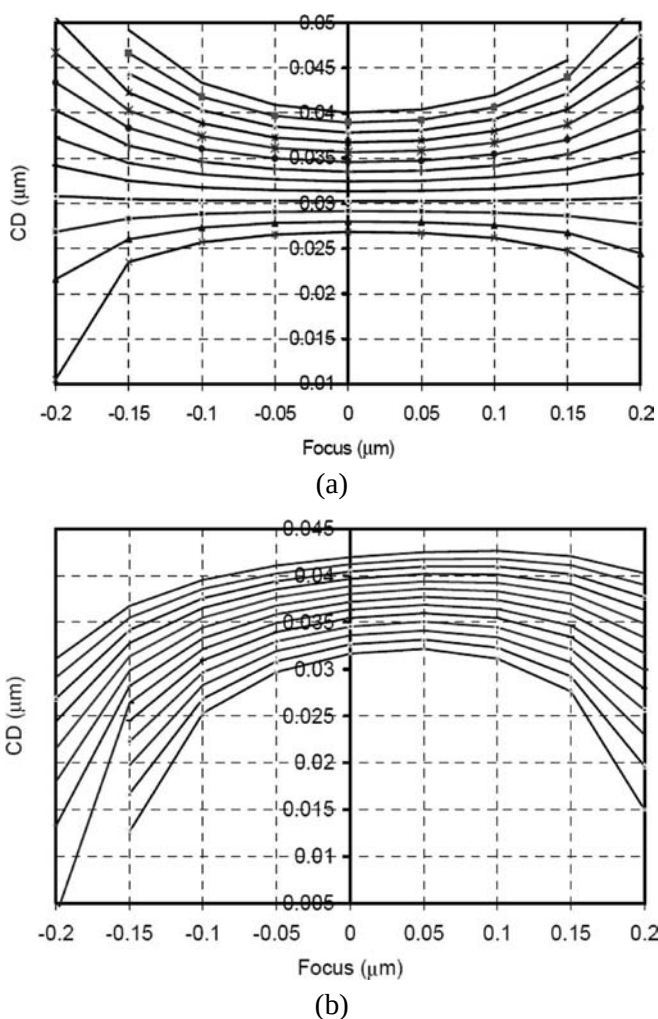


Figure 7.28 Bossung curves of (a) 30-nm dense lines, and (b) 30-nm lines at a 200-nm pitch. The mask has a 100-nm TaN absorber with no buffer. (Reprinted from Ref. 87.)

stringent flatness requirements for the EUV mask chuck. An e-chuck should be adopted to support and flatten the mask in various process tools as well as the exposure tool. Mask distortion—both in-plane distortion (IPD) and out-of-plane distortion (OPD)—will occur due to the residual stress of the ML, buffer layer, absorber layer, and ARC. However, consistency in mask mounting during e-beam writing and wafer exposure will minimize IPD and OPD as long as the substrate flatness meets the requirements. Also, the mounting scheme for inspection must be coordinated.

Another critical issue in the EUVL process is mask protection from particle contamination during storage, handling, and exposure. A pellicle placed in front of the masks plays an important role in protecting the masks from particle contamination in conventional optical lithography. However, for an EUV mask, there are

no organic films that can be used to build pellicles due to the extreme absorption at that wavelength. The system improvement that solved this problem was a specially designed mask carrier. Recently, a dual pod approach of the removable pellicle led to nearly particle-free use during a simulated life cycle at ~ 50 -nm inspection sensitivity.⁹⁶

7.6 Mask Patterning

Like conventional optical mask fabrication, the EUV mask patterning process consists of several steps plus some EUVL-specific steps like buffer etch. The critical processing steps for mask patterning are e-beam writing, absorber stack etch, absorber defect inspection, absorber defect repair, buffer layer etch, buffer defect inspection, buffer defect repair, mask cleaning, and final defect inspection.

7.6.1 E-beam writing

EUV mask e-beam patterning is similar to that of the conventional optical mask. However, it requires an e-chuck that is consistent with that of the wafer exposure tool to minimize the mask distortion effect. Another EUVL-specific restriction in mask patterning is the temperature (post-exposure bake, dry etch, and repair), which should be maintained below 150°C due to ML thermal instability and mask distortion.^{97,98} One of the continuing challenges in e-beam lithography is the proximity effect, which can severely degrade pattern fidelity and CD control. The proximity effect is due to electron scattering in the resist and electron backscattering from the substrate materials. The range of proximity effects depends on the energy of incident electrons, the substrate material, and the thickness of the resist and substrate. A high-energy e-beam results in high-resolution resist patterns due to the minimized exposure by forward scattering, as well as dispersed backscattered electrons. Materials with a high atomic number have high electron backscattering cross-sections and are expected to have larger proximity effects than that of materials with a lower atomic number. Since EUV masks generally contain high atomic number elements for the absorber, the proximity effects are expected to be higher on these substrates than the low atomic number materials like Si. Experimental results on the proximity effect during e-beam writing have been reported for some absorber stacks.⁹⁹ As shown in Fig. 7.29, a structure with a TaSiN top layer results in a larger proximity effect due to a larger number of backscattered electrons from the high atomic number TaSiN layer exposing the resist.

7.6.2 Absorber stack etch

The EUV mask structure requires two different dry etch processes: one for the absorber, and the other for the buffer layer. The absorber etch process must stop with a sufficient selectivity to the buffer, while the buffer etch process must stop on the ML capping layer. A wet etch is another option for the buffer etch, but this can

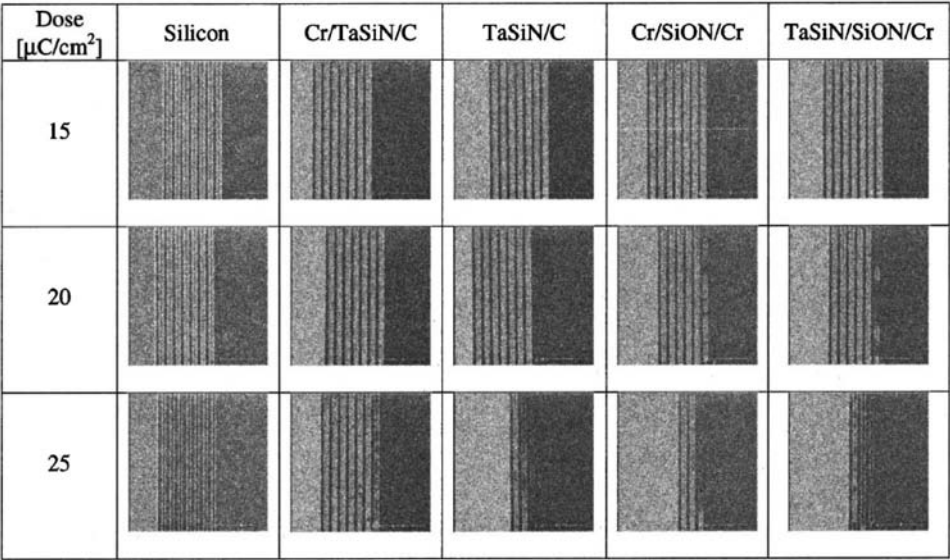


Figure 7.29 Proximity effect test patterns of a 200-nm line & space (L/S) on the selected absorber stack for different exposure doses. (Reprinted from Ref. 99 with permission from AVS—The Science & Technology Society.)

result in undercutting of the repair buffer beneath the absorber features. Cr is currently used for the optical binary and PSMs. Cr can be etched by chlorine plasma with an oxygen addition, and an etch selectivity higher than 20 has been demonstrated with a SiO₂ buffer layer. But an etch bias of several tens of nanometers has been pointed out as a drawback of Cr absorber patterning.⁸⁵ For TaN absorber etching with dichloride (Cl₂) chemistry, a high etch selectivity of 20 was reported against a SiO₂ buffer layer.⁸⁶ An etch bias of less than 5 nm was obtained that was independent of both structure and size, which contrasts with the results of the Cr absorber. Other important issues in the absorber etch process are the sidewall angle and LER. Also, the absorber etch process should have a minimal effect on the EUV reflectivity of the ML. Possible contributing factors for reflectivity loss are the surface oxidation or surface morphology change. Sufficient uniformity with only a small loss of reflectance has been reported with a Ta-based absorber etch process.⁹⁷ When ARC is adopted for inspection efficiency, it is preferable to etch it with the same etch chemistry as that of the absorber layer. Durability during the buffer etch is an important issue as well, because any reduction of the ARC thickness can impact the DUV inspection contrast. If the buffer layer can be eliminated from the mask process, this problem is not an issue. When TaN is used with a Ru-capped ML, the very high etch selectivity between these two layers eliminates the need for an additional buffer layer; the Ru can function as both the buffer and capping layers.^{43,93}

7.6.3 Absorber defect inspection

As for ML inspection, actinic and nonactinic inspection techniques are used for the absorber defect inspection. It is not clear yet whether a nonactinic inspection tool (DUV or e-beam) can detect all the absorber defects printed with an EUV wavelength. It is likely that a high-throughput inspection tool will be operated at DUV wavelengths where the resolution can be improved by reducing the inspection wavelength.⁶¹ High contrast is important for mask inspection because the interference effects obtained from the reflection inspection image can complicate the edge profiles between the ML and the absorber. It is especially troublesome when the step height of the absorber is on the order of a quarter of the inspection wavelength, which yields significant destructive interference between the light reflected from the absorber and the ML at the edges unless the absorber's reflectivity is very low. The mask contrast can be improved by choosing an absorber that has a low reflectivity and a buffer layer thickness close to half-wavelength. From the standpoint of mask inspectability, an absorber reflectivity of between 5 and 10% has been suggested since this will not place too tight a constraint on the EUV absorber reflectivity.⁶¹

7.6.4 Absorber defect repair

After absorber patterning, the mask is inspected and all CDs are repaired before the buffer layer is etched to form a final mask, so the buffer layer material must have adequate etch selectivity during patterning and repair. Two kinds of absorber defects are expected; one is the clear defect (where the absorber is missing from its desired position), and the other is the opaque defect (where there is an extra absorber in the clear region; see Fig. 7.30). The two main challenges for EUV mask repair are (1) how to avoid or limit ML damage during repair, and (2) how to remove small printable defects.

Several techniques have potential for repairing opaque defects, including laser ablation, FIB, and scanning probe-based mechanical nanomachining.^{100–102} Laser repair has limited potential for EUV mask repair due to its poor spatial resolution.¹⁰¹ A FIB with a gallium (Ga) ion is widely used for critical layer optical mask repair due to its high spatial resolution. The minimum effective beam size is reported to be about 120 nm, which meets the requirements for the 35-nm generation.¹⁰⁰ However, the use of Ga ions has the fundamental problem of substrate damage. For EUV mask repair by FIB-based gas-assisted etching (GAE), Ga ions can cause reflectivity loss in two ways when they reach the ML stack: by intermixing the interface and thereby disrupting the ML, and by absorbing EUV light from the implanted Ga ions.¹⁰³ For the protection of the ML, a buffer layer should be used that is thicker than the ion-projected range plus the thickness loss during repair. About 70-nm of SiO₂ has been suggested for preventing the 30-kV gas ions from reaching the ML surface,¹⁰³ but the minimum required buffer layer thickness varies depending on the FIB voltage and absorber etch selectivity. Since

carbon (C) has the lowest sputter yield of all the elements on the periodic table, it is a strong candidate for the buffer layer. High-density C film has been reported to be thermally and electrically conductive and to exhibit extremely high reactive-ion etch selectivity to the Si capping layer on the EUV mask.⁹⁹ The key progress with this technique will be accompanied by the use of (1) a low-kV FIB to avoid ML damage, and (2) limited overscan to avoid re-deposition and ensure complete defect removal. Figure 7.31 shows the AFM images of a programmed opaque edge defect at three stages of a repair process using FIB.

For clear defect repair, ion-beam-induced metal deposition has been performed. Since ML damage is less of a concern during deposition in clear-defect repair as long as the ion beam is confined within the defect area, a FIB can be operated at a higher voltage to take advantage of the higher spatial resolution and smaller

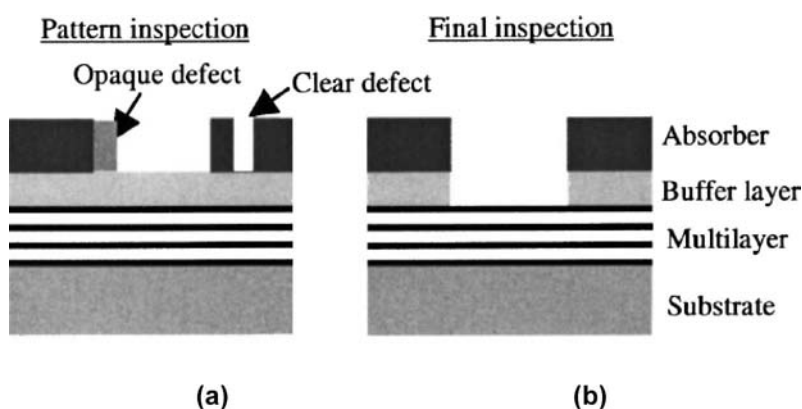


Figure 7.30 Schematic diagram of an EUV mask (a) before, and (b) after the absorber defect repair. (Reprinted from Ref. 100 with permission from AVS—The Science & Technology Society.)

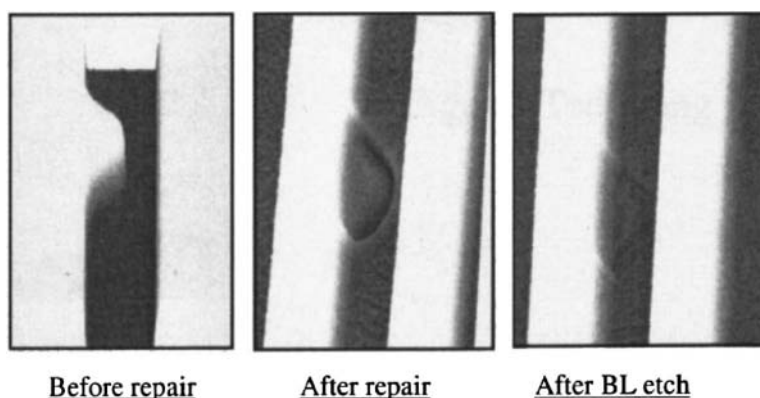


Figure 7.31 AFM images of a programmed opaque edge defect at three stages of repair process. (Reprinted from Ref. 100 with permission from AVS—The Science & Technology Society.)

deposition size.¹⁰⁰ A post-deposition trim by GAE at low kV may be necessary to eliminate the overspray and attain the correct repair size (see Fig. 7.32).

For a better spatial resolution and ML damage prevention, e-beam-based repair techniques can be used (Fig. 7.33).^{103–107} The advantages of e-beam repair technology include: (1) an e-beam can induce chemical reactions to deposit materials that are adequate for clear defect repair and can etch away materials for opaque defect repair; (2) unlike ions, an e-beam does not damage the substrate; and (3) e-beams have excellent spatial resolution. The typical diameter of the primary beam is about 5 nm with a beam current of 30 pA at 1 kV. The higher-energy electron results in a slightly bigger effective beam size and a wider spatial distribution of secondary electrons, which are commonly believed to be responsible for the deposition and etching of materials.¹⁰⁴ The electrons can induce chemical reactions at the surface in the presence of proper gas chemistries, resulting in etching or deposition. Since this e-beam-induced process is a pure chemical process, high etch selectivity can be obtained. Excellent selectivity has been reported with xenon fluoride (XeF₂) using TaN and tantalum boron nitride (TaBN) against Ru and CrN, and with carbon hydro-trifluoride (CHF₃) using TaBN against CrN. This excellent selectivity allows the elimination or minimization of the buffer layer (2 to 4 nm) compared to the ~30-nm-thick buffer for nanomachining or FIB repair.¹⁰⁴ Surface charging has been a major problem for e-beam and ion-beam applications for photomasks (non-conductive quartz substrates) including CD metrology and mask repair. Charging is much more problematic for repair than for metrology due to high electron fluence in the small repair area over the relatively long duration of the repair process. A recent breakthrough in charge compensation (e.g., depositing a removable platinum carbon mixture using an organometallic platinum precursor) has eliminated a primary barrier that has prevented e-beam technology from reaching its full potential for mask repair.^{108–110}

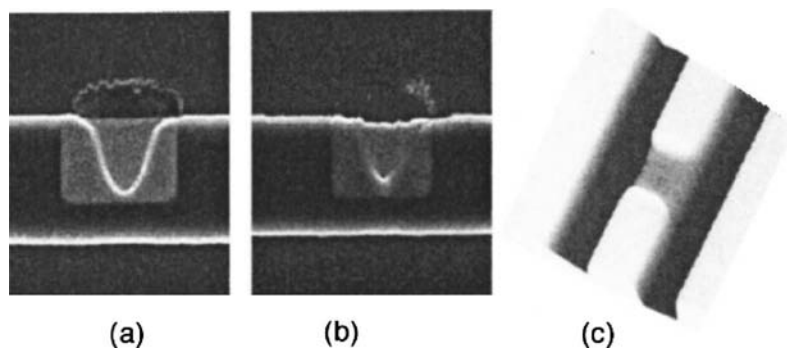


Figure 7.32 Scanning electron microscopy (SEM) micrographs of clear defect repair by W deposition (a) without, and (b) with a post-deposition trim. (c) AFM image showing a good edge profile after a trim. (Reprinted from Ref. 100 with permission from AVS—The Science & Technology Society.)

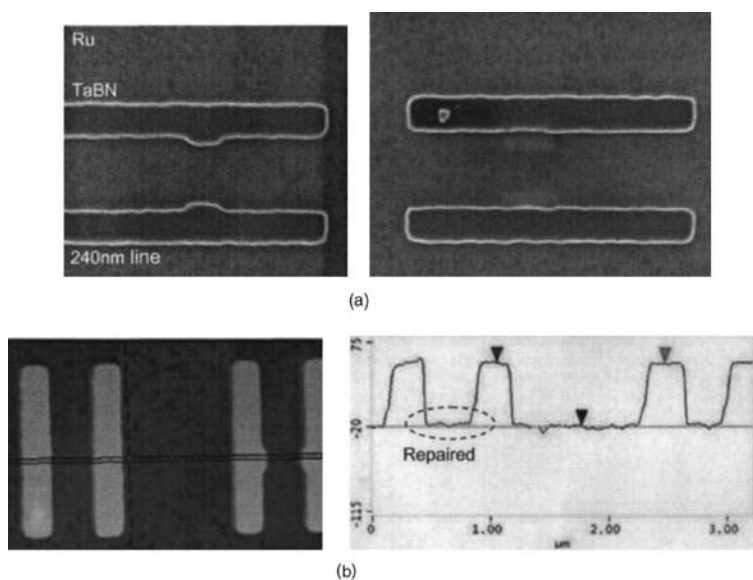


Figure 7.33 (a) SEM images, and (b) AFM line scans of programmed defects on an EUV mask before and after e-beam repair. The AFM scan shows no loss of Ru capping. (Reprinted from Ref. 104 with permission from AVS—The Science & Technology Society.)

7.6.5 Buffer layer etch

Buffer layer etch is an EUV-mask-specific process step. Reflectivity loss on the ML has been reported after dry etching of the buffer layer, and the main reason was attributed to oxidation growth on the Si capping layer surface. Since the damage to the ML etched in a low-pressure gas is caused by ions with higher energy generated in plasma, a high-pressure etching process was adopted to minimize the reflectivity loss (Fig. 7.34).⁹¹ Since the buffer etch uses an absorber stack instead of resist as a hard mask, a high etch selectivity between the buffer layer and the top layer of the absorber stack should be guaranteed, in addition to the etch selectivity between the capping and buffer layers. In the case of a thin buffer layer, wet etching is also applicable.

7.6.6 Buffer layer defect inspection and repair

A buffer layer defect has a lower inspectability than an absorber defect because the contrast between a thin buffer layer defect and the clear ML region can be lower than that between the absorber layer and the ML. As a result, buffer layer defect inspection must be based on defect edge detection or phase detection. Similar to an absorber pattern repair, the buffer layer repair can be performed with an e-beam repair strategy. In this case, however, only the etching process—not the deposition process—is needed, and the etch selectivity between the buffer layer and the ML capping layer is the primary process concern.

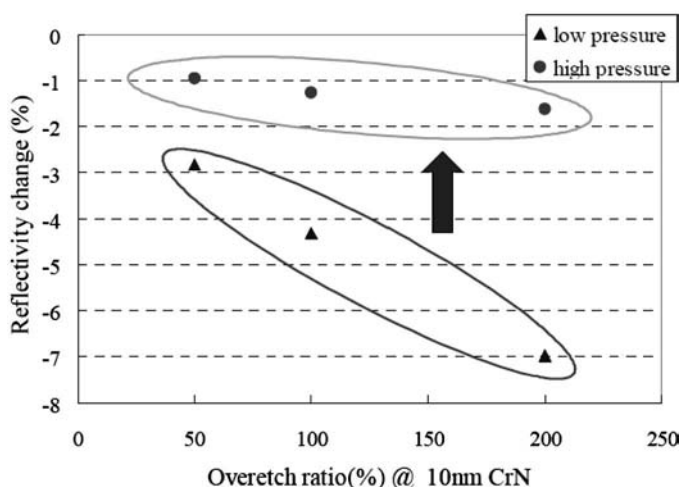


Figure 7.34 Reflectivity loss as a function of an over-etch amount under high and low gas pressure conditions. (Reprinted from Ref. 91.)

7.7 Mask Cleaning

To provide clear pattern transfer during exposure, it is important to maintain the mask surface free from contamination. For this purpose, a cleaning process during mask fabrication and in-between lithography process steps should be developed. Since a pellicle cannot be used in EUVL due to its strong light absorption, an EUV mask should be cleaned more frequently to remove residue and airborne particles. However, mask damage like pinhole generation, reflectivity degradation, and mask CD changes should be avoided during the cleaning process. Conventional wet cleaning processes such as RCA and Piranha cleaning might be applied,¹¹¹ but cleaning efficiency depends on the particle-surface adhesion force, which depends in turn on the pH value as well as the combination of particle and mask surface characteristics. Adhesion force measurement by AFM showed that a SiO₂ buffer layer has a better cleaning efficiency at neutral and alkaline pH, and a Cr absorber layer has lower particle removal efficiency.¹¹² Mask cleaning requires not only the tool capability to remove particles > 50 nm, but also a tool and cleaning process that does not add any particles > 50 nm during cleaning.⁵³ The latter condition is challenging because different tool parts, chemicals, ultra-pure water (UPW), cleaning processes, and airborne particles all contribute to defects added during cleaning. Extremely tight controls on the quality of the UPW, chemicals, cleaning tools, and airborne particulates, as well as fully automatic handling processes, are required to achieve sub-50-nm particle removal capability. Several cleaning technologies have been suggested for EUV mask cleaning: (1) UV cleaning, (2) supersonic hydrocleaning (SHC), (3) plasma-assisted cleaning by electrostatics (PACE), and (4) laser shock wave cleaning (LSC).

UV cleaning of carbon contamination has been demonstrated by irradiation with a 172-nm excimer lamp (Fig. 7.35).¹¹³ A high density of active oxygen was

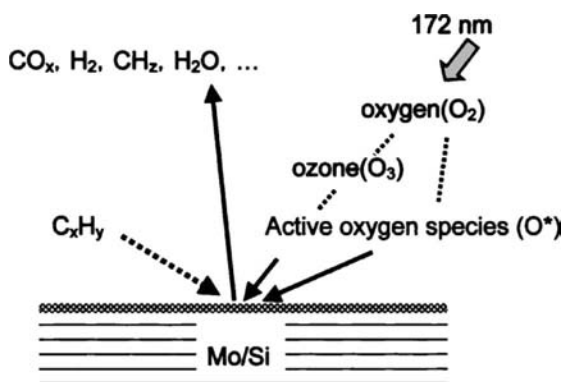


Figure 7.35 Mechanism of removing contamination by UV irradiation. (Reprinted from Ref. 113 with permission from the *Japanese Journal of Applied Physics*.)

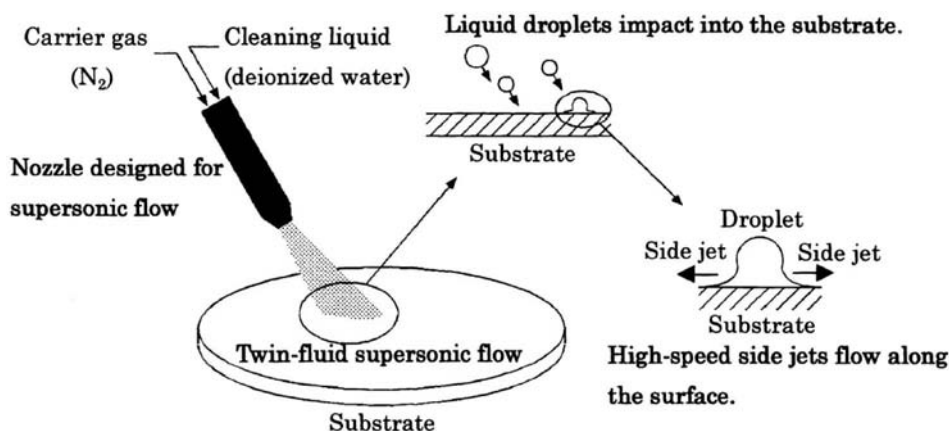


Figure 7.36 Schematic illustration of the SHC technique. (Reprinted from Ref. 114.)

generated directly from molecular oxygen by 172-nm light irradiation (where the absorption coefficient of molecular oxygen is very high), which enabled efficient mask cleaning. The contamination removal rate was 2 nm/min in the low-pressure (2×10^{-3} Pa) O_2 environment.

Figure 7.36 shows the concept of SHC, where a supersonic flow is created by the ejection of a carrier gas from a nozzle under high pressure. A cleaning liquid is mixed with the carrier gas in the nozzle, and the droplets ejected from the nozzle strike the substrate to physically remove particles. Since the organic contaminants on the mask surface reduce the particle removal efficiency, they must be removed by UV irradiation prior to particle removal by SHC.^{114,115}

PACE technology utilizes the potential drop in a plasma sheath electric field and the charge imbalance between the particle and the mask to propel the particles off the surface.¹¹⁶ By applying a positive bias to the substrate and using weak local plasma to charge the particles, the contamination is removed from the surface.

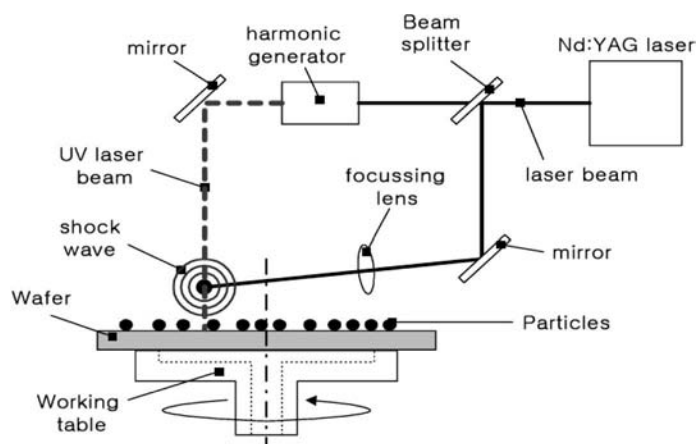


Figure 7.37 Schematic diagram of a LSC/UV cleaning system. (Reprinted from Ref. 117 with permission from the *Japanese Journal of Applied Physics*.)

As the particle size decreases, the amount of time to charge the particle becomes longer, leading to a longer cleaning process.

LSC technology, which uses a dry laser shock wave generated by a Nd:YAG laser, has been studied recently (see Fig. 7.37).¹¹⁷ To avoid any possible surface damage, the UV energy and the gap distance between the laser shock focal point and the surface were optimized.¹¹⁸ The organic particles could not be removed effectively from the surface by LSC, but the particle removal efficiency could be significantly improved by combining the technology with UV cleaning. The enhanced particle removal by UV irradiation may be attributed to photothermal and photochemical effects, by which the former effect evaporates any remaining water molecules from the surface explosively, and the latter effect breaks any possible chemical bonds between the surface and particles. A more than 95% removal efficiency of 63-nm fluorescent PSL particles was achieved by UV irradiation followed by a laser shock wave exposure. The biggest advantage of this technique is that the targeted local cleaning is possible when combined with defect inspection tools.

7.8 Advanced Mask Structure

Due to the advancement of optical lithography (e.g., immersion technology), the introduction of EUVL will likely be postponed further. Therefore, the improvement of imaging performance below the 22-nm node should be made using advanced mask technologies. Various kinds of advanced EUV masks have been proposed, including the phase shift concept shown in Fig. 7.38. Other types include (1) an etched binary mask, (2) an attenuated PSM (embedded or etched), (3) an alternating PSM (substrate or ML etched), and (4) a modified alternating PSM (double etched or with an absorber stack).^{119–122} Most of the studies have been based on simulation, but some of the experimental results have revealed the possibility of practical implementation. One such achievement used CHF_3/Ar plasma chemistry

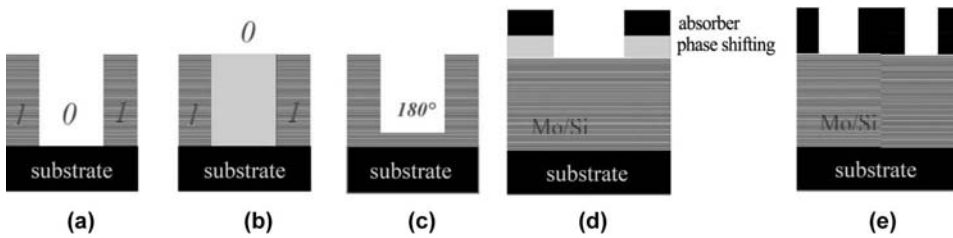


Figure 7.38 Advanced EUV masks: (a) etched binary mask, (b) refilled ML binary mask, (c) etched attenuated PSM, (d) embedded attenuated PSM, and (e) substrate-etched alternating PSM. (Reprinted from Ref. 121.)

with a three-level mask; the sidewall angles in the Mo/Si ML were 85 deg, without undercut, bowing, and ripples, resulting in smooth sidewalls.¹²³ More recently, the printability of unattenuated PSM has been demonstrated using etched ML masks (etch depth ~ 100 nm, sidewall slope ~ 60 deg), and the phase shift edge on the mask was printed at 13.5 nm.¹²⁴ The results showed an improved exposure and focus latitude with good agreement between the simulation and experiments compared to the binary masks, but the reflectivity degradation ($\sim 2\%$) of the etched ML mask without a capping layer was pointed out as a problem. A more detailed practical methodology has been proposed based on the experimental results.¹²⁵ Direct measurement of the phase shift on a reflected wavefront at 13.5 nm was performed with a Fresnel bimirror interferometer using a phase shift sample based on the theoretical design. The measured phase shift was found close to the expected value. Based on the papers presented previously, the etched ML mask generally shows (1) larger depth of focus, (2) higher contrast, (3) no line width variation due to interference phenomenon, and (4) reduced H-V bias and image placement error (IPE) due to the shadow effect. An additional expected benefit is transmission-type inspectability with DUV wavelengths due to reduced absorption in the etched areas.

7.8.1 Etched binary mask

In addition to the mask patterning method that defines layout patterns in the absorber stack, it is possible to subtractively pattern the ML structure by etching without an absorber stack. It is possible to etch into the ML to leave the pattern trenches on the mask where the EUV light is either not reflected or less reflected so the etched region appears dark. The remaining bilayers in the etched region contribute to attenuated reflectivity, and the depth of the etched trench contributes to the phase shift with the round-trip optical path difference. The resultant reflectivity and phase shift can be designed to achieve different types of masks with different imaging functionalities. If all the MLs are removed in the trench region, a much higher aerial image contrast of 99.96% can be obtained, since only 0.09% EUV light reflects off the substrate surface in the etched trench.¹²¹ The reflected near-field intensities show no edge streamer and fewer shadow effects at the edges compared with those from the conventional mask with an absorber stack. The other

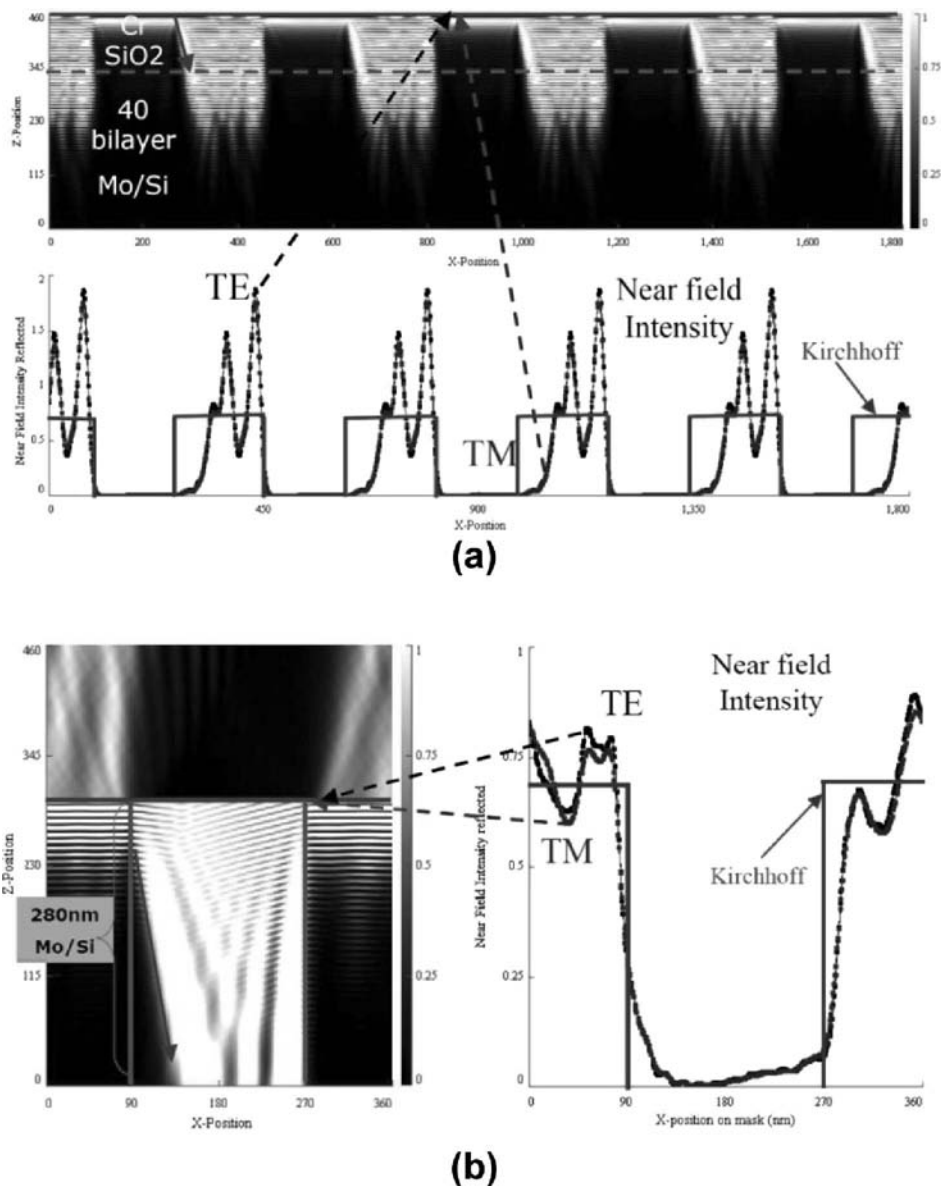


Figure 7.39 Near-field intensities reflected at the top with the oblique light incidence from the left for (a) a binary mask with absorber stacks, and (b) an etched binary ML mask. (Reprinted from Ref. 121.)

difference is that photon attenuation (the dark region) is created at the bottom of the trench (lower in position) for a ML-etched mask architecture, while it is created at the top of the ML stack (higher in position) for the conventional mask architecture with an absorber layer on top. As a result, the shadow effects are in the opposite tone in two cases and are not problematic in a ML-etched mask. Figure 7.39 clearly shows less asymmetry and more similarity between the near fields reflected from

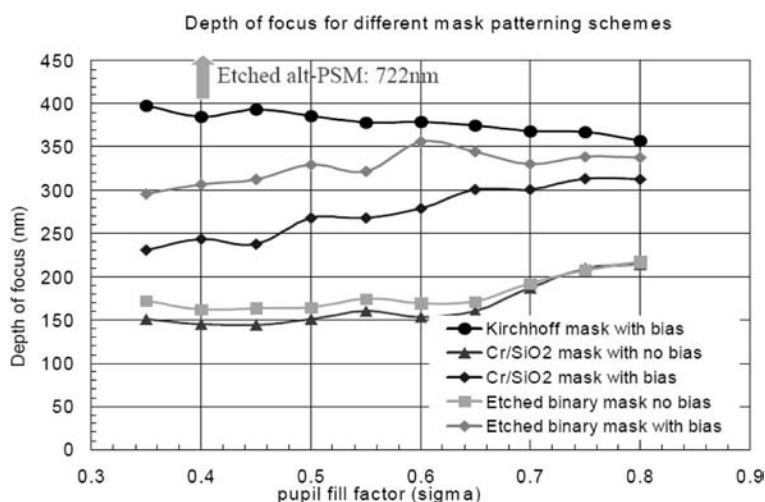


Figure 7.40 DOF for different mask patterning schemes, with or without mask CD bias. (Reprinted from Ref. 121.)

the etched bilayer mask and that from a Kirchhoff mask (thin mask model). Also, the DOF can be improved with etched ML structure, especially with the bias-etched binary ML mask (Fig. 7.40).

One suggested modification of the etched binary mask is the refilled ML binary mask, where the ML is patterned and etched to a certain required depth.¹²² The trench is refilled with a material having a high absorbing coefficient; 70-nm chrome is reported to be enough to provide good contrast (99.3%) and a small CD variation with the etching depth. The planar geometry of refilled masks avoids a large shadowing effect. Both refilled and etched near-fields show much less shadowing effect at the right edge (light incidence from the left) than that of the absorber binary mask, so they will produce better images in terms of H-V bias and IPE (Fig. 7.41). IPE is defined as the maximum component deviation (X or Y) error of the array of centerline images relative to a defined reference grid after removal of the isotropic magnification error.

7.8.2 Attenuated phase shift mask

An attenuated PSM can be fabricated in two ways. One is by etching the ML with proper thickness without an absorber stack, and the other is by implementing a phase shifter on top like the PSM in optical masks. As mentioned in Sec. 7.8.1, the remaining bilayers in the etched region contribute to attenuated reflectivity, and the depth of the etched trench contributes the phase shift with the round-trip optical path difference. If the ML stack is etched with only four bilayers remaining, the etched region has about a 6% attenuated field intensity. By removing a partial number of bilayers, a 180-deg phase shift can be obtained between the near field reflected from the etched region and that from the unetched region (Fig. 7.42).

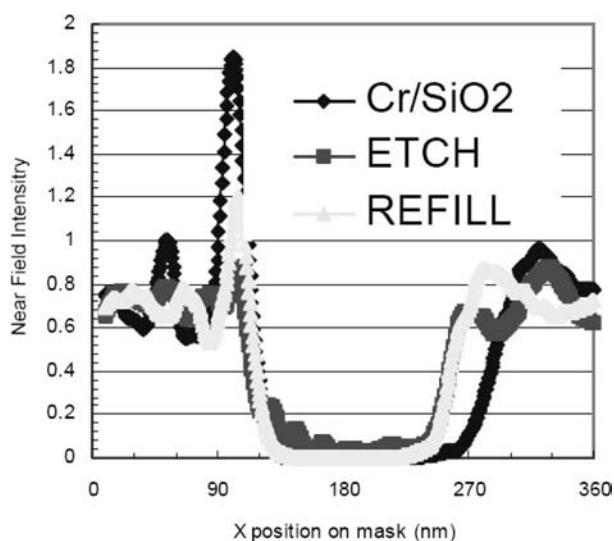


Figure 7.41 Comparison of the near-field intensities reflected at the top for a refilled ML binary mask and those of conventional and etched ML masks. (Reprinted from Ref. 122.)

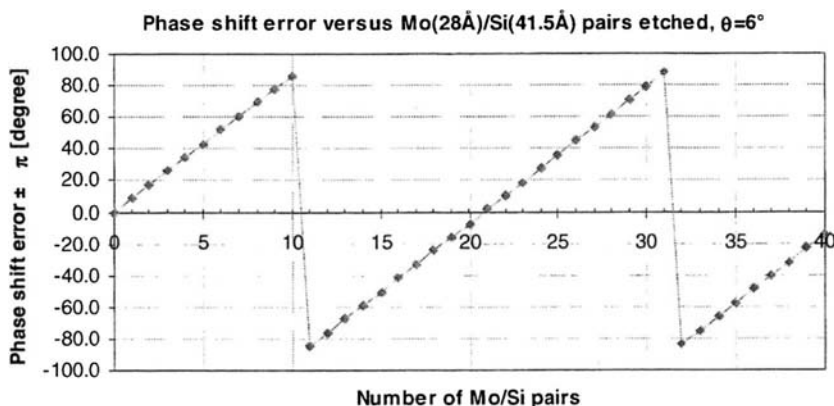


Figure 7.42 Phase shift versus number of Mo/Si etched pairs. (Reprinted from Ref. 125.)

This process can be implemented by precisely controlling the etch depth or by adopting an etch stop layer (ESL). An etch stop layer allows good control of the etch process, but the material and thickness need to be chosen carefully so it will not decrease total reflectivity of the ML and yet provide good etch selectivity for processing (Fig. 7.43). Silicon dioxide is one of the ESL candidates due to its high etch selectivity ($\text{Mo}/\text{SiO}_2 \sim 90$ with $\text{Cl}_2/\text{HBr}/\text{He}/\text{O}_2$ plasma chemistry) and wet etchability.¹²³ The low EUV absorption of SiO_2 may allow a PSM without removing the ESL, which can act as a capping layer in the etched region. This phase shift of the near fields is mainly due to the optical path difference of light propagation down to and up from the trench, which can be calculated by $2 \times (2\pi/\lambda) \times \text{etch depth} \times [n_{\text{air}} - (0.6n_{\text{Si}} + 0.4n_{\text{Mo}})]$ for a normal incident angle. The simulation

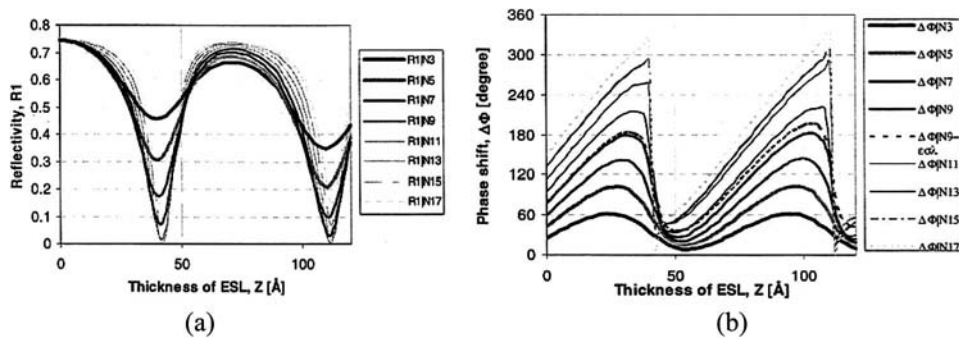


Figure 7.43 (a) Reflectivity (R1) for the unetched region vs the thickness of the SiO₂ ESL coated on a 40-Mo/Si ML for a different number of MLs covering the ESL (N3 to N17 pairs by a step of 2). (b) Phase shift ($\Delta\phi$) versus SiO₂ ESL thickness. The dotted curve for N9 shows $\Delta\phi$ if the ESL is removed from the etched region. (Reprinted from Ref. 125.)

results show a linear relationship with a slope of 2.43-deg phase shift per nm of the etched depth, which gives a tolerance of 2.47 nm in the etched depth for a ± 3 -deg phase variation at a 180-deg phase shift point (Fig. 7.44).¹²¹

Another attenuated PSM is the embedded PSM, which is similar to an optical PSM.¹²⁰ However, the phase-shifting layer for EUV should satisfy both the phase and the desired absorption, and the most plausible approach is a two-layer structure. The main function of one layer is as an absorber and that of the other layer is a phase shifter. The optimization methodology is explained in detail by P.-Y. Yan, as shown in Fig. 7.45.¹²⁶ Among the several material variations for the two-material attenuated PSM, four optical parameters and two thicknesses must be optimized. The EUV attenuation is governed by the absorption coefficient (k) and the film thickness, and the attenuated EUV intensity in the absorber region after a round-trip reflection from the ML is given by

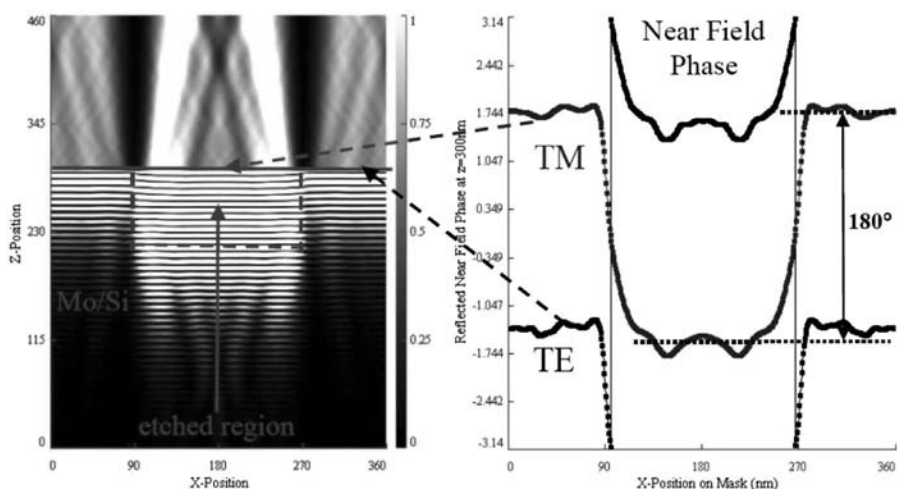
$$I \cong I_0 \left| \left[- \left(\frac{2\pi}{\lambda} \right) \left(\frac{2k_1 d_1}{\cos \theta} + \frac{2k_2 d_2}{\cos \theta} \right) \right] \right|^2, \quad (7.8)$$

where I is the EUV light intensity reflected from the absorber region (round trip), I_0 is the incident EUV light intensity, λ is the EUV light wavelength, k_1 and k_2 are the imaginary parts of the refractive index of films 1 and 2, d_1 and d_2 are the thicknesses of films 1 and 2, and θ is the light incident angle to the mask normal.

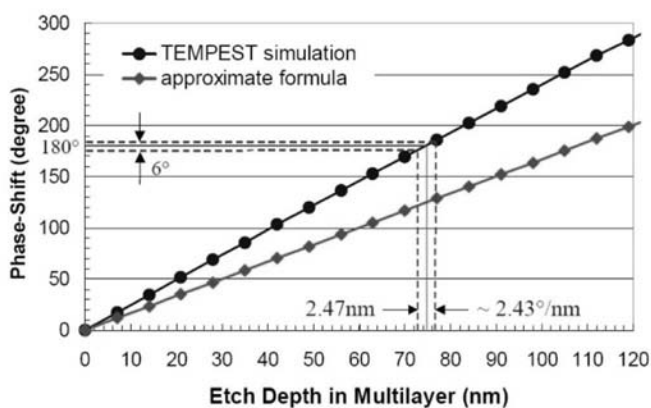
The phase shift is determined by the film thickness as well as the real part of the refractive index. An attenuated PSM with a 180-deg phase shift should satisfy the following condition:

$$\left| \frac{2\pi}{\lambda} \left(\frac{2\Delta n_1 d_1}{\cos \theta} + \frac{2\Delta n_2 d_2}{\cos \theta} \right) \right| = \pi, \quad (7.9)$$

where $\Delta n_1 = 1 - n_1$ and n_1 is the real part of the refractive index of film 1, and $\Delta n_2 = 1 - n_2$ and n_2 is the real part of the refractive index of film. In Eqs. (7.8)



(a)



(b)

Figure 7.44 (a) Near-field phase reflected from the etched PSM. (b) Phase shift as a function of etched depth. (Reprinted from Ref. 121.)

and (7.9), the reflected light from the thin film to the thin film interface, and the thin film to the vacuum interface, are ignored due to the closely matched real parts of the refractive indices. By solving these two equations, we get d_1 and d_2 values determined by the following equations:

$$d_1 = \cos \theta \left(\frac{-\lambda \Delta n_1 \ln \frac{I}{I_0}}{8\pi} + \frac{\lambda \alpha_1}{4} \right) \div (\Delta n_1 \alpha_2 - \Delta n_2 \alpha_1) \quad (7.10)$$

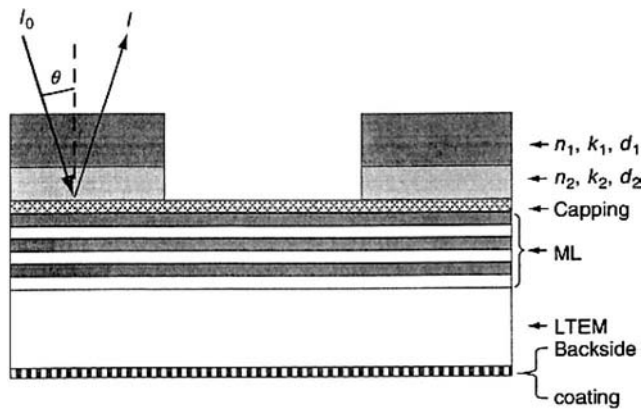


Figure 7.45 Schematic of the two-material EUVL embedded PSM structure. (Reprinted from Ref. 126 with permission from CRC Press.)

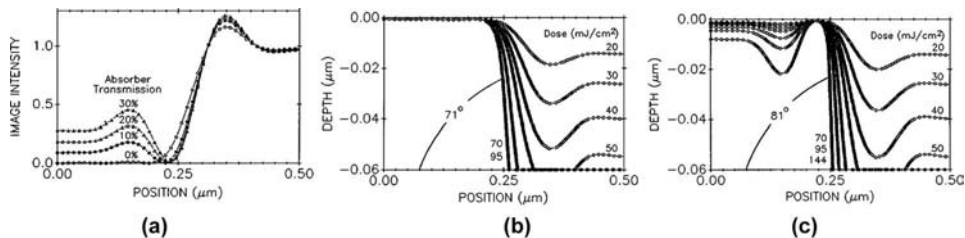


Figure 7.46 (a) Calculation of the image intensity of a 180-deg PSM with absorber transmissions of 0%, 10%, 20%, and 30%, and the resulting resist profile simulations produced by (b) a binary mask (0% transmission), and (c) a 10% transmission 180-deg PSM. (Reprinted from Ref. 119 with permission from AVS—The Science & Technology Society.)

and

$$d_2 = \cos \theta \left(\frac{-\lambda \Delta n_2 \ln \frac{I}{I_0}}{8\pi} + \frac{\lambda \alpha_2}{4} \right) \div (\Delta n_2 \alpha_1 - \Delta n_1 \alpha_2). \quad (7.11)$$

For a given attenuation I/I_0 , any combination of two films can be used if d has a reasonable number for the mask thickness. This two-layer approach is consistent with the absorber/buffer structure of a conventional EUV mask. However, several considerations should be made for etch selectivity and compatibility with other processes.

Figure 7.46 shows simulation results of aerial images and corresponding resist profiles produced with a binary mask and with an attenuated PSM using varying amounts of absorber transmission. The simulation shows that a larger absorber transmission results in a sharper aerial image but at a reduced contrast due to the increased illumination in regions that would normally be dark.¹¹⁹

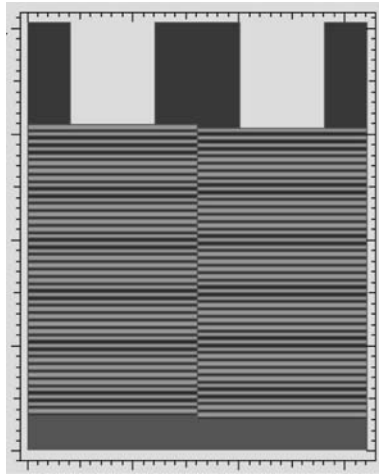


Figure 7.47 APSM with the minimum step height ($m = 0$). The light reflected in the two reflector regions that is separated by the step is out of phase by 180 deg. (Reprinted from Ref. 120.)

7.8.3 Alternating phase shift mask

The phase difference due to mismatching of the ML in the two regions (0- and 180-deg phase regions) can be created by a phase step in the substrate before the ML coating, known as an alternating PSM (APSM; see Fig. 7.47). The step height that induces a 180-deg phase mismatch in the ML is determined by $[\lambda/(4 \cos \theta)](2m + 1)$, where m are integers (0, 1, 2, ...).¹²⁰ With an exposure wavelength of 13.5 nm, the first few allowed step heights are 3.37, 10.1, 16.84, 23.58 nm, etc. In the normal deposition process, the surface roughness decreases with ML deposition and the minimum step may not be easily controllable. One well-known issue with APSM is the image imbalance effect, which shifts the line positions. The image imbalance phenomenon in EUVL strongly depends on the interference between the reflected light in the reflector and the reflected light on the top of the absorber, and this effect increases with a step height increase. As the pattern pitch increases, the image imbalance effect diminishes, even with higher etched phase steps. Compared to the conventional binary mask, a larger exposure and focus latitude can be observed for 15-nm mask lines at a 50-nm pitch and a targeted CD of 10 nm for the 22-nm technology node with APSM (Fig. 7.48).

With the etched ML structure similar to the attenuated PSM, an APSM can be fabricated. If the etched region has enough bilayers remaining for high reflectivity, which is similar to the unetched region (e.g., 77-nm etching depth starting with 60-period bilayers), this etched region can work as a 180-deg phase shift region in an APSM.¹²¹

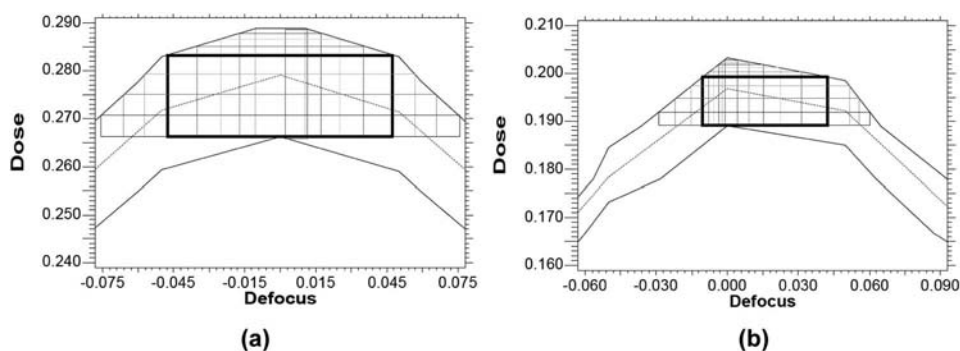


Figure 7.48 Process windows of (a) APSM, and (b) conventional binary mask for 15-nm mask lines at a 50-nm pitch and a targeted CD of 10 nm. The allowable CD variation is ± 1 nm ($1\times$). The bold-faced E-D window is the largest one for a 10-nm target CD. (Reprinted from Ref. 120.)

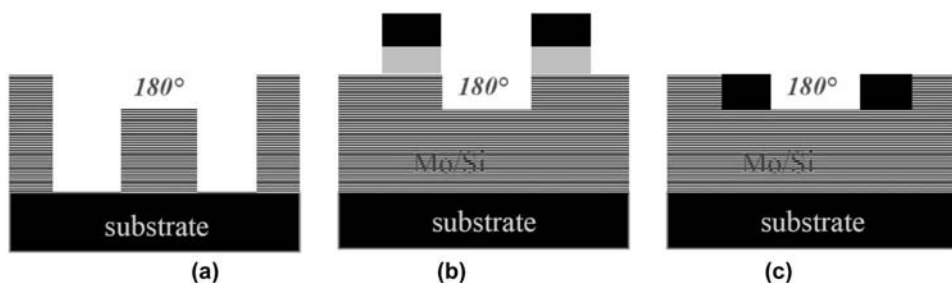


Figure 7.49 (a) Double-etched APSM. (b) APSM with an absorber stack. (c) Refilled APSM. (Reprinted from Ref. 121.)

7.8.4 Modified alternating phase shift mask

Modification of the APSM can be made by etching once more down to the substrate, by depositing absorber stacks on the unetched region, or by partially refilling the etched APSM (Fig. 7.49). It was reported that the double-etched APSM has a larger DOF of ~ 722 nm compared to those of the binary mask and the APSM with an absorber.

7.9 Summary and Future Outlook

EUVL is an extension of optical lithography that uses 13.5-nm light. The characteristics of this wavelength require major modifications from standard optical lithography techniques, primarily due to the very strong absorption of EUV light by most materials. Refractive optics can no longer be used, necessitating the use of a ML mirror-based mask as well as an oblique incident angle of light. The imaging performance of the mask strongly depends on the mask structure and materials, which cannot be confirmed with existing inspection systems. The key challenge of

an EUV mask is to meet all the requirements simultaneously. The basic technologies related to the LTEM substrate, ML, absorber stack, mask patterning, cleaning, and metrology recently have shown significant improvements, but further systematic studies are needed to meet the requirements of below-32-nm technology node applications. Resolution enhancement technology like PSMs might be a solution for the technology's extension, but this will require collaborative studies related to the simulation, metrology, and fabrication processes.

Acknowledgments

We would like to thank all the authors of technical papers referenced in this chapter, especially Pey-Yang Yan, who summarized much of the previous mask-related activities. The authors would also like to thank Vivek Bakshi, the editor of this book, for providing the chance to participate in this meaningful work. We are indebted to Tae Geun Kim, Chang Young Jeong, Sangsul Lee, and Sungmin Huh for their dedicated assistance.

References

1. P. Seidel, "Commercial EUV mask blank readiness for 32 nm HP manufacturing," *Proc. SPIE* **6607**, 66070I (2007).
2. P.-Y. Yan, in *Handbook of Photomask Manufacturing Technology*, ed. S. Rizvi, CRC Press/Taylor & Francis Informa Group, Boca Raton, FL, p. 234 (2005).
3. S. Hector, "Standards for EUV mask," in *SEMI EUV Mask Standards Meeting*, San Francisco, California (July 2005).
4. C. Heckle, K. Hrdina, B. Ackerman, and D. Navan, "Development of mask materials for EUVL," *Proc. SPIE* **4889**, 1113–1120 (2002).
5. K. E. Hrdina, B. Z. Hanson, P. M. Fenn, and R. Sabia, "Characterization and characteristics of a ULEGlass Tailored for the EUVL needs," *Proc. SPIE* **4688**, 454–461 (2002).
6. W. Rosch, L. Beall, J. Maxon, R. Sabia, and R. Sell, "Characterization of striae in ULE for EUVL optics and masks," *Proc. SPIE* **6151**, 615122 (2006).
7. Mitra, J. Alkemper, U. Nolte, et al., "Improved materials meeting the demands for EUV substrates," *Proc. SPIE* **5037**, 219–226 (2003).
8. Y. Takeichi, I. Nishiyama, and N. Yamada, "High-precision (<1 ppb/ $^{\circ}$ C) optical heterodyne interferometric dilatometer for determining absolute CTE of EUVL materials," *Proc. SPIE* **6151**, 61511Z (2006).
9. Y. Takeichi, I. Nishiyama, and N. Yamada, "Performance of dilatometer for determining absolute CTE of EUVL LTEMs," *Microelec. Eng.* **83**, 1617–1620 (2006).
10. S. Hector, "Update on SEMI standards for EUV masks," in *EUV Mask Workshop*, Miyazaki, Japan (Nov. 2004).

11. E. Gullikson, K. Blaedel, C. Larson, S. L. Baker, and J. S. Taylor, "EUV scattering from mask substrate roughness," in *1st International Symposium on Extreme Ultraviolet Lithography*, Dallas, Texas, Oct. 2002, SEMATECH Inc.
12. K. L. Blaedel, J. S. Taylor, S. D. Hector, et al., "Vendor capability for low thermal expansion mask substrates for EUV lithography," *Proc. SPIE* **4688**, 767–778 (2002).
13. F. Ruggeberg, T. Leutbecher, S. Kirchner, et al., "Flatness correction of polished quartz glass substrates," in *2nd International Symposium on Extreme Ultraviolet Lithography*, Antwerp, Belgium, Oct. 2003, SEMATECH Inc.
14. P. B. Mirkarimi and D. G. Stearns, "Investigation the growth of localized defects in thin films using gold nanospheres," *Appl. Phys. Lett.* **77**(14), 2243–2245 (2000).
15. P. B. Mirkarimi, E. Spiller, S. L. Baker, et al., "Advancing the ion beam thin film planarization process for the smoothing of substrate particles," *Microelec. Eng.* **77**, 369–381 (2005).
16. P. B. Mirkarimi, E. Spiller, S. L. Baker, et al., "Developing a viable multilayer coating process for extreme ultraviolet lithography reticles," *J. Microlith., Microfab., Microsyst.* **3**(1), 139–145 (2004).
17. E. M. Gullikson, C. Cerjan, D. G. Stearns, P. B. Mirkarimi, and D. W. Sweeney, "Practical approach for modeling extreme ultraviolet lithography mask defects," *J. Vac. Sci. Technol. B* **20**(1), 81–86 (2002).
18. T. W. Barbee, Jr., S. Mrowka, and M. C. Hettrick, "Molybdenum-silicon multilayer mirrors for the extreme ultraviolet," *App. Opt.* **24**(6), 883–883 (1985).
19. J. M. Slaughter, D. W. Schulze, C. R. Hills, et al., "Structure and performance of Si/Mo multilayer mirrors for the extreme ultraviolet," *J. Appl. Phys.* **76**(4), 2144–2156 (1994).
20. P.-Y. Yan, in *Handbook of Photomask Manufacturing Technology*, ed. S. Rizvi, CRC Press/Taylor & Francis Informa Group, Boca Raton, FL, p. 239 (2005).
21. S. Bajt, J. Alameda, T. Barbee, et al., "Improved reflectance and stability of Mo/Si multilayers," *Proc. SPIE* **4506**, 65–75 (2001).
22. S. Braun, H. Mai, M. Moss, R. Scholz, and A. Leson, "Mo/Si multilayers with different barrier layers for applications as extreme ultraviolet mirrors," *Jpn. J. Appl. Phys.* **41**, 4074–4081 (2002).
23. S. Yulin, N. Benoit, T. Feigl, and N. Kaiser, "Interface-engineered EUV multilayer mirrors," *Microelec. Eng.* **83**, 692–694 (2006).
24. S. Bajt, J. B. Alameba, T. W. Barbee Jr., et al., "Improved reflectance and stability of Mo-Si multilayers," *Opt. Eng.* **41**(8), 1797–1804 (2002).
25. S. Y. Lee, S. M. Hur, H. J. Kim, et al., "Analysis of multilayer structure for reflection of extreme-Ultraviolet Wavelength," *Jpn. J. Appl. Phys.* **41**, 4086–4090 (2002).
26. P.-Y. Yan, in *Handbook of Photomask Manufacturing Technology*, ed. S. Rizvi, CRC Press/Taylor & Francis Informa Group, Boca Raton, FL, p. 238 (2005).

27. P. A. Kearney, C. E. Moore, S. I. Tan, S. P. Vernon, and R. A. Levesque, "Mask blanks for extreme ultraviolet lithography: Ion beam sputter deposition of low defect density Mo/Si multilayers," *J. Vac. Sci. Technol. B* **15**(6), 2452–2454 (1997).
28. J. A. Folta, J. C. Davidson, C. C. Larson, C. C. Walton, and P. A. Kearney, "Advances in low-defect multilayers for EUVL mask blanks," *Proc. SPIE* **4688**, 173–181 (2002).
29. P. B. Mirkarimim, E. A. Spiller, D. G. Stearns, V. Sperry, and S. L. Baker, "An ion-assisted Mo-Si deposition process for planarizing reticle substrates for extreme ultraviolet lithography," *IEEE J. Quantum Electron.* **37**(12), 1514–1516 (2001).
30. E. Spiller, S. L. Baker, P. B. Mirkarimi, et al., "High-performance Mo-Si multilayer coatings for extreme-ultraviolet lithography by ion-beam deposition," *App. Opt.* **42**(12), 4049–4058 (2003).
31. Ma, P. Kearney, D. Krick, et al., "Progress towards the development of a commercial tool and process for EUVL mask blanks," *Proc. SPIE* **5751**, 168–177 (2005).
32. D. G. Stearns, R. S. Rosen, and S. P. Vernon, "Fabrication of high-reflectance Mo-Si multilayer mirrors by planar-magnetron sputtering," *J. Vac. Sci. Technol. A* **9**(5), 2662–2669 (1991).
33. M. Shiraishi, N. Kandaka, and K. Murakami, "Mo/Si multilayers deposited by low-pressure rotary magnet cathode sputtering for extreme ultraviolet lithography," *Proc. SPIE* **5037**, 249–256 (2003).
34. J. C. Bravman and R. Sinclair, "The preparation of cross-section specimens for transmission electron microscopy," *J. Electron Microsc. Technol.* **1**, 53–61 (1984).
35. D. E. Kim, D. H. Cha, and S. W. Lee, "Structural characterization of a Mo/Si multilayer reflector by means of x-ray diffraction measurements," *J. Vac. Sci. Technol. A* **15**(4), 2291–2296 (1997).
36. B. Vidal and P. Vincent, "Metallic multilayers for x rays using classical thin-film theory," *Appl. Phys. Lett.* **23**, 1794–1801 (1894).
37. U. Hinze and B. Chichkov, "Table-top EUV-reflectometer," *Proc. SPIE* **6151**, 615136 (2006).
38. Egbert and S. Becker, "Advanced at-wavelength reflectometry with the EUV tube," *Proc. SPIE* **6151**, 61512X (2006).
39. J. H. Underwood and R. C. C. Perera, "An automated reflectometer for measurement of reflectivity of EUV lithography masks: results from our recently delivered tools," in *EUVL Symposium 2005*, San Diego, California, Nov. 2005.
40. S. Bajt, H. N. Chapman, N. Nguyen, et al., "Design and performance of capping layers for EUV multilayer mirrors," *Proc. SPIE* **5037**, 236–248 (2003).
41. P. Y. Yan, G. Zhang, S. Chegwidan, E. Spiller, and P. Mirkarimi, "EUVL mask with Ru ML capping," *Proc. SPIE* **5256**, 1281–1286 (2003).

42. S. Bajt, Z. R. Dai, E. J. Nelson, et al., "Oxidation resistance of Ru-capped EUV multilayers," *Proc. SPIE* **5751**, 118–127 (2005).
43. H. Takase, S. Terashima, Y. Gomei, et al., "Study of ruthenium-capped multilayer mirror for EUV irradiation durability," *Proc. SPIE* **6151**, 615135 (2006).
44. Nishiyama, "Model of Ru surface oxidation for the lifetime scaling of EUVL projection optics mirror," *Proc. SPIE* **6151**, 61510G (2006).
45. J. Hollenshead and L. Klebanoff, "Modeling extreme ultraviolet/H₂O oxidation of ruthenium optic coatings," *J. Vac. Sci. Technol. B* **24**(1), 118–130 (2006).
46. T. G. Kim, S. Y. Lee, C. Y. Kim, et al., "Characterization of Ru layer for capping/buffer application in EUVL mask," *Microelec. Eng.* **83**, 688–691 (2006).
47. S. T. Prisbrey, S. P. Vernon, and W. M. Clift, "Iridium/silicon capping layer for soft x-ray and extreme ultraviolet mirrors," *J. Vac. Sci. Technol. B* **23**(6), 2378–2383 (2005).
48. P.-Y. Yan, in *Handbook of Photomask Manufacturing Technology*, ed. S. Rizvi, CRC Press/Taylor & Francis Informa Group, Boca Raton, FL, pp. 241–246 (2005).
49. S. Bajt, D. G. Stearns, and P. A. Kearney, "Investigation of the amorphous-to-crystalline transition in Mo/Si multilayers," *J. Appl. Phys.* **90**, 1017–1025 (2001).
50. R. Randive, A. Ma, I. Reiss, et al., "Defect mitigation and reduction in EUVL mask blanks," in *EUVL Symposium 2006*, Barcelona, Spain, Oct. 2006.
51. Rastegar, S. Eichenlaub, V. Kapila, A. J. Kadaksham, and P. Marmillion, "New requirements for the cleaning of EUV blanks," *Proc. SPIE* **6517**, 65171D (2007).
52. R. Randive, A. Ma, I. Reiss, et al., "Defect mitigation and reduction in EUVL mask blank," *Proc. SPIE* **6517**, 651726 (2007).
53. Rastegar, S. Eichenlaub, H. Popp, K. Goncher, and P. Marmillion, "Removing sub-50 nm particles during blank substrate cleaning," *Solid State Technol.* **49**, 47 (2006).
54. E. Gullikson, C. Cerjan, D. Stearns, P. Mirkarimi, and D. Sweeney, "Practical approach for modeling extreme ultraviolet lithography mask defects," *J. Vac. Sci. Technol. B* **20**, 81–86 (2002).
55. P. B. Mirkarimi, E. Spiller, S. L. Baker, et al., "A silicon-based, sequential coat-and-etch process to fabricate nearly perfect substrate surfaces," *J. Nanosci., Nanotech.* **6**, 28–35 (2006).
56. R. Randive, P. Mirkarimi, E. Spiller, et al., "Recent advances in the development of low-defect Mo/Si deposition tool and process for EUVL mask blanks," in *EUVL Symposium 2005*, San Diego, California, Nov. 2005.
57. P. B. Mirkami, "Stress, reflectance, and temporal stability of sputter-deposited Mo/Si and Mo/Be multilayer films for extreme ultraviolet lithography," *Opt. Eng.* **38**, 1246–1259 (1999).

58. Barty, P. B. Mirkarimi, D. G. Stearns, et al., "EUVL mask blank repair," *Proc. SPIE* **4688**, 385–394 (2002).
59. N. Kikuri, S. Murakami, H. Tsuchiya, et al., "Development of advanced reticle inspection apparatus for hp 65 nm node device and beyond," *Proc. SPIE* **6283**, 62830Y (2006).
60. K. Lim, J. Park, D. Chung, et al., "Novel mask inspection flow for better defect review and analysis," *Proc. SPIE* **6283**, 62830Z (2006).
61. D. Pettibone, A. V. Veldman, T. Liang, et al., "Inspection of EUV reticles," *Proc. SPIE* **4688**, 363–374 (2002).
62. E. Golan, D. Meshulach, N. Raccach, et al., "Immersion lithography defectivity analysis at DUV inspection wavelength," *Proc. SPIE* **6518**, 65180S (2007).
63. M. Yi, T. Haga, C. Walton, and J. Bokor, "High sensitivity actinic detection of native defects on extreme ultraviolet lithography mask blanks," *J. Vac. Sci. Technol. B* **19**, 2401–2405 (2001).
64. V. Farys, P. Schiavone, F. Polack, et al., "Highly sensitive detection technique of buried defects in extreme ultraviolet masks using at-wavelength scanning dark-field microscopy," *Appl. Phys. Lett.* **87**, 024102 (2005).
65. Y. Tezuka, M. Ito, T. Terasawa, and T. Tomie, "Actinic detection and signal characterization of multilayer defect on EUV mask blanks," *Proc. SPIE* **5567**, 791 (2004).
66. T. Tananka, T. Terasawa, N. Iriki, H. Aoyama, and T. Tomie, "Detection signal analysis of actinic inspection of EUV mask blanks using dark-field imaging," *Proc. SPIE* **6517**, 65171Y (2007).
67. Barty, Y. Liu, E. Gullikson, J. S. Taylor, and O. Wood, "Actinic inspection of multilayer defects on EUV masks," *Proc. SPIE* **5751**, 651–65 (2005).
68. Y. Liu, A. Barty, E. Gullikson, et al., "A dual-mode actinic EUV mask inspection tool," *Proc. SPIE* **5751**, 660–669 (2005).
69. K. Hamamoto, Y. Tanaka, S. Y. Lee, et al., "Mask defect inspection using an extreme ultraviolet microscope," *J. Vac. Sci. Technol. B* **23**(6), 2852–2855 (2005).
70. K. Hamamoto, Y. Tanaka, T. Yoshizumi, et al., "Phase defect observation using an EUV microscope," *Proc. SPIE* **6151**, 615119 (2006).
71. M. Booth, O. Brisco, A. Brunton, et al., "High-resolution EUV imaging tools for resist exposure and aerial image monitoring," *Proc. SPIE* **5751**, 78–89 (2005).
72. U. Neuhausler, J. Lin, A. Oelsner, et al., "A new approach for actinic defect inspection of EUVL multilayer mask blanks: Standing wave photoemission electron microscopy," *Microelec. Eng.* **83**, 680–683 (2006).
73. U. Neuhausler, A. Oelsner, J. Slieh, et al., "High-resolution actinic defect inspection for extreme ultraviolet lithography multilayer mask blanks by photoemission electron microscopy," *Appl. Phys. Lett.* **88**, 053113 (2006).
74. R. Stivers, T. Liang, M. J. Penn, et al., "Evaluation of the capability of a multibeam confocal inspection system for inspection of EUVL mask blanks," *Proc. SPIE* **4889**, 408–417 (2002).

75. S.-S. Kim, J. Park, R. Chalykh, et al., "Defect inspection of EUV mask blank using confocal microscopy: simulation and experiment," *Proc. SPIE* **6151**, 61511C (2006).
76. P. B. Mirkarimi, D. G. Stearns, S. L. Baker, et al., "Method for repairing Mo/Si multilayer thin film phase defects in reticles for extreme ultraviolet lithography," *J. Appl. Phys.* **91**(1), 81–89 (2002).
77. S. Y. Lee, T. G. Kim, J. G. Park, et al., "Investigation of multilayer structural changes in phase and amplitude-defects correction process," *J. Vac. Sci. Technol. B* **23**(6), 2866–2869 (2005).
78. S. P. Hau-Riege, A. Barty, P. B. Mirkarimi, et al., "Repair of phase defects in extreme-ultraviolet lithography mask blanks," *J. Appl. Phys.* **96**(11), 6812–6821 (2004).
79. K. Ray-Chaudhuri, G. Cardinale, A. Fisher, P.-Y. Yan, and D. W. Sweeney, "Method for compensation of extreme-ultraviolet multilayer defects," *J. Vac. Sci. Technol. B* **17**, 3024–3028 (1999).
80. P.-Y. Yan, G. Zhang, P. Kofron, et al., "EUV mask absorber characterization and selection," *Proc. SPIE* **4066**, 116–123 (2000).
81. M. Niibe, T. Watanabe, H. Nii, T. Tanaka, and H. Kinoshita, "Contrast measurement of reflection masks fabrication from Cr and Ta absorbers for extreme ultraviolet lithography," *Jpn. J. Appl. Phys.* **39**, 6815–6818 (2000).
82. P. Mangat, S. Hector, S. Rose, et al., "EUV mask fabrication with Cr absorber," *Proc. SPIE* **3997**, 76–82 (2000).
83. E. Hoshino, T. Ogawa, N. Hirano, et al., "Dry etching of Ta absorber for EUVL masks," *Proc. SPIE* **4186**, 749–755 (2000).
84. H.-J. Voorma, E. Louis, N. B. Koster, et al., "Fabrication and analysis of extreme ultraviolet reflection masks with patterned W/C absorber bilayers," *J. Vac. Sci. Technol. B* **15**(2), 293–298 (1997).
85. G. Zhang, P.-Y. Yan, and T. Liang, "Cr absorber mask for extreme-ultraviolet lithography," *Proc. SPIE* **4186**, 774–780 (2000).
86. P.-Y. Yan, G. Zhang, A. Ma, and T. Liang, "TaN EUVL mask fabrication and characterization," *Proc. SPIE* **4343**, 409–414 (2001).
87. P.-Y. Yan, "The impact of EUVL mask buffer and absorber material properties on mask quality and performance," *Proc. SPIE* **4688**, 150–160 (2002).
88. F. Sobel, L. Aschke, M. Renno, et al., "Absorber stack optimization towards EUV lithography mask blank pilot production," *Proc. SPIE* **5567**, 781–790 (2004).
89. J. Wasson, K. Smith, P. J. S. Mangat, and S. Hector, "An infinitely selective repair buffer for EUVL reticles," *Proc. SPIE* **4343**, 402–408 (2001).
90. F. Letzkus, J. Butschke, C. Koepernik, et al., "SiO₂ buffer-etch process with a TaN absorber for EUV mask fabrication," *Proc. SPIE* **5567**, 1407–1416 (2004).
91. M. Kureishi, R. Ohkubo, M. Hosoya, et al., "Development of low damage mask making process on EUV mask with thin CrN buffer layer," *Proc. SPIE* **5751**, 158–167 (2005).

92. B. T. Lee, E. Hoshino, M. Takahashi, et al., "Characteristics of Ru buffer layer for EUVL mask patterning," *Proc. SPIE* **4343**, 746–753 (2001).
93. S. Y. Lee, T. G. Kim, C. Y. Kim, et al., "Combined absorber stack for optimization of the EUVL mask," *Proc. SPIE* **6151**, 61511Y (2006).
94. J. R. Wasson, S.-I. Han, N. V. Edwards, et al., "Integration of anti-reflection coating on EUV absorber stacks," *Proc. SPIE* **4889**, 382–388 (2002).
95. C. G. Krautschik, M. Ito, I. Nishiyama, and K. Otaki, "Impact of the EUV mask phase response on the asymmetry of Bossung curves as predicted by rigorous EUV mask simulations," *Proc. SPIE* **4343**, 392–401 (2001).
96. L. He, K. Orvek, P. Seidel, et al., "Status and path to a final EUVL reticle-handling solution," *Proc. SPIE* **6517**, 375–384 (2007).
97. P. J. S. Mangat, S.D. Hector, M. A. Thompson, et al., "Extreme ultraviolet lithography mask patterning and printability studies with a Ta-based absorber," *J. Vac. Sci. Technol. B* **17**(6), 3029–3033 (1999).
98. H. Kim, S.-H. Huh, D.-W. Kim, et al., "Effect of EUV dry etch process on image placement (IP) errors," in *EUVL Symposium 2006*, Barcelona, Spain, Oct. 2006.
99. J. R. Wasson, B. Lu, P. J. S. Mangat, K. Nordquist, and D. J. Resnick, "Writing, repairing and inspecting of extreme ultraviolet lithography reticles considering the impact of the materials," *J. Vac. Sci. Technol. B* **19**(6), 2635–2640 (2001).
100. T. Liang, A. Stivers, R. Livengood, et al., "Progress in extreme ultraviolet mask repair using a focused ion beam," *J. Vac. Sci. Technol. B* **18**(6), 3216–3220 (2000).
101. Wagner, R. A. Haight, and P. Longo, "MARS2: An advanced femtosecond laser mask repair tool," *Proc. SPIE* **4889**, 457–468 (2002).
102. R. White, M. Verbeek, R. Bozak, and M. Klos, "Use of nanomachining as a technique to reduce scrap of high-end photomasks," *Proc. SPIE* **4562**, 213–224 (2002).
103. T. Liang and A. Stivers, "Damage-free mask repair using electron beam induced chemical reactions," *Proc. SPIE* **4688**, 375–384 (2002).
104. T. Liang, E. Frendberg, B. Lieberman, and A. Stivers, "Advanced photolithographic mask repair using electron beams," *J. Vac. Sci. Technol. B* **23**(6), 3101–3105 (2005).
105. S. Matsui, T. Ichihashi, and M. Mito, "Electron beam induced selective etching and deposition technology," *J. Vac. Sci. Technol. B* **7**(5), 1182–1190 (1989).
106. K. Nakamae, H. Tanimoto, T. Takase, H. Fujioka, and K. Ura, "Electron beam assisted high aspect ratio, submicrometre etching of passivation SiO₂ on large-scale integrated circuits," *J. Phys. D: Appl. Phys.* **25**, 1681–1686 (1992).
107. D. Winkler, H. Zimmermann, M. Mangerich, and R. Trauner, "E-beam probe station with integrated tool for electron beam induced etching," *Microelec. Eng.* **31**, 141–147 (1996).

108. K. Edinger, H. Becht, J. Bihr, et al., "Electron-beam-based photomask repair," *J. Vac. Sci. Technol. B* **22**, 2902–2906 (2004).
109. T. Liang, A. R. Stivers, M. Penn, et al., "Demonstration of damage-free mask repair using electron beam-induced processes," *Proc. SPIE* **5446**, 291–300 (2004).
110. C. Ehrlich, K. Edinger, T. Hofmann, and W. Degel, "Recent application results from the novel e-beam based mask repair system MeTiTTMMG," *Proc. SPIE* **6281**, 62810M (2006).
111. H. Nii, H. Kinoshita, T. Watanabe, Y. Matsuo, and Y. Sugie, "Studies on EUV mask cleaning by dry and wet processes," *Proc. SPIE* **4409**, 687–694 (2001).
112. S. H. Lee, Y. K. Hong, J. H. Song, et al., "Particle adhesion and removal on EUV mask layers during wet cleaning," *Jpn. J. Appl. Phys.* **44**(7B), 5479–5483 (2005).
113. K. Hamamoto, Y. Tanaka, T. Watanabe, et al., "Cleaning of extreme ultraviolet lithography optics and mask using 13.5 nm and 172 nm radiation," *J. Vac. Sci. Technol. B* **23**(1), 247–251 (2005).
114. N. Hirano, H. Hoko, E. Hoshino, et al., "Surface preparation of EUVL-mask substrate for multi-layer coating by supersonic hydrocleaning technique," *Proc. SPIE* **4066**, 430–437 (2000).
115. T. Yoneda, H. Hoko, E. Hoshino, et al., "Evaluation of cleaning techniques for EUVL mask by using a highly sensitive particle detection system," *Microelec. Eng.* **61–62**, 213–218 (2002).
116. W. M. Lytle, M. J. Neumann, and D. N. Ruzic, "Plasma-assisted cleaning by electrostatics (PACE)," *Proc. SPIE* **6151**, 61511B (2006).
117. S. H. Lee, Y. J. Kang, J. G. Park, et al., "Laser shock removal of nanoparticles from Si capping layer of extreme ultraviolet lithography masks," *Jpn. J. Appl. Phys.* **44**(7B), 5560–5564 (2005).
118. Varghese and C. Cetinkaya, "Non-contact removal of 60-nm latex particles from silicon wafers with laser-induced plasma," *J. Adhesion Sci. Technol.* **18**, 795–806 (2004).
119. R. Wood II, D. L. White, J. E. Bjorkholm, et al., "Use of attenuated phase masks in extreme ultraviolet lithography," *J. Vac. Sci. Technol. B* **15**(6), 2448–2451 (1997).
120. P.-Y. Yan, "EUVL alternating phase shift mask imaging evaluation," *Proc. SPIE* **4889**, 1099–1105 (2002).
121. Y. Deng, B. L. Fontaine, H. J. Levinson, and A. R. Neureuther, "Rigorous EM simulation of the influence of the structure of mask patterns on EUVL imaging," *Proc. SPIE* **5037**, 302–313 (2003).
122. Y. Deng, B. L. Fontaine, A. R. Pawloski, and A. R. Neureuther, "Simulation of fine structures and defects in EUV etched multilayer masks," *Proc. SPIE* **5374**, 760–769 (2004).
123. L. Dreeskornfeld, G. Haindl, U. Kleineberg, et al., "Nanostructuring of Mo/Si multilayer by means of reactive ion etching using a three-level mask," *Thin Solid Films* **458**, 227–232 (2004).

124. B. L. Fontaine, A. R. Pawloski, O. Wood, et al., "Demonstration of phase-shift masks for extreme-ultraviolet lithography," *Proc. SPIE* **6151**, 61510A (2006).
125. C. Constancias, M. Richard, D. Joyeux, et al., "Phase shift mask for EUV lithography," *Proc. SPIE* **6151**, 61511W (2006).
126. P.-Y. Yan, in *Handbook of Photomask Manufacturing Technology*, ed. S. Rizvi, CRC Press/Taylor & Francis Informa Group, Boca Raton, FL, pp. 264–267 (2005).



Han-Ku Cho received his BS (1982) and MS (1984) degrees from Seoul National University in electronic engineering and his PhD (1995) from the University of Arizona in electrical and computer engineering. He joined the semiconductor division at Samsung Electronics in 1995. With 12 years of experience in lithography and photomask (currently as a vice president and team leader), he is in charge of production, management, and technology development with the Photomask Team, Semiconductor R&D Center in Memory Division.



Jinho Ahn received his BS (1986) and MS (1988) degrees from Seoul National University and his PhD (1992) from the University of Texas at Austin—all in materials science and engineering (MSE). He worked for NEC Japan from 1993 to 1995 and joined Hanyang University in 1995 as a professor in the MSE department. He also works as a director for the New Growth Engine Semiconductor Research Center of the Ministry of Commerce, Industry, and Energy. Additionally, he leads national projects for EUVL technology and stepper development for displays.

Chapter 8

Photoresists for Extreme Ultraviolet Lithography

Robert L. Brainard

Contents

8.1	Introduction	384
8.2	Earliest EUV Resist Imaging	385
8.3	Absorption Coefficients of EUV Photoresists	391
8.3.1	Absorption coefficient definitions	391
8.3.2	Absorption cross-sections of the elements	392
8.3.3	Methods for determining EUV absorbance	393
8.4	Multilayer Resists and Pattern Transfer	394
8.4.1	Multilayer resist approaches	395
8.4.2	Defects in ultrathin resist films	397
8.4.3	Pattern transfer of UTR into hard masks	400
8.4.4	Integration of UTRs into integrated circuit manufacturing processes	401
8.5	Resist Types	403
8.5.1	Environmentally stable chemically amplified photoresists (ESCAP)	404
8.5.1.1	ESCAP at 0.088 NA	404
8.5.1.2	ESCAP at 0.3 NA	407
8.5.1.3	Best examples of ESCAP UTRs	412
8.5.2	KRS photoresists	413
8.5.3	PMMA	416
8.5.4	Negative resists	418
8.5.4.1	Lactonization polarity switch	419
8.5.4.2	Calixarenes	421
8.5.5	Resists with silicon or boron	422
8.5.5.1	Hydrogen silsesquioxane	422
8.5.5.2	Other silicon resists	422
8.5.5.3	Boron-containing resists	425
8.6	PAGs and Acids	426
8.6.1	Acid diffusion	426
8.6.2	New PAGs for EUV	426
8.6.3	Exposure mechanisms	426
8.7	Line Edge Roughness	428

8.7.1 Added base	429
8.7.2 Polymer size	430
8.7.3 Shot noise	432
8.7.4 Film quantum yield	434
8.8 Summary and Future Outlook	435
Acknowledgments	435
References	437

8.1 Introduction

Extreme ultraviolet lithography (EUVL) has advanced dramatically since its inception in 1986. Current EUV technology is challenging conventional 193-nm lithography for the 32-nm node and is the likely technology that will be used for the 22-nm node. Progress in EUV research has required an interdisciplinary approach involving partnerships of scientists and engineers within both industry and academics. Contributions from the fields of physics, optics, computer science, business, materials science, and chemistry have been critical to all phases of EUV technical advances.

One of the most important components of EUVL is the technological advancement of photoresists. Although EUV photoresist performance has made dramatic advances over the years, resist requirements for 2013 are extremely demanding [Fig. 8.1(a)]. In the future, resists must show considerable improvement in resolution, line edge roughness (LER),^{1–3} and sensitivity. Unfortunately, these three resist properties are in opposition to each other and have been described as the RLS (resolution, LER, and sensitivity) tradeoff typified by the triangular image in Fig. 8.1(b)⁴ and evaluated theoretically by Gallatin^{5,6} and van Steenwinckel.^{7,8} While resists exist that can demonstrate each requirement individually, there are currently no resists that can meet all three requirements at once.⁹

The purpose of this review is to describe the history of the first resists imaged by EUV light up to present-day resist technology. The emphasis will be on describing early EUV challenges and questions, and on chemical approaches that were

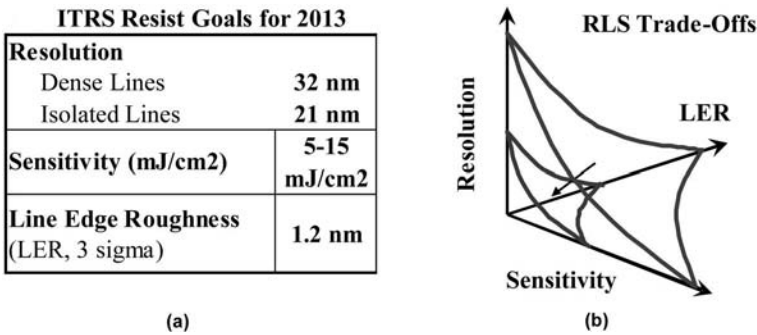


Figure 8.1 (a) *International Technology Roadmap for Semiconductors* (ITRS) resist goals for 2013 (from the 2006 ITRS update). (b) RLS tradeoffs.

applied to further EUV resist technology. The development of photoresists has occurred through the successful collaboration of industry and academia. Typically, the best-performing resists come from industry; however, most industrial research is proprietary, so technical details are generally not publicly disclosed. Fortunately, the role played by academics lends balance to the industry by advancing and evaluating new chemical approaches and publishing the results. This review will cover contributions from both industry and academia but will primarily emphasize publications that reveal the most information available during each period of research.

8.2 Earliest EUV Resist Imaging

This section reviews the work of several pioneers in the field from 1986 to 1995. This was a time when there were few researchers and many critical problems to solve. The decisions made by these researchers set the foundation upon which today's technology has been built. Perhaps the most critical decision was which wavelength to use. Wavelengths from 5 to 40 nm were considered. The determination of what wavelength to use (~ 13.5 nm) was made by analysis of the work described in this section.

The earliest published EUV imaging is that of Kinoshita et al. in Japan in 1986¹⁰ and a few years later in the U.S. in 1989.¹¹ In Kinoshita et al.'s work, the developed depth of polymethylmethacrylate (PMMA) was plotted against the incident absorbed dose for 5- and 11.8-nm light (Fig. 8.2). The 11.8-nm light leveled off at a depth of ~ 90 -nm film thickness, whereas the 5-nm light easily penetrated to 300 nm of PMMA. These results led Kinoshita and coworkers to conclude that bilayer processes would need to be developed for imaging wavelengths of 10 nm or greater.

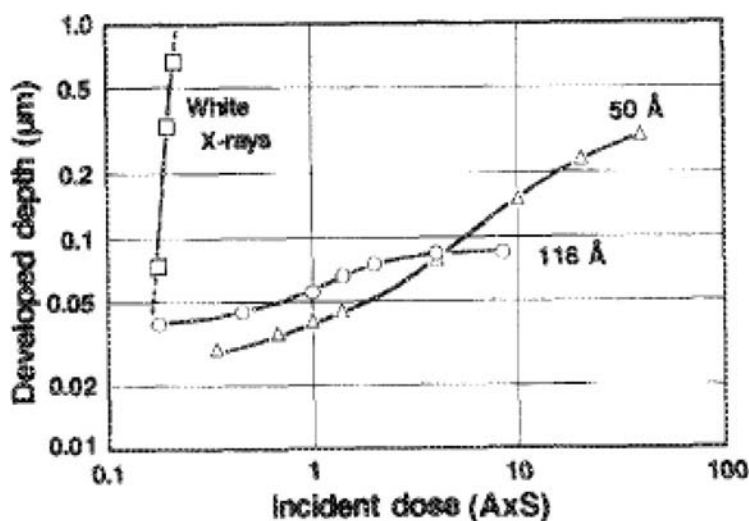


Figure 8.2 Spectral characteristics of PMMA resist using 5 nm, 11.8 nm, and white x-rays. (Reprinted from Ref. 11 with permission from AVS—The Science & Technology Society.)

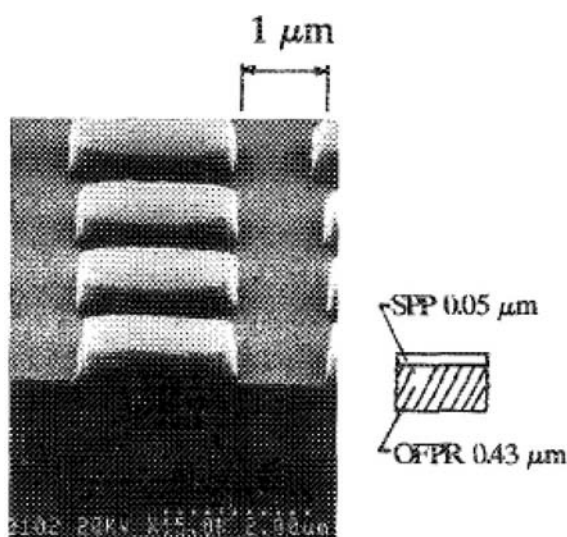


Figure 8.3 Scanning electron micrograph (SEM) of a 1.0- μm line pattern in a Si-based negative resist/over PMMA (OFPR) as a planarizing layer.^{11–14} (Reprinted from Ref. 11 with permission from AVS—The Science & Technology Society.)

Kinoshita et al. built a Schwarzschild 1/8 reduction optic with two spherical mirrors for use at 5- and 12.4-nm wavelengths. The spherical mirrors were coated with carbon and tungsten multilayers (MLs), but no reflectivity values were reported for these mirrors.^{12,13} They printed 500-nm lines in PMMA using 12.4-nm light and a reflection mask. The numerical aperture (NA) was estimated to be >0.032 . Similarly, the printed 1.0- μm trenches use a positive-tone bilayer resist—silicone-based positive photoresist (SPP) and OFPR-Novolak resist developed by TOK.¹⁴ The top SPP layer was 50-nm thick and was exposed using the stencil mask and 12.4-nm light, followed by O_2 reactive ion etching (RIE), producing fairly vertical profiles (Fig. 8.3).^{11–13}

In 1990, Bjorkholm et al. first published their work about printing images into PMMA films using 14-nm light.¹⁵ They used a Schwarzschild objective with a molybdenum-silicon (Mo/Si) ML coating to provide $\sim 40\%$ reflectivity at 14 nm. They printed 50-nm lines in a 60-nm film of PMMA on primed Si (Fig. 8.4). They also printed 100- and 150-nm dense lines using a trilayer resist composed of PMMA/germanium/hard-baked photoresist. They successfully transferred the pattern in PMMA (60-nm thick) to the germanium (Ge) and hard-baked resist using RIE with CF_3Br , then oxygen. The resulting patterns showed excellent LER.^{1–3}

In 1991, Mansfield et al. measured the lithographic parameters of PMMA at 37.5- and 14-nm and used them to simulate resist profiles.¹⁶ They determined the resist thickness removed as a function of dose at 37.5 nm and 14 nm (Fig. 8.5). They also determined the clearing dose (E_0) for 60-nm films of PMMA to be 23 and 55 mJ/cm^2 for 37.5- and 14-nm light, respectively. Similarly, they also determined the volumetric sensitivity to be 3000 J/cm^3 for both wavelengths using

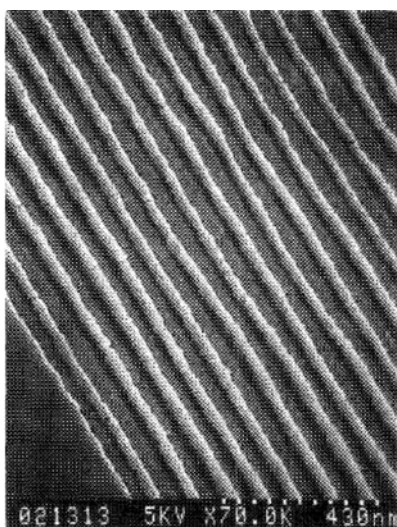


Figure 8.4 SEM micrograph showing 50-nm lines and spaces printed in 60 nm of PMMA on Si using 14-nm EUV light. (Reprinted from Ref. 15 with permission from AVS—The Science & Technology Society.)

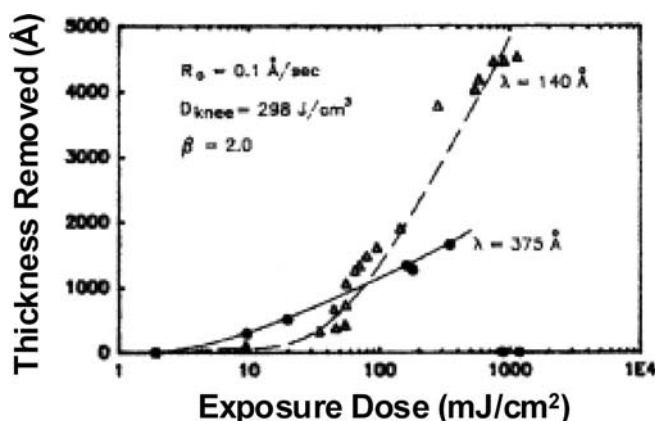


Figure 8.5 PMMA thickness removed versus exposure dose using 14-nm (triangles) and 37.5-nm (circles) light. (Reprinted from Ref. 16 with permission from AVS—The Science & Technology Society.)

Eq. (8.1):

$$\text{Volume sensitivity} \equiv (E_0 \times \text{absorbance}) / \text{film thickness.} \quad (8.1)$$

The identical values of PMMA volumetric sensitivity for these two wavelengths indicate that the exposure mechanism^{17,18} depends only upon the amount of energy absorbed, not on the number of photons absorbed. This further indicates that the film quantum yield¹⁹ for the PMMA imaging mechanism is higher with higher energy photons, since 37.5-nm light has $2.7 \times$ more photons/mJ than 14-nm light.

According to this result, the 14-nm light would have $2.7\times$ higher film quantum yield. Mansfield et al. determined the Dill B- and C-parameters (absorption and optical sensitivity, respectively)²⁰ using 37.5- and 14-nm light by a combination of fitting the experimental data in Fig. 8.5 and by using Henke's data (Table 8.1).²¹ The modeling predicted that the sidewall angle in 200-nm dense lines printed with 37.5-nm light in 60-nm-thick films of PMMA would be much shallower than when using 14-nm light as verified by cross-sectional SEMs.

In 1992, Early et al.^{24,25} evaluated a series of variables in pursuit of high-resolution imaging: radiation type (14-nm EUV light, 50-keV e-beam); resist type (negative chemically amplified resist AZ PN114²⁶ and PMMA); film thickness (50–200 nm); substrate (Si and trilayer); developer (NaOH, TMAH); and post-exposure bake (PEB) temperature (105–115°C). This work demonstrated three interesting aspects:

- The first 75-nm dense lines using a chemically amplified resist (PN114);
- Studies of pinhole density versus film thickness studies; and
- Early investigations into LER and discussions of shot-noise effects.

The AZ PN114 resist was coated in a 50-nm film over primed Si, and exposed with 14-nm light using a $20\times$ Schwarzschild camera ($NA = 0.08$). These conditions allowed the resist to print 75-, 100-, and 150-nm lines at 10 mJ/cm^2 , but it did not resolve 50-nm dense lines. The pinhole density was studied using a defect magnification technique²⁴ and was found to increase dramatically with decreasing film thickness of AZ PN114 (Table 8.2). This pinhole data raised important questions about the possibility of single-layer resist films to remedy the imaging issues encountered with higher absorbance. Lastly, this group compared the LER

Table 8.1 PMMA B- and C-parameters determined by Mansfield et al.¹⁶ and by using the Website for the Center for X-ray Optics (CXRO) at Lawrence Berkeley National Laboratory.^{22,23}

Wavelength	B-parameter (base e absorbance)		C-parameter optical sensitivity
	Mansfield	CXRO-LBL	
14 nm	6.2/ μm	5.6/ μm	0.01 cm^2/mJ
37.5 nm	26/ μm	35/ μm	0.042 cm^2/mJ

Table 8.2 Pinhole densities found in spin-cast films of AZ PN114.

Thickness (nm)	Pinholes ($1/\text{cm}^2$)
380	0.2
250	1
100	4
50	15

of PMMA and PN114 in 100- and 200-nm dense lines. Unfortunately, this LER study was performed using e-beam (50 keV) rather than EUV light. Nonetheless, this work was an early indication of the tradeoffs between LER and sensitivity; they found that the 3σ LER for PMMA was significantly lower than the faster, chemically amplified negative resist (PN114) (9 versus 24 nm, respectively).

Kubiak et al.²⁷ compared the imaging and modeling of PMMA and SAL601 using a $20\times$ Schwarzschild optic with 13.9 nm EUV light. They experimentally measured the absorbance of PMMA at 13.9 to be 5.95 1/mm (nearly identical to calculations)^{21,22} and a C-parameter of 0.42 cm²/mJ. They calculated the absorbance of SAL601 making assumptions about composition and density (~ 1.14 g/cm³). They also determined the C-parameters from the contrast curves shown in Fig. 8.6.

Dense lines (100 nm) were printed from 100-nm-thick films of PMMA, and 150-nm dense lines from 120-nm-thick films of the negative resist SAL601. Optical modeling predicted that PMMA would print 135-nm lines with a sidewall angle of $\sim 79^\circ$, whereas the negative resist SAL601 would print lines with re-entrant wall angles of $\sim 85^\circ$.

In 1994, Wood et al.^{28,29} performed a series of experiments to fully investigate the wavelength options for EUV. They assembled three Schwarzschild cameras that used 37.5-, 13.9-, and 6.8-nm light. Characteristics for each camera and some resist results are summarized in Table 8.3. The 37.5 wavelength was evaluated because it is the shortest wavelength that can be used without resorting to ML technology for reflective surfaces in the optic. The 37.5-nm camera was fabricated using spherical mirrors coated with iridium (Ir) since these coatings can attain reflectivities as high as 20%.^{30,31} Molybdenum-silicon MLs were used in the 13.9-nm camera and are available today near the theoretical reflectivity of 68%. Carbon-based MLs were used in the 6.8-nm camera and provided only poor reflectivity.

Table 8.3 shows the results of printing 500-nm dense lines in 60-nm-thick PMMA. Sidewall angles were measured using scanning tunneling microscopy (STM) and by measurement of cross-section SEMs. PMMA optical density was determined experimentally by Kubiak^{27,32} or through calculation.^{21,22} The PMMA absorption coefficient increases dramatically with increasing wavelength; conse-

Table 8.3 Summary of characteristics for three Schwarzschild cameras and resist results.

Wavelength (nm)	Optic		PMMA resist			PN114 resist	
	Reflective surface	NA	Absorbance* (1/ μ m)	E size (mJ/cm ²)	Sidewall angle	Absorbance* (1/ μ m)	Sidewall angle
37.5	Iridium	0.113	37	80	19°	—	—
13.9	Mo/Si Multilayer	0.0835	5.95	66	65°	4.4	Undercut $\sim 75^\circ$
6.8	Ru/B4C Multilayer	0.07	1.2	—	87°		Nearly Verticle

*Absorbance values taken from Kubiak et al.³² except PMMA at 37.5 and 6.8 nm, which were calculated.²²

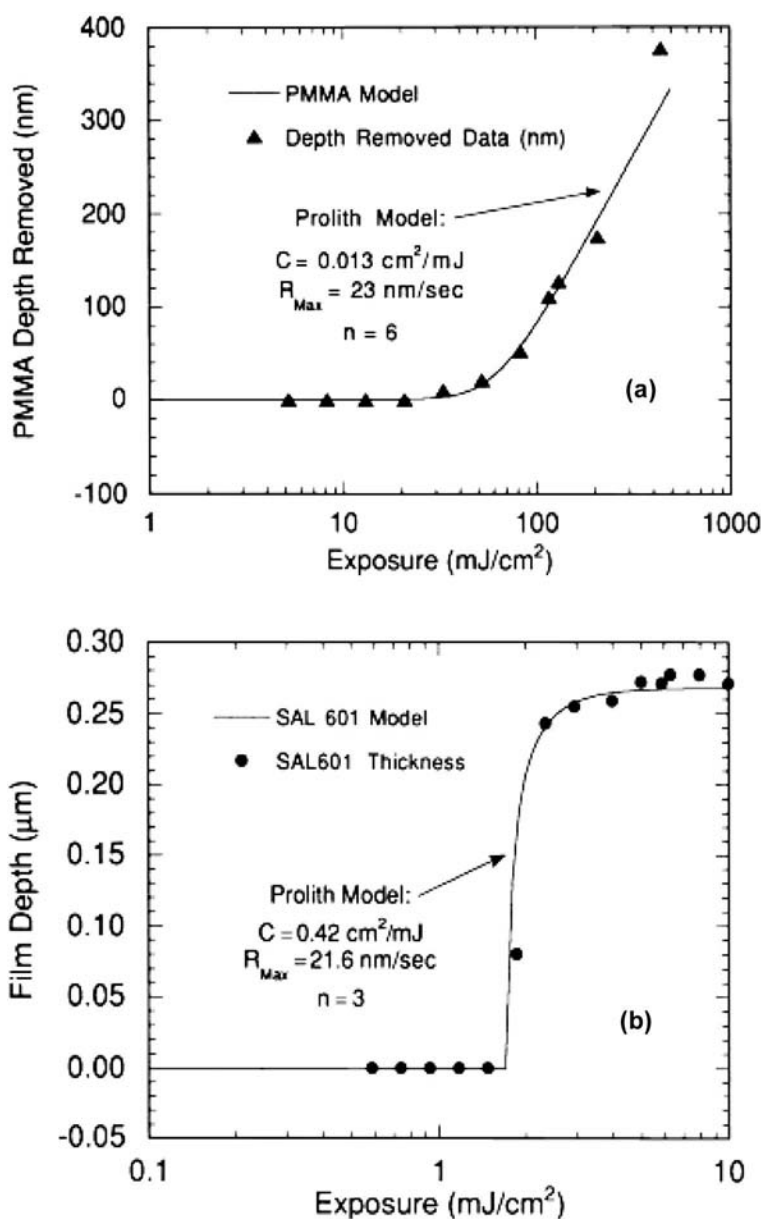


Figure 8.6 (a) Exposure sensitivity curves of PMMA. (b) SAL 601 at 13.9 nm (points) and best-fit model sensitivity curves (solid lines).

quently, the sidewall angle decreases at longer wavelengths. Wood et al. concluded that wavelengths shorter than 13.9 nm should be pursued for increased transparency and steeper sidewall angles, and they also concluded that bilayer or trilayer resist schemes may be necessary for EUVL to remedy problems such as pinholes and low etch resistance.

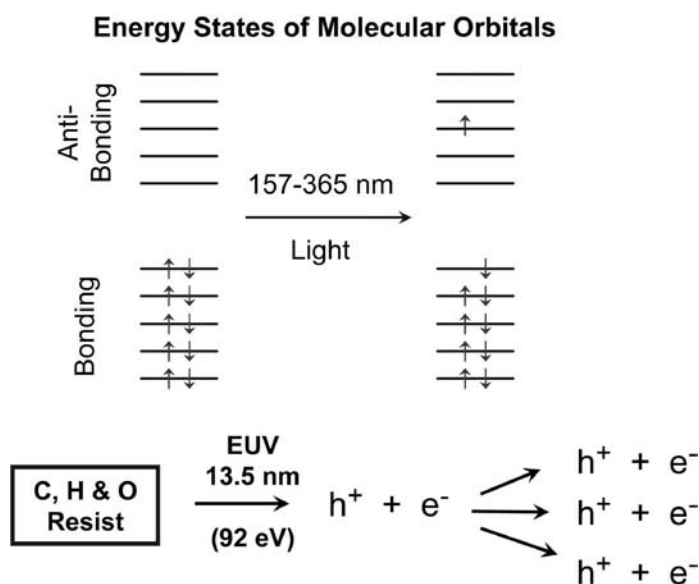


Figure 8.7 Comparison of exposure mechanisms at EUV and longer wavelengths.

8.3 Absorption Coefficients of EUV Photoresists

Transparency to imaging light is one of the most important resist properties.³³ In fact, transparency has been an important principle driving the development of new polymers for i-line (365 nm, novolaks), deep ultraviolet (DUV) (248 nm, polyhydroxystyrene), 193 nm (aliphatic esters), and 157 nm (fluoropolymers). Photoresist absorption of EUV light is just as important as in the previous four wavelengths; however, the mechanism by which EUV photons are absorbed by organic polymers is very different than the mechanisms for absorbance of longer wavelengths (157 to 365 nm). At longer wavelengths, the light interacts with the molecules in the resist—polymers, photo acid generators (PAGs), etc.—by exciting an electron from a molecular (or lone-pair) orbital to an empty (often antibonding) orbital (Fig. 8.7). In EUV, however, the 92-eV photons remove the electrons from the molecule, creating high-energy electrons (~ 80 to 87 eV) and holes. One important consequence of these mechanistic differences is that the EUV absorbance is primarily determined by the empirical formula and the density of the resist—not the arrangement of these elements within the molecule (its structure) as it does at longer wavelengths.

8.3.1 Absorption coefficient definitions

The absorption coefficient (A) of a resist of thickness (t , μm) is defined in Eqs. (8.2), (8.3), and (8.4):

$$\text{Transmittance} \equiv I/I_0 = At = e^{-At}, \quad (8.2)$$

$$\ln(I_0/I) = At = 2.303 \log(I_0/I), \quad (8.3)$$

$$\text{Absorbance (base e)} = 2.303 \text{ absorbance (base 10)}, \quad (8.4)$$

where I_0 is the incident light intensity, and I is the intensity after the light has passed through the resist film. This absorption definition is based on the natural logarithm of the transmittance and is equivalent to the Dill B-parameter. A source of great confusion is the fact that absorbance using both the base e and the base 10 definitions are in common practice. Care must be exercised in comparing literature values for absorbance since the base e value will always be 2.303 times larger than the value reported at base 10. Whenever possible, base e values will be used in this chapter.

8.3.2 Absorption cross-sections of the elements

The atomic absorption-cross-section tables published by Henke, Gullikson, and Davis²¹ have been the cornerstone for much of the absorption values determined in EUV. Figure 8.8 shows the absorption coefficients for the elements in the first four rows of the periodic table using the density of the pure element as a solid or liquid in the calculations.^{22,23} The elemental absorption coefficients shown here make it clear why hydrocarbons are desirable to have in resists, while the levels of oxygen and fluorine must be kept low.

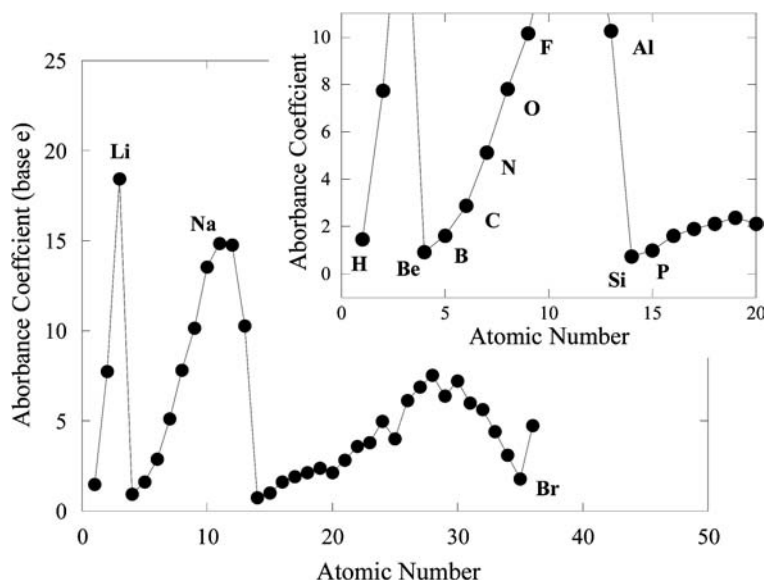


Figure 8.8 Absorption coefficients for the elements in the first four rows of the periodic table using the density of the pure element as a solid or liquid in calculations.^{22,23} Absorption coefficients are reported in base e and are for 1.0- μm -thick films.

8.3.3 Methods for determining EUV absorbance

One of the first direct measurements of resist absorbance was done by Kubiak et al.³² They determined the absorbance of several thicknesses (75 to 500 nm) of PMMA coated on 360-nm-thick membranes of Si_3N_4 . EUV light passing through the Si_3N_4 -resist sandwiches and attenuation of the light intensity were measured with a photodiode. The resulting value for the absorbance of PMMA, 5.95 $1/\mu\text{m}$, was very close to that determined using tabulations maintained by CXRO at LBNL²² and published values of PMMA density.

In 1999, Matsuzama et al.^{34–36} combined Biverano's graph-theoretical method³⁷ for calculating polymer density with the Henke elemental absorption coefficients²¹ to calculate the absorption coefficients of 150 polymers at EUV (13.5 nm). They found that polymers used in i-line, DUV, and 193-nm photoresists all had roughly similar transmittance: 13.5-nm light of $\sim 30\%$ for 300-nm films, and $\sim 65\%$ for 100-nm films, respectively. They also made four additional conclusions:

1. Lower-density polymers are more transparent.
2. Two silane polymers $[(\text{SiHMe})_n \text{ and } (\text{SiMe}_2)_n]$ have exceptionally low absorbances of 1.0 and 1.25, respectively, at 13 nm, primarily because of the high Si content and very low densities.
3. Polymers with aromatic rings give the best combination of low absorbance and low (good) Ohnishi numbers.³⁸
4. Fluoropolymers give high absorption values because of the large fluorine cross section with EUV and the higher density.

In 2002, Irie et al.^{39,40} experimentally measured the EUV transmittance of thin films prepared from eight polymers and eleven photoresists by coating these materials onto Mo-Si MLs and measuring their reflectivity over a range of reflection angles. They concluded that polymers high in carbon and silicon would be relatively transparent, whereas polymers containing fluorine would have low transparency. They also concluded that the addition of $\sim 10\%$ PAG would not make the resist absorption significantly different than that of the polymer.

In 2003, Chandhok et al.^{41,42} examined four methods for evaluating the absorption of the EUV tool test resist, EUV-2D (Fig. 8.9).⁴³ The first two methods experimentally determined the density followed by the absorption calculation.²² The first method weighed the resist film on a wafer, producing a density value that was about 10% higher than that determined in the second method by NIST using x-ray reflection. Consequently, the calculated absorption values of 13.5-nm EUV light also varied by 10%, or 4.64 and 4.16, respectively.

The third method, conducted at LBNL, measured the s-polarization reflectivity as a function of incident angle on a 120-nm film of EUV-2D. This method determined the absorption of EUV-2D to be 4.20. The fourth method involved coating EUV-2D onto a Mo-Si ML stack with an average reflectivity of 60%. EUV-2D

Absorbance of EUV-2D				
			Dill B	Base 10
Method I.				
Empirical	Density	Calculate		
Formula	Weigh Resist	CXRO		
$C_xH_yO_z...$	On Wafer	Web Site	4.64	2.01
	1.28 g/cm ³			
Method II.				
Empirical	Density	Calculate		
Formula	NIST X-Ray	CXRO	4.16	1.81
$C_xH_yO_z...$	Reflection	Web Site		
	1.1497 g/cm ³			
Method III.				
EUV-2D	Glancing Angle		4.20	1.82
On Silicon	Reflection At EUV			
Method IV.				
EUV-2D	Reflection At EUV		4.07	1.77
On Multilayer				

Figure 8.9 Four methods used to determine the Dill B/ μm (base e) and base 10 absorbance/ μm of an EUV-2D photoresist.

was exposed at DUV using a contrast curve pattern so that several film thicknesses from 0 to 120 nm were available. The reflectivity was measured through the various thicknesses of EUV-2D film (similar to the method of Irie et al.)^{39,40} to determine an absorption of 4.07 1/ μm . Thus, this work revealed that the four methods for determining the absorption of an EUV photoresist resulted in absorbance estimates from 4.1 to 4.6. It appears that the second and third methods were the best methods, with NIST’s method using an x-ray glancing angle to determine density in combination with the empirical formula method using the CRXO Website, and LBNL’s method using a grazing angle with 13.5-nm light.

8.4 Multilayer Resists and Pattern Transfer

The high absorption of EUV light by nearly every material led to the clear conclusion that imaging layers must be “ultrathin”—less than 120 nm—to achieve sufficient transparency and ensure good resolution and steep sidewall angles. These ultrathin resists, however, were thought to have three possible problems. First, pinhole defects were shown to increase dramatically with decreasing film thicknesses.^{24,25} Second, etch resistance might be insufficient for all necessary pattern transfer processes. Third, these films might be too thin to function over uneven topography.

This section reviews some important studies that investigated bilayer, trilayer, and top surface imaging (TSI) as potential solutions to these problems. Additionally, we will review a detailed study of coating defects as a function of film thickness and discuss a few pattern transfer studies.

8.4.1 Multilayer resist approaches

Bilayer and trilayer resist schemes were investigated from the very beginning of EUVL. Kinoshita investigated a bilayer resist system in his first papers on EUV imaging.^{10–13} Similarly, Bjorkholm et al. evaluated the use of the PMMA/Ge/hardbaked resist approach. Indeed, these ML approaches were available for use in the first EUV experiments because they were developed some five years earlier for use in DUV and e-beam lithography.⁴⁴

In 1990, Taylor et al. discussed the possibility of using ML resists in EUVL.⁴⁵ One important assumption at that time was that future Si devices would have a minimum of 200-nm topography; therefore, resist/planarization layers would need to be at least 500 nm thick. Since Taylor's paper was written, however, the use of chemical-mechanical polishing (CMP) was introduced and has seen widespread use in the industry. As of 2007, the topography that EUV resists will contend with is expected to be much closer to 30 to 50 nm.⁴⁶ Nonetheless, coating and imaging resists over significant topography was considered to be one of the problems to be solved by ML and TSI resists.

Figure 8.10 compares single-layer organic bilayer and trilayer resist schemes proposed by Taylor et al. for use in EUVL.⁴⁵ All four approaches shown here use a metallic or Si containing layer to transfer the pattern to the planarizing layer using a "plasma development" step. Figure 8.11 shows a more detailed scheme for one plasma-developed resist using a surface imaging scheme at EUV. Two coating and two baking steps produced a bilayer resist with a hard-baked 550-nm planarization layer (PPL) and an imaging layer (IL). The imaging layer (50 to 250 nm) was a chemically amplified resist composed of a novolak polymer and a melamine cross-linker. The imaging layer was exposed at 13.5 nm using a 10 $\times$, 0.08-NA Schwarzschild objective⁴⁷ followed by PEB to cause cross-linking in the imaging layer. Samples were silylated using dimethylaminopentamethyldisilane (DMAP-MDS). The final two steps involved plasma development within the same chamber. The first step was the plasma descumming with Ar/Cl₂ plasma to remove a thin layer (~20 to 40 nm) from all surfaces. This removed some unwanted silylation in the cross-linked area. The second step was the oxidation plasma development using a silylated resist film as the etch mask.

Figure 8.12 shows 150- and 100-nm dense lines imaged at EUV using this method. While the 150-nm lines were nicely resolved, both images show large LER. The authors proposed three explanations why LER was an issue in this system:

1. Acid diffusion that must occur in this system to promote cross-linking may have increased LER and limited the resolution. The diffusion may have occurred during the PEB and/or the silylation step (~100°C).
2. Silylation could have led to LER problems, because the glass-transition temperature (T_g) of the image layer decreased to nearly room temperature during silylation. This change in T_g may have caused stresses in the resist, creating nonuniformity of the silylated reaction at the line edge.

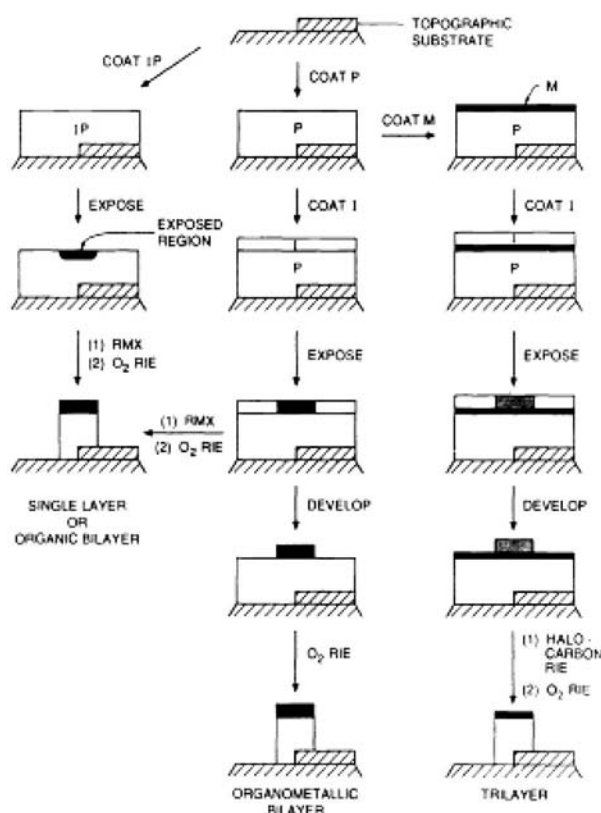


Figure 8.10 Comparison of single-layer, organic bilayer, organometallic bilayer, and trilayer resist schemes, where *P* is a thick (~ 500 nm) planarizing layer, *I* is a thin (~ 100 nm) imaging layer, *M* is the metal layer, and RMX is a metal precursor.

3. The plasma descum or plasma development steps may have amplified any nonuniformity at the line edge, increasing LER.

In 2002, Ryoo et al.⁴⁸ made a comparison of (1) TSI, (2) bilayer, and (3) single-layer/hard mask approaches to EUV imaging using the highest NA (0.147) EUV imaging system that was available at that time (Fig. 8.13). They printed 70-nm lines with low LER and straight sidewalls (Fig. 8.14) and were able to characterize the three methods for dose and LER (Fig. 8.15). The TSI resist (Sumitomo NTS-4) and the bilayer resist (TOK Si-containing resist, EUV-008S) are shown after the O_2 plasma etch, whereas the single-layer resist (Rohm and Haas XP99146P) was coated in relatively thick films (180 nm) and was not etched. It is not clear what effect the etch process would have on LER; in many cases it improves LER.^{49–51} Nonetheless, all three resists gave fairly low LER (3.5 to 4.2 nm, 3σ), but were quite slow. The very poor sensitivity of the TSI approach (150 mJ/cm^2) makes it less effective than the other two approaches.

One particularly innovative approach to the development of thin-layer EUV imaging was that of Calvert et al. in 1993.⁵² They used a monolayer surface-

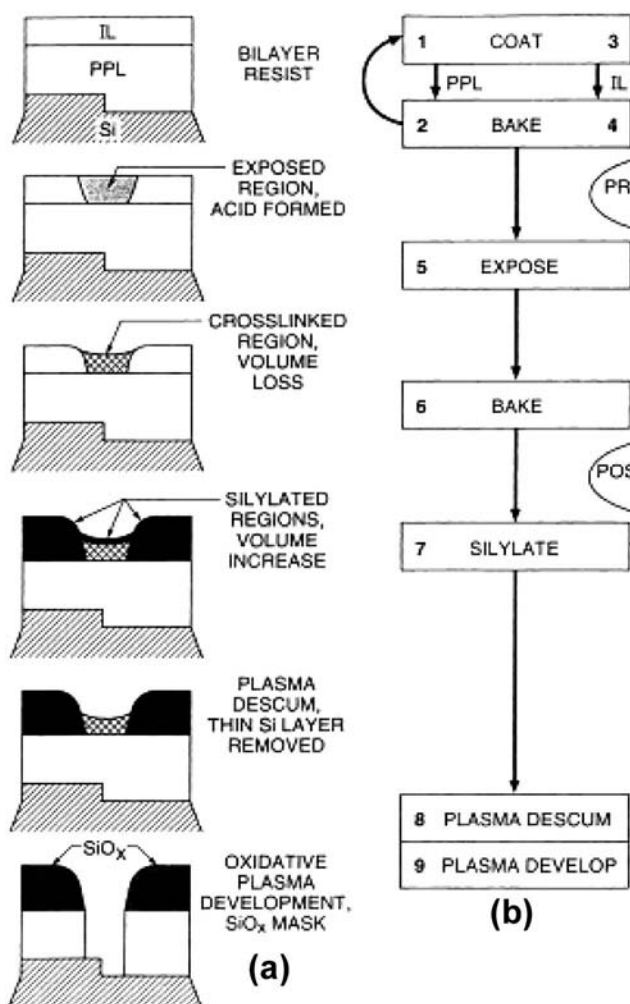


Figure 8.11 Schematic representation of (a) the silylated positive tone bilayer resist process, and (b) the corresponding DUV flow diagram.

imaging approach in which self-assembled monolayer films containing bidentate ligands were exposed to EUV light. Exposure destroyed the film's capability for binding a palladium (Pd) catalyst. Catalyst treatment followed by metallization with electroless nickel produced metal films in the unexposed areas. Imaging experiments performed using a 20× Schwarzschild camera at Brookhaven National Laboratory (BNL) resulted in the printing of 250- and 500-nm features with 50 mJ/cm² doses.

8.4.2 Defects in ultrathin resist films

Several reports in the literature (1988–1993) indicated that pinhole defects in spin-coated ultrathin resist (UTR) films were very high and increased with decreasing

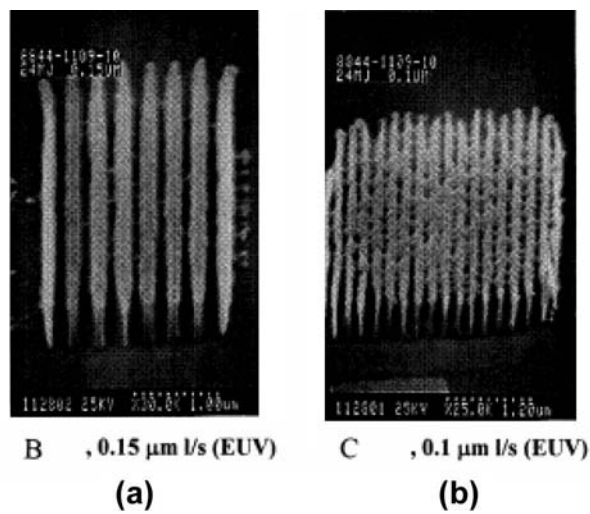


Figure 8.12 Dense lines printed using TSI at EUV: (a) 150 nm, and (b) 100 nm.

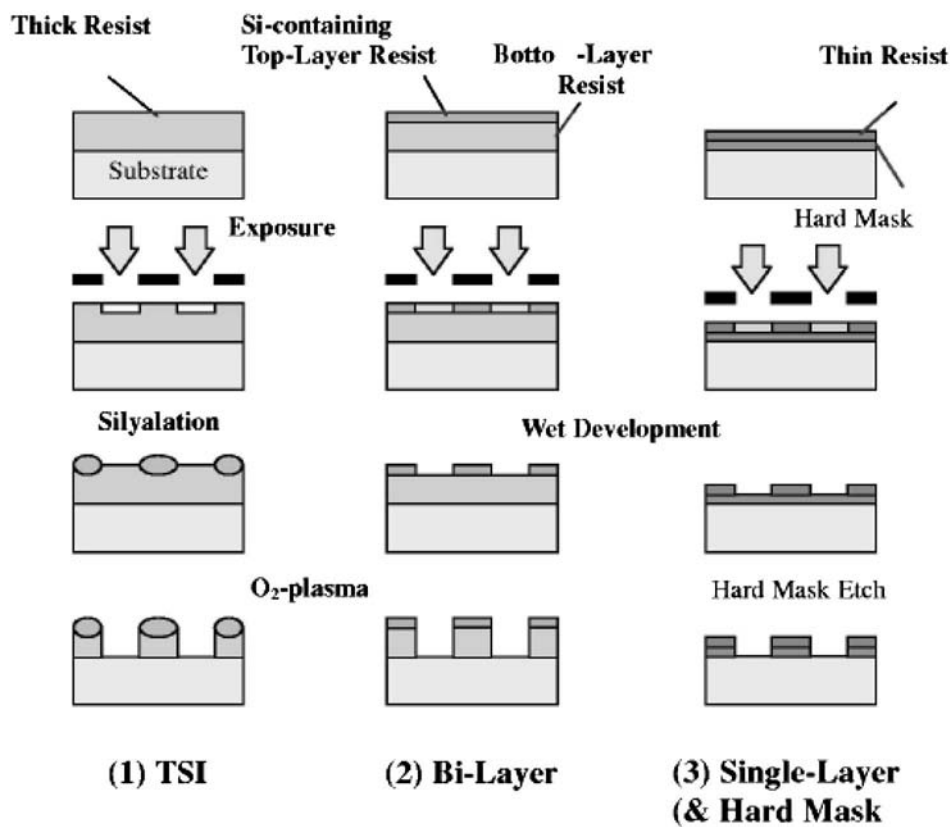


Figure 8.13 Thin-layer imaging processing schemes for EUVL. (Reprinted from Ref. 48 with permission from Elsevier.)

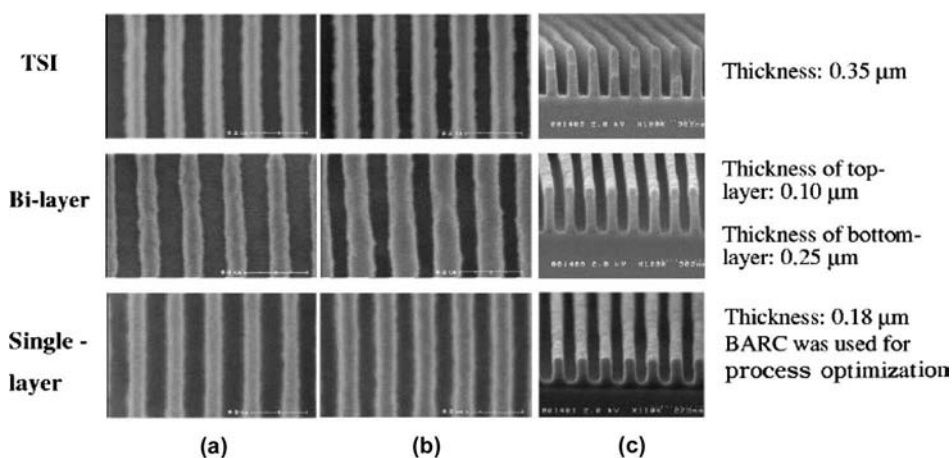


Figure 8.14 SEM images of (a) 70-nm, (b and c) 85-nm line/space (L/S) patterns printed at a wavelength of 13.5 nm with TSI, bilayer, and single-layer resists. (Reprinted from Ref. 48 with permission from Elsevier.)

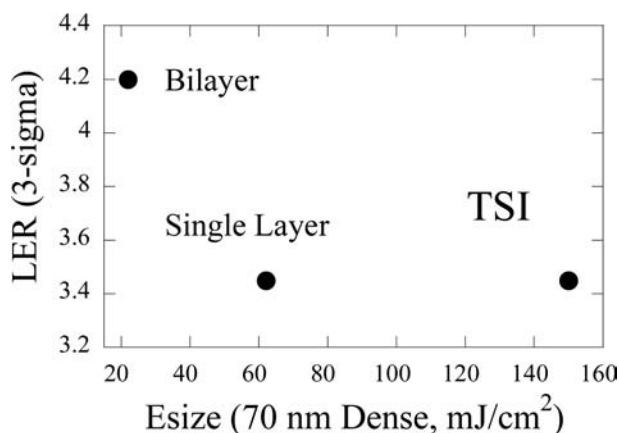


Figure 8.15 LER versus E_{size} plot for three lithographic approaches.⁴⁸ (Reprinted from *Microelectronic Engineering* with permission from Elsevier.)

film thickness.^{24,53} However, the need to use a thin imaging layer in EUV prompted Okoroanyanwu et al.⁵⁴ to perform a detailed investigation into this issue using the state-of-the-art defect detection instrumentation available in 1999. Four resist samples used in this study were prepared from the same batch of UV6 (Rohm and Haas) but were diluted so they would coat to a range of thicknesses (100-, 200-, 300-, and 400-nm at 3,000 rpm). Each resist sample was spin-coated onto hexamethyldisilazane (HMDS)-primed Si wafers using a range of spin speeds from 1000 to 5000 rpm, which created a spread in thickness of 80 to 420 nm. At least 25 wafers were coated and soft-baked from each resist sample. Figure 8.16 shows the relative defect count as a function of film thickness. No significant increase in defect level with decreasing film thickness was observed. They suggested that

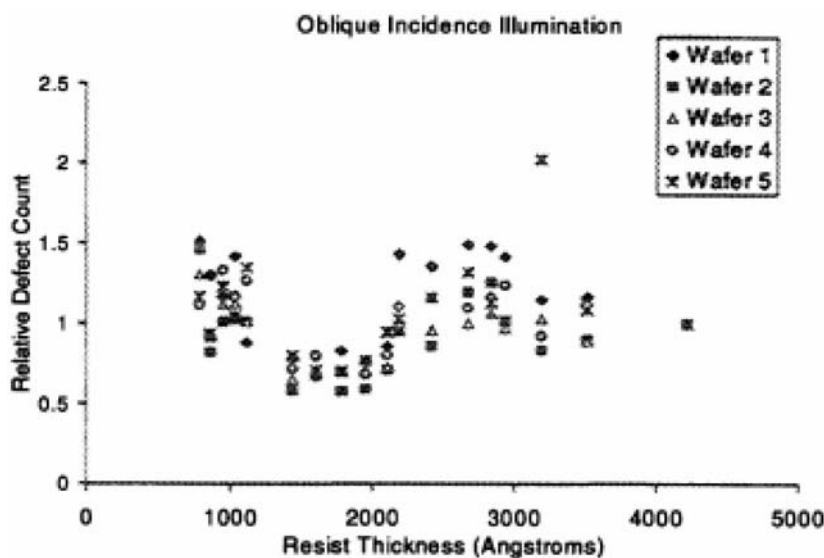


Figure 8.16 Relative defect count as a function of resist thickness.

their results differed from prior work (Table 8.2)^{24,53} because previous experiments relied on decoration etches to illuminate pinholes, which may have introduced the film thickness contribution to defect detection.

8.4.3 Pattern transfer of UTR into hard masks

Pattern transfer of UTR into hard masks has become the method of choice for EUVL. The first successful demonstrations of this method were done by Rao⁵⁵ and Brainard.⁴³ They evaluated the lithographic properties of 80-nm-thick films using the 10×1 , 0.088-NA exposure system at Sandia National Laboratory (SNL). These experiments led to the discovery of the tool-test resist EUV-2D (XP98248B from Rohm and Haas). One of the primary goals of this work was to determine if UTRs would provide enough etch resistance to transfer a pattern to a hard mask. EUV-2D (80 nm) was coated over 100-nm SiO_2 or 50-nm silicon oxynitride (SiO_xN) and imaged using EUVL to print 100-nm dense lines. The hard masks were then etched using a standard oxide etch process. Figure 8.17 shows cross sections of these pattern-transfer experiments. Resist remained in both experiments: 30 nm of EUV-2D remained after removing 87 nm of SiO_2 , and 55 nm of resist remained after removing 50 nm of SiO_xN .

One year later, Cardinale⁵⁶ performed a more detailed study of pattern transfer from EUV-2D. Dense line patterns were printed into 175-nm EUV-2D over 300-nm polysilicon. The lines were printed in resist with good linearity from 80 to 140 nm L/S and with 5.5 to 8.0 nm 3σ LER (Fig. 8.18). After etch, the line width of the patterns was maintained, and LER was slightly improved (5.5 to 7.5 nm 3σ ; see Fig. 8.19). This work provided additional evidence that resists as thin as 175 nm would provide enough etch resistance for normal pattern transfer.

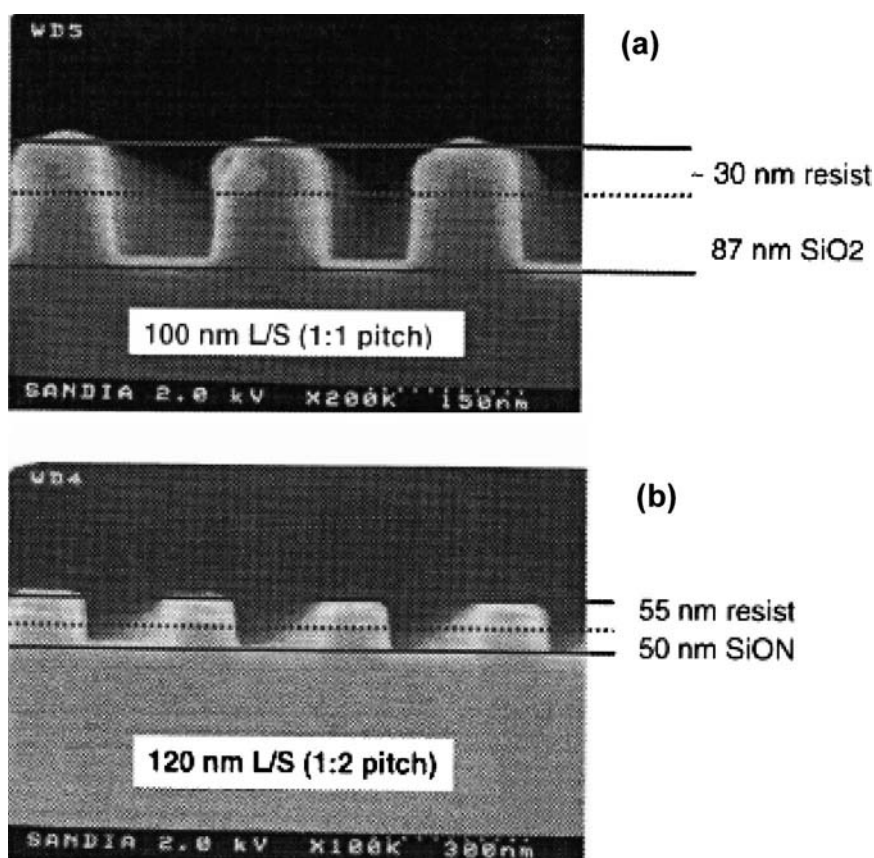


Figure 8.17 (a) 100-nm dense lines etched into an 87-nm SiO₂ hard mask. (b) 120-nm L/S etched into a 50-nm SiO_xN hard mask. In both cases, there is significant resist remaining after etch.

8.4.4 Integration of UTRs into integrated circuit manufacturing processes

Two excellent studies by Pike et al.⁵⁷ and Cobb et al.^{58,59} explored the issues of integrating UTR lithography and image transfer into transistor gate and back-end integrated circuit (IC) pilot-scale DUV processes.

Pike et al.⁵⁷ used 248-nm lithography to demonstrate that the UTR/hard mask process is manufacturable. They patterned 150-nm polysilicon with 150-nm UTR over a proprietary antireflection coating (ARC) and focused on four key areas: defectivity of UTR films, sensitivity to substrate topography, quality of pattern transfer, and comparisons of device yield with conventional single-layer resist (SLR) processes. Their results on defectivity supported the conclusions of Okoroanyanwu et al.⁵⁴ in that the intrinsic defectivity of UTR films as thin as 65 nm was no greater than that of films with thicknesses >500 nm. None of the defects detected on etched device wafers could be attributed to pinholes in the UTR. As expected, UTR films were very sensitive to substrate topography, but the

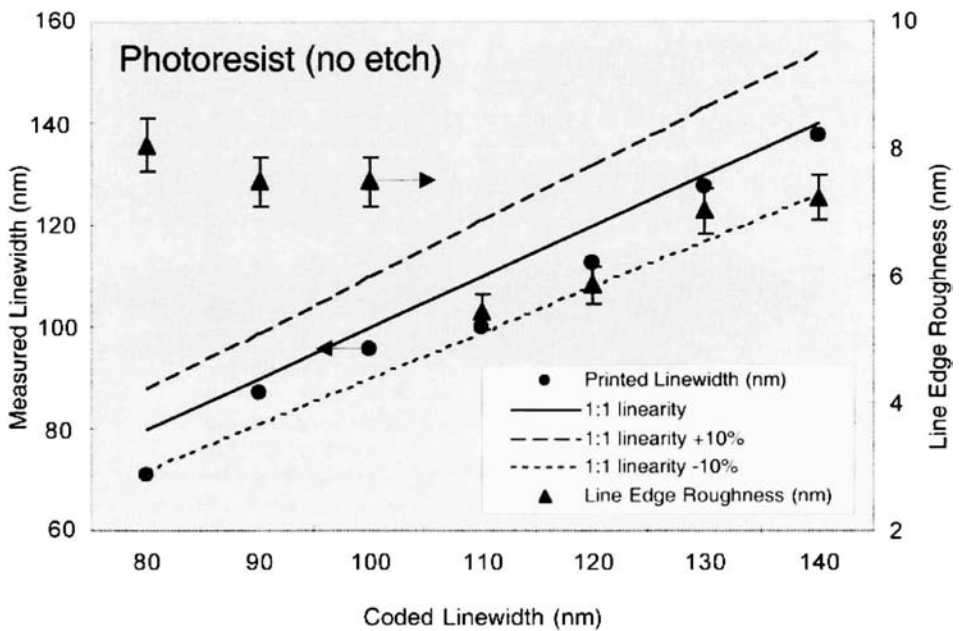


Figure 8.18 Measurements of 3σ LER and printed line width as a function of the coded line width for 175-nm-thick EUV-2D photoresist L/S features. The solid black line represents 1:1 linearity; dashed lines represent +10% critical dimension (CD) process latitude.

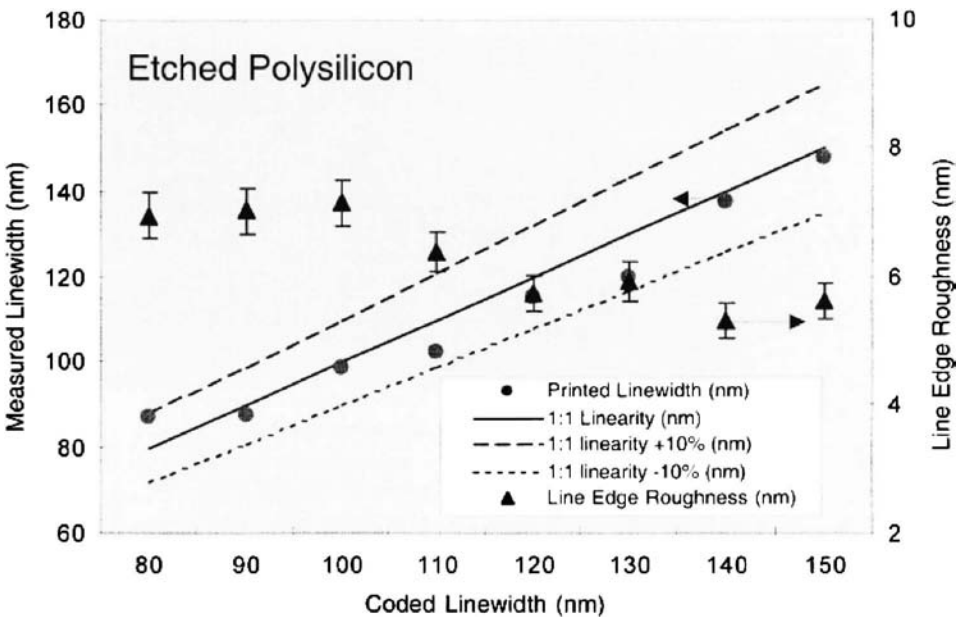


Figure 8.19 Measurements of 3σ LER and printed line width as a function of the coded line width for etched polysilicon L/S features. The solid black line represents 1:1 linearity; dashed lines represent +10% CD process latitude.

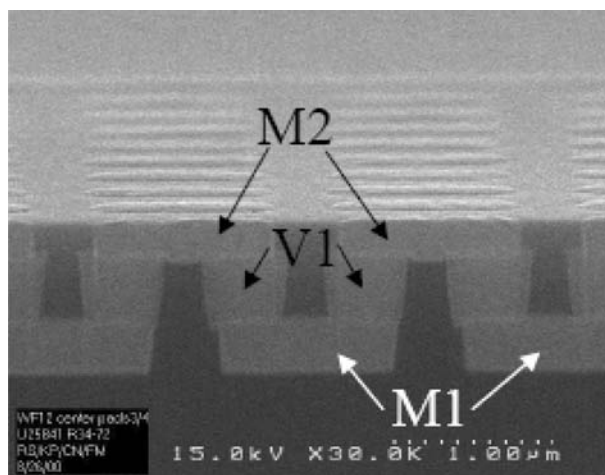


Figure 8.20 Cross-section image of an M1-M2 test structure with UTR processing on V1 and M2 layers and a copper (Cu) damascene metal fill process.

topography was much less (~ 50 nm) than that expected by Taylor et al. (~ 200 nm) during their evaluation of ML resists for EUV in 1990,⁴⁵ and Pike et al. were able to manage the topography in these studies. They were able to integrate the UTR/hard mask processes onto the transistor gate level of a high-performance microprocessor to produce comparable results to a conventional SLR process after etch. Relative yields were 1.05, 0.66, and 1.0 for the 150-nm UTR, 180-nm UTR, and baseline processes, respectively.

Cobb et al.^{58,59} fabricated via chains using UTRs (140 nm) and DUV processes to print metal-2 and via-1 levels, then compared their results against control SLR processes. They encountered no difficulty with spin-coating pinhole-free UTR films; and gate etches with 120- and 140-nm UTRs were demonstrated without problems. Most importantly, however, the authors prepared via chains with excellent contact resistance performance (Figs. 8.20 and 8.21). Four processes were run, in which the control SLR processes for via-1 or metal-2 layers were substituted with UTR processes, either separately or together. Interestingly, the process with two UTR layers gave the lowest overall contact resistance.

In summary, the research described in Sec. 8.4 evaluated potential solutions to problems of highly absorbing imaging layers such as pinhole defects, etch resistance, and uneven topography. The results indicated that UTRs would not have significant pinhole problems and would have sufficient pattern-transfer capability if used in combination with hard masks. Similarly, CMP advances have reduced some concerns about uneven topography.

8.5 Resist Types

EUVL presents many interesting challenges to resist chemists. Some challenges are unique to EUV resists (e.g., absorption, low source output), while others will

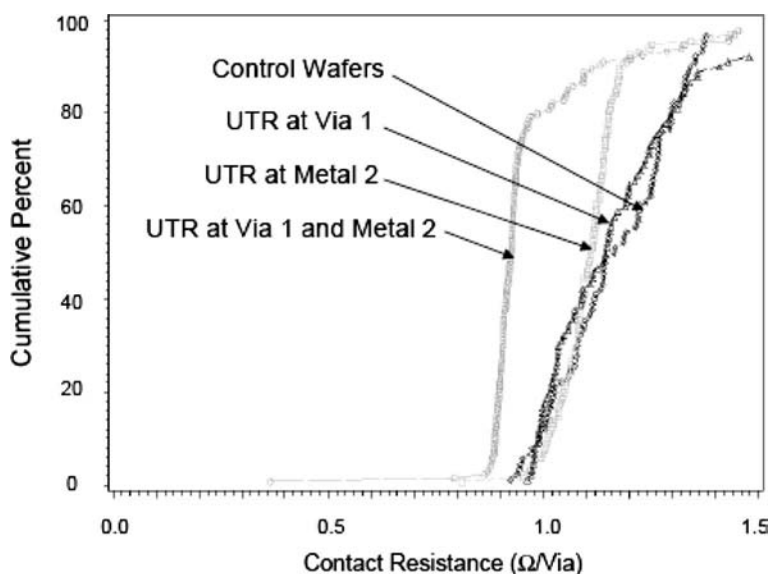


Figure 8.21 Electrical data from M1-M2 test structures.

need to be met by any resist technology vying for the 32- or 22-nm nodes (e.g., LER, resolution, etch resistance, acid diffusion blur). Resist chemists have responded with several approaches to address these challenges. In this section, resist platforms based on environmentally stable chemically amplified photoresists (ESCAP), KRS, and PMMA are evaluated for their capacity for addressing these resist needs. Additionally, negative resists and positive resists featuring Si and boron are also reviewed.

8.5.1 Environmentally stable chemically amplified photoresists (ESCAP)

One of the most successful polymer platforms for use in DUV lithography is ESCAP. This term was coined by workers at IBM primarily to describe t-butylacrylate/p-hydroxystyrene chemically amplified resists.⁶⁰

8.5.1.1 ESCAP at 0.088 NA

Two 1999 papers by Rao⁵⁵ and Brainard et al.⁴³ explored the use of ESCAP platforms for use in EUVL. EUV imaging was performed using 85-nm films and the 0.088-NA, 10×1 EUV camera at SNL⁶¹ and compared with DUV imaging (100-nm films) using a GCA 0.53-NA stepper. This work led to the development of EUV-2D resist that served the EUV community as a tool-test resist from 1998 to 2005. In fact, the 100-nm dense line sizing dose of EUV-2D ($E_{\text{size}} = 6.8 \text{ mJ/cm}^2$) has been used to calibrate the sensitivity of several tools around the world.⁶²

The evaluation of the first round of six commercial DUV photoresists diluted to coat in 85-nm films resulted in only two imageable resists at EUV. The

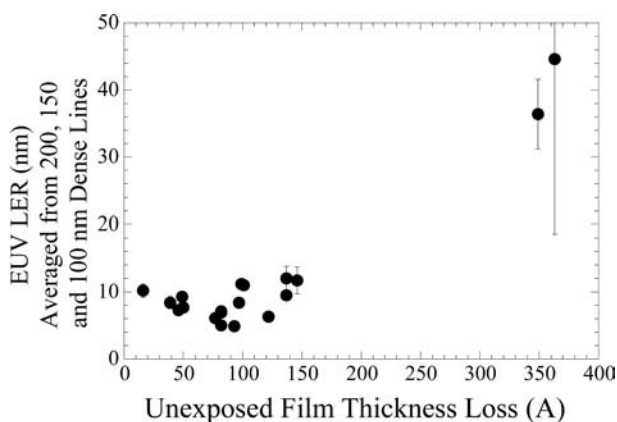


Figure 8.22 EUV LER versus unexposed film thickness loss. (Reprinted from Ref. 43 with permission from AVS—The Science & Technology Society.)

unsuccessful resists had large unexposed film thickness losses (UFTL or dark losses) of 25 to 100 nm, whereas the two successful resists had UFTL values of 5 to 12 nm. Therefore, one of the early lessons learned in exploring UTRs was the importance of UFTL. Indeed, Fig. 8.22 shows a plot of LER versus UFTL for 19 ESCAP resists imaged at EUV. For DUV resists, which are typically coated to thicknesses of 600 to 1000 nm, the loss of 30 to 80 nm of resist in unexposed areas is a relatively minor problem, and in some instances can be beneficial. For the UTRs, however, even modest levels of UFTL (35 nm; see Fig. 8.22) yielded lines with rounded tops and very poor EUV LER. Conversely, the best LER was not achieved at the lowest UFTL. Instead, the best LER performance was achieved in a range of 7- to 10-nm UFTL. It is not clear whether very low UFTL (1.5 to 5 nm) is truly detrimental to LER. Today's EUV exposure systems have larger NAs and larger field sizes, and consequently have much more flare than the 10×1 exposure systems used in 1999. The best resists for these more modern aerial images may indeed have extremely low UFTL.

A comparison was also made for 19 ESCAP UTRs between EUV and DUV. The mechanism for photochemical degradation of the PAGs is expected to be very different when the same materials are subjected to DUV (248 nm) and EUV (13.5 nm) radiation. Mechanistic studies indicate that PAGs absorb 248-nm photons to yield an excited state, which typically decomposes via homolytic cleavage of a weak bond. The resulting radicals abstract hydrogen atoms from their local environment, yielding super acids. The phenolic matrix of DUV polymers also sensitizes PAG decomposition through energy transfer. The 92-eV EUV radiation, however, deposits energy less selectively due to the atomic excitation and decay by formation of secondary electrons. Since the resists studied here are composed of >95% polymer, the initial absorption of an incoming EUV photon will be mainly with polymer atoms and much less with PAG atoms. Mechanistic studies of chemically amplified compositions in solution indicate that irradiation of phenolic polymers by x-ray or electron beams yield protons directly.⁶³ These protons then

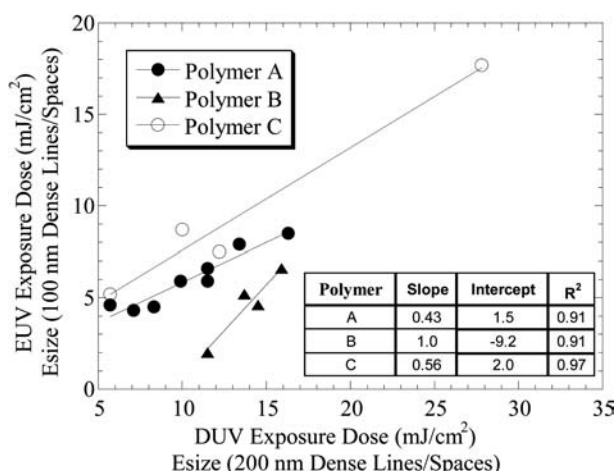


Figure 8.23 Comparison of EUV and DUV exposure energies as a function of polymer type. (Reprinted from Ref. 43 with permission from AVS—The Science & Technology Society.)

interact with PAGs in subsequent steps to yield the super acids capable of catalyzing deblocking reactions. Nonetheless, PAG decomposition occurs efficiently by both routes,⁶⁴ and similar lithographic results might be possible. Thus, we compare the relative sizing energies of 200-nm dense lines at DUV versus the 100-nm sizing energies at EUV as a function of PAG and polymer composition.

Figure 8.23 compares sizing energies for 16 resists based on three polymers and five PAGs. Excellent correlations were observed among resists prepared from the same polymer ($R^2 = 0.91$, 0.91 , and 0.97), whereas a very poor correlation was observed between the resists prepared from the same PAGs ($R^2 = 0.75$ and 0.02). The polymer correlations afford excellent predictability of EUV photospeed performance within a single polymer family, but they are independent of PAG type. This result emphasizes the importance of the polymer in the mechanism of acid generation by the two radiation types.

Another interesting comparison between EUV and DUV is shown in Fig. 8.24, where the LERs at DUV and EUV are shown for three resists as a function of calculated image log slope (ILS). DUV exposure gives LER values that are relatively independent of ILS at values above $11 \text{ } 1/\mu\text{m}$ but increase dramatically as ILS decreases (for small features). The DUV data at high ILS scale with that of the EUV LER data but converge at low ILS. Therefore, it appears that the best way to model the LER of EUV imaging ($\text{ILS} = 17 \text{ to } 27 \text{ } 1/\mu\text{m}$) is with DUV features at high CDs ($\text{CD} = 300 \text{ to } 500 \text{ nm}$) and high ILS ($\sim 11 \text{ to } 13 \text{ } 1/\mu\text{m}$). The strongest response between LER and ILS appears to be at low ILS in which line roughness increases greatly.

The lithographic performance of 19 chemically amplified resists imaged at DUV and EUV were compared.⁴³ The photosensitivity of these resists at 248 nm shows a good correlation with photosensitivity at EUV for three polymer types but appears to be independent of PAG type. This study yielded several interesting

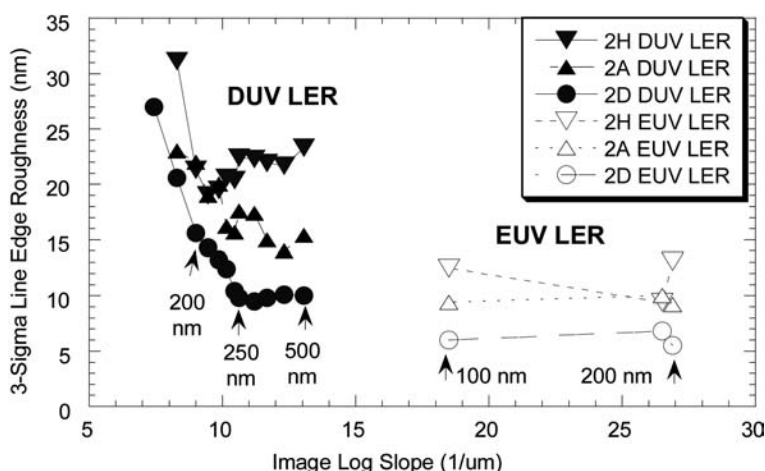


Figure 8.24 LER of three resists versus ILS imaged using 0.088-NA EUV and 0.53-NA DUV exposure tools. Apparently the best way to model EUV LER is by using large features printed on DUV steppers. (Reprinted from Ref. 43 with permission from AVS—The Science & Technology Society.)

insights into the nature of LER of UTRs. These UTRs were more sensitive to UFTL than thicker resists; but like other resists, they delivered their best LER when UFTL was optimized. Both contrast and ILS play important roles in defining LER performance, where the best LER is achieved at high contrast and high ILS. Finally, the LER of resists exposed at DUV showed good correlation with resists imaged at EUV, particularly when the DUV features were relatively large with relatively high ILS.

8.5.1.2 ESCAP at 0.3 NA

The 2004 work of Kohler⁶⁵ and van Steenwinckel et al.⁶⁶ extended the original ESCAP UTR resists done using a NA of 0.088 described above⁴³ to evaluate the relatively new 0.30-NA microexposure tool (MET) at LBNL. The initial work compared the resists EUV-2D to MET-1K (XP98248B and XP3454C, respectively, both from Rohm and Haas). EUV-2D was a popular tool-test resist from 1998 to 2005, and MET-1K became the reference resist for the MET as a result of this work. Figure 8.25 shows the resolution capability of EUV-2D with SEMs of dense lines from 90 to 40 nm. Image quality was relatively constant for the 50- to 90-nm lines, but worsened in the 40- to 45-nm lines. The MET-1K resist was developed from a strategy of using high base loading, because earlier work^{19,67} showed that LER and other imaging characteristics were improved at high levels of added base. Unfortunately, the approach also leads to resists with lower sensitivity. MET-1K was used to print 50-nm isolated lines (1:5, $E_{\text{size}} = 22.7 \text{ mJ/cm}^2$) with excellent LER values of 4.7 nm. Dense lines ($E_{\text{size}} = 31 \text{ mJ/cm}^2$) gave a LER of 4.8 nm and could be overexposed to 37 nm. The exposure latitude values were 6 and 12% for isolated and dense lines, respectively.

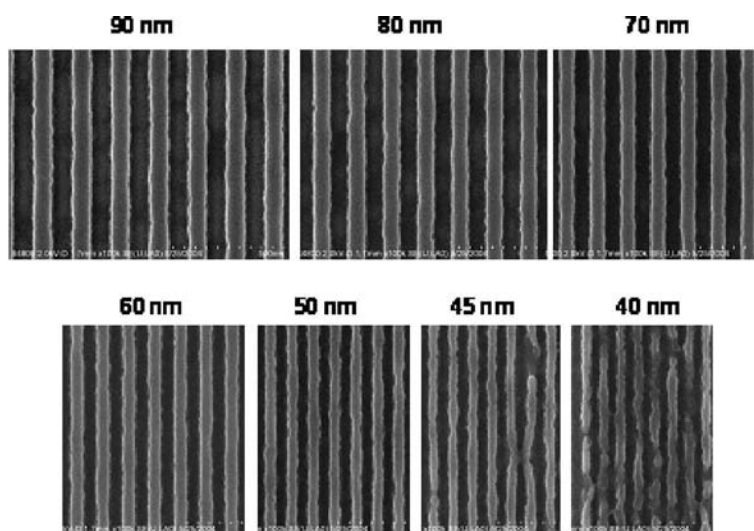


Figure 8.25 Resolution of EUV-2D resist. Dose: 6.8 mJ/cm².

Figure 8.26 shows the resolution capability of MET-1K with SEMs of dense lines from 35 to 100 nm. The LER average for dense lines from 50 to 100 nm was 4.7 nm, and increased to 6.3 nm (45 nm), 10.1 nm (40 nm), and 13.9 nm (35 nm). The average LER of isolated lines remained steady at 5.0 nm (40- to 100-nm lines) and increased to 8.6 nm at the 35-nm feature size. Cross-sectional SEMs of 40- to 70-nm dense lines printed using MET-1K, shown in Fig. 8.27, depict the footing and top-loss. The footing is probably due to the relatively high optical density of EUV resists.⁴¹ The top-loss is partly due to the fairly highly levels of flare in the MET at LBNL's Advanced Light Source (ALS) tool (measured to be 5–7% for isolated microfields).⁶⁸ The cross sections of isolated lines (Fig. 8.28) show similar problems. At a line width of 60 nm, the foot was measured to be 110 nm. At higher doses and smaller line widths, top erosion leads to the complete disappearance of the lines as only the foot remains at the Si surface.

A direct comparison between EUV-2D and MET-1K shows the dramatic improvement in the size of the process window for 50-nm dense lines (Fig. 8.29). The process window of MET-1K at 50-nm dense lines almost tripled and had a depth of focus (DOF) of 400 nm.

After identification and characterization of MET-1K,^{65,66} the authors explored the surrounding formulation space by varying base loading and the size of the acid molecule generated by the PAG. The experimental design is shown in Fig. 8.30. Figures 8.31 and 8.32 show dense and isolated 50-nm lines, respectively. As expected from previous work,^{19,67} the high base loading gave better imaging (lower LER, better resolution, and less footing). Increasing the molecular size of the acid decreased the image quality. In a plot of LER versus E_{size} for 14 resists, shown in Fig. 8.33, the resists from the first row (MET-2A, 2B, 2C, and 2D; XP-0971A through XP-0971D, respectively) appear to show the best combinations of resolu-

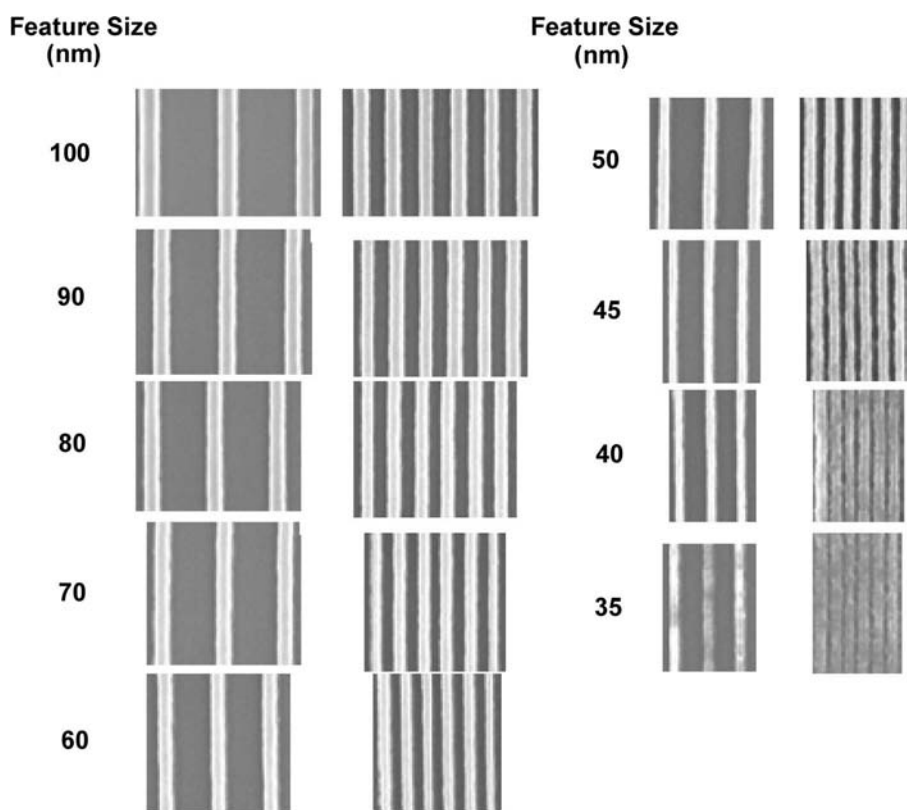


Figure 8.26 Masking linearity of MET-1K resist for dense and 1:5 isolated lines. The LER average for dense lines from 50- to 100-nm is 4.7 nm and increases to 6.3 nm (45 nm), 10.1 nm (40 nm), and 13.9 nm (35 nm). The averaged LER of isolated lines remains steady at 5.0 nm (40- to 100-nm lines) and increases to 8.6 nm for the 35-nm lines.

tion, LER, and sensitivity. These four resists are close derivatives of MET-1K but appear to have more advanced imaging capabilities; however, they use a PAG that generates a smaller acid. This is a somewhat surprising result, because a large body of work indicates that acid diffusion is a primary reason for a chemically amplified resist's inability to resolve below ~ 50 nm.^{69,70}

In an attempt to improve adhesion, profile, and iso-dense bias, Koehler et al. evaluated the influence of soft bake (SB) and PEB temperatures. They printed multiple pitch lines ranging from 1:1 to 1:10 to evaluate adhesion and iso-dense bias responses to changes in process (Fig. 8.34). These SEMs show that the control bake temperatures (SB/PEB = 130/130°C) led to a large iso-dense bias and adhesion loss. Resist films processed using PEB temperatures of 110 or 120°C produced more robust adhesion, and all of the lines were retained independent of pitch. One possible explanation for the improved adhesion at lower bake temperatures is that acid diffusion is too high at 130°C for best performance. The PEB is very crucial to producing robust lines, as depicted in Fig. 8.34. At SB/PEB of 120/120°C, isolated 50-nm lines were overexposed to 27 nm with an LER of 4.7 nm.

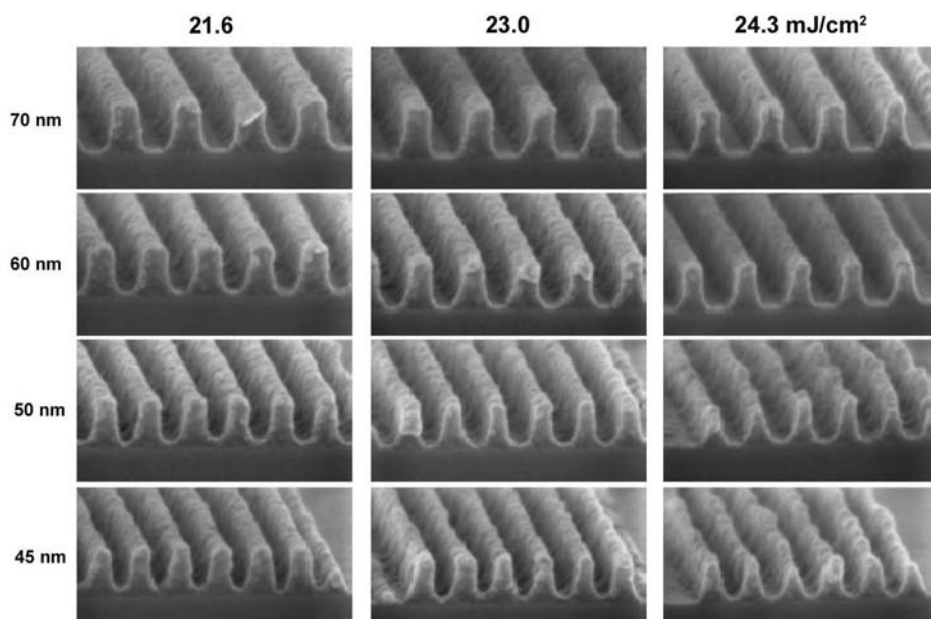


Figure 8.27 Cross sections of MET-1K resist for 45-, 50-, 60-, and 70-nm dense lines.

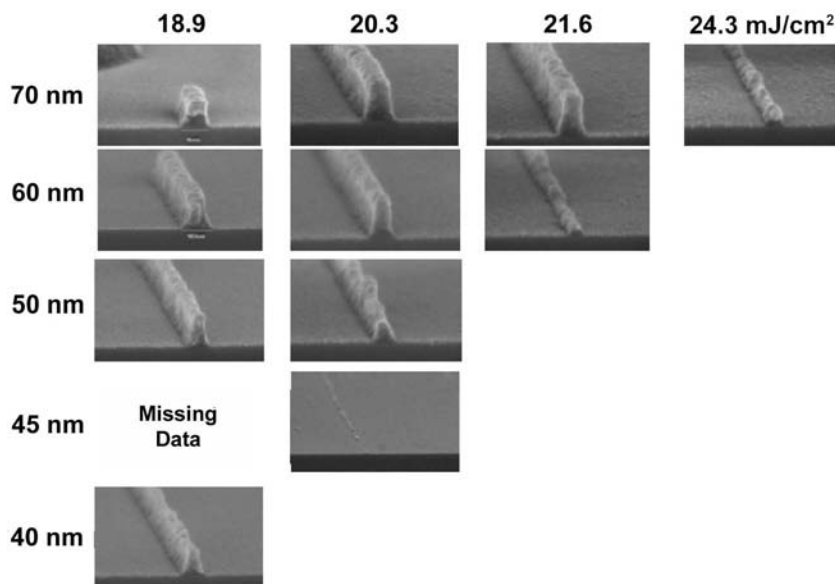


Figure 8.28 Cross sections of MET-1K resist for 40-, 45-, 50-, 60-, and 70-nm isolated lines.

In summary, the first MET rounds led to the identification of a high-performance resist (MET-1K, XP3454C). MET-1K shows a dramatic improvement over the EUV-2D resist. Its process window for printing 50-nm dense lines is much larger, and it prints smaller lines with good LER. Optimization of the MET-1K process has

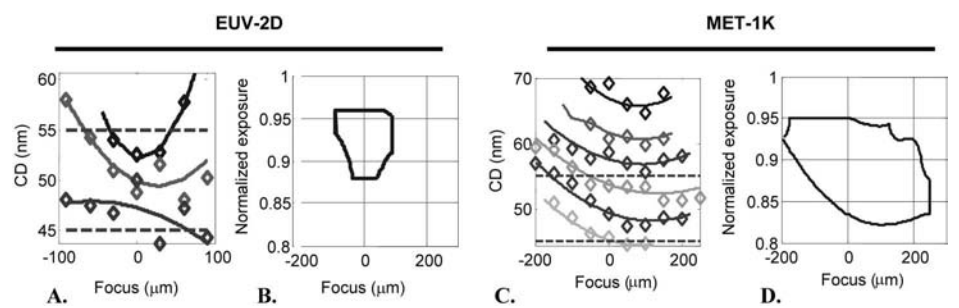


Figure 8.29 Process window comparison between EUV-2D and MET-1K for 50-nm dense 1:1 lines.

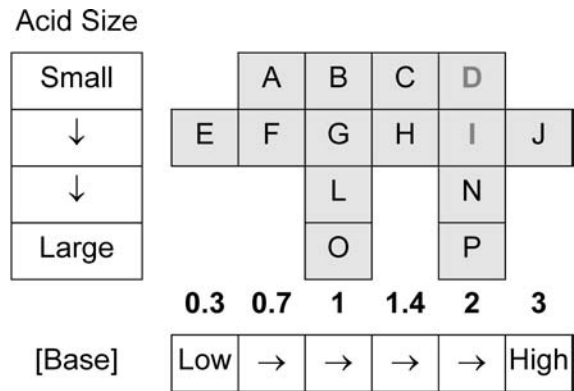


Figure 8.30 Design of MET-1K design of experiments (DOE). Resists D and I shown in the figure represent the well-known MET-2D and MET-1K resists, respectively.

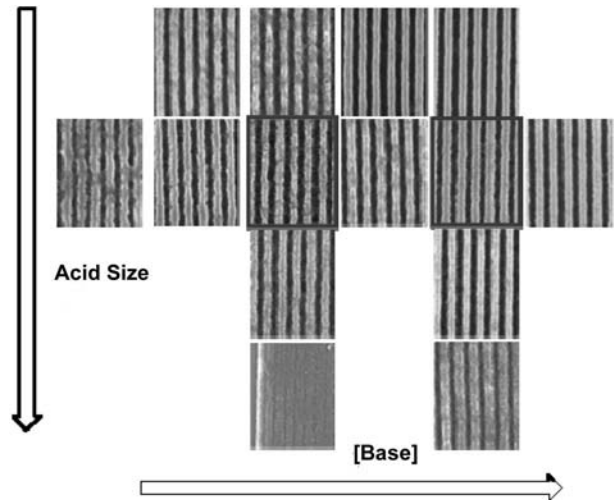


Figure 8.31 Top-down SEMs of 50-nm dense lines for 14 resists with dipole illumination.

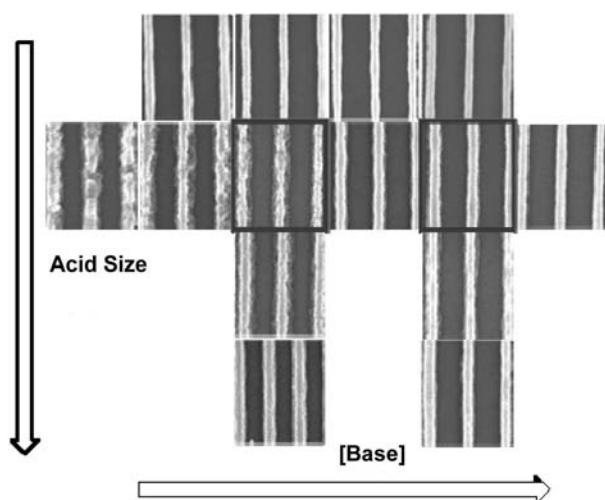


Figure 8.32 Top-down SEMs of 50-nm isolated lines for 14 resists with dipole illumination.

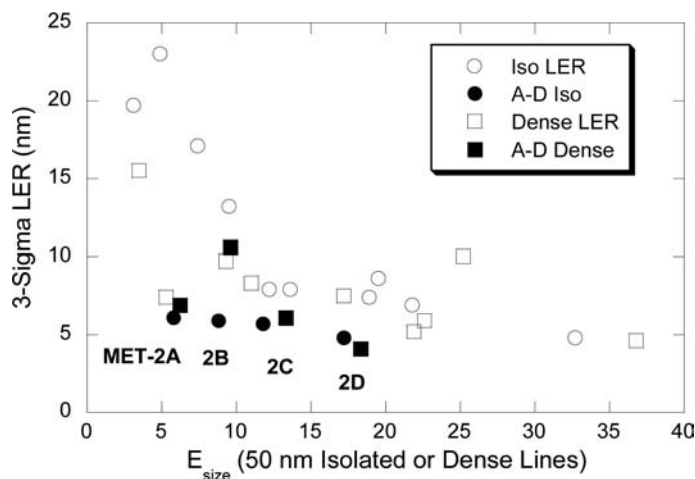


Figure 8.33 LER versus E_{size} for 14 resists.

shown improvements in resolution, adhesion, iso/dense bias, and LER. The formulation DOE around MET-1K (XP3454C) led to a new resist: MET-2D (XP0971D), which has been used by ASML as a tool-test resist for the development of their full-field alpha tools. Early results show an increase in sensitivity paired with better LER.

8.5.1.3 Best examples of ESCAP UTRs

Golovkina et al.⁷¹ printed 50-nm dense and 30-nm semidense lines using 80-nm-thick XP9947W-100 with interference lithography at the Center for NanoTechnology at the University of Wisconsin-Madison (Fig. 8.35). This ESCAP resist

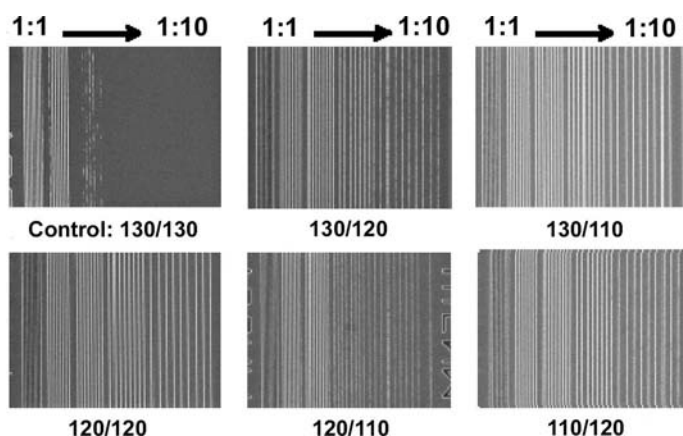


Figure 8.34 Top-down SEMs of 50-nm isolated lines as a function of pitch and bake process. SBs were for 60 seconds, PEBs were for 90 seconds.

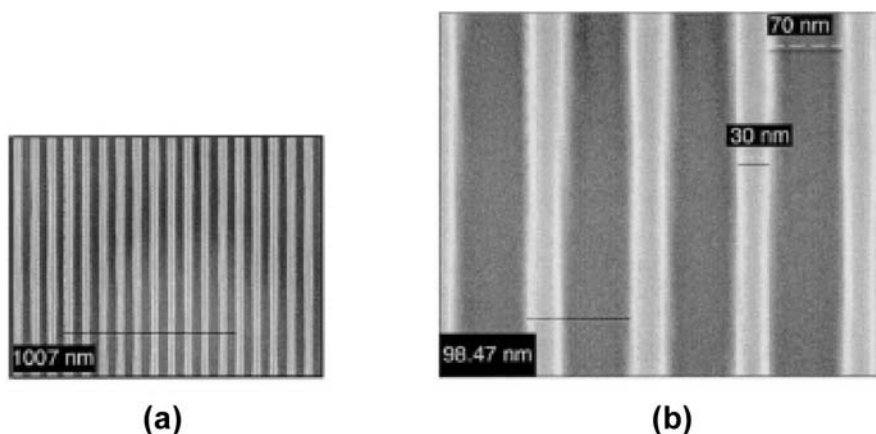


Figure 8.35 One-dimensional patterns created in Shipley XP9947W-100 resist with transmission-grating EUV-IL: (a) 50-nm L/S dense lines, and (b) 30/70 nm L/S. (Reprinted from Ref. 71 with permission from AVS—The Science & Technology Society.)

was originally developed for e-beam lithography.^{49,72} They were also able to print fairly rough 26-nm lines using this same resist (Fig. 8.36).

Jouve et al.⁷³ used the EUV-IL imaging system at the Paul Scherrer Institut to print high aspect ratio 50-nm dense lines from EUV-2D in 140-nm-thick films (Fig. 8.37).

8.5.2 KRS photoresists

KRS photoresists (Fig. 8.38) are chemically amplified resists based on ketal-protected polyhydroxystyrene (PHS) that were developed by IBM researchers. These resists exhibit resolution when imaged using DUV, e-beam,⁵⁰ and EUV.⁷⁴ One hallmark of these resists is their ability to function at room temperature

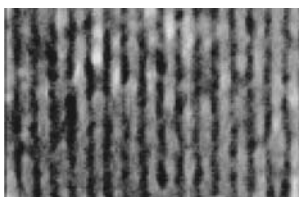


Figure 8.36 SEM images of a 26-nm L/S pattern exposed in Shipley XP9947W-100 photoresist with transmission-grating EUV-IL. (Reprinted from Ref. 71 with permission from AVS—The Science & Technology Society.)

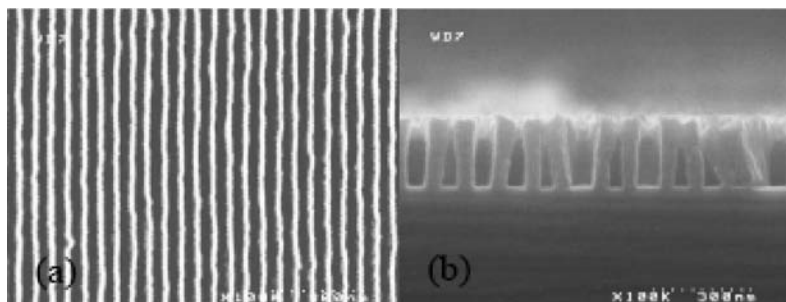


Figure 8.37 (a) SEM top view of 50-nm dense lines printed in resist EUV-2D with EUV interferometry. (b) Cross sections of some of these lines suffering from pattern collapse.

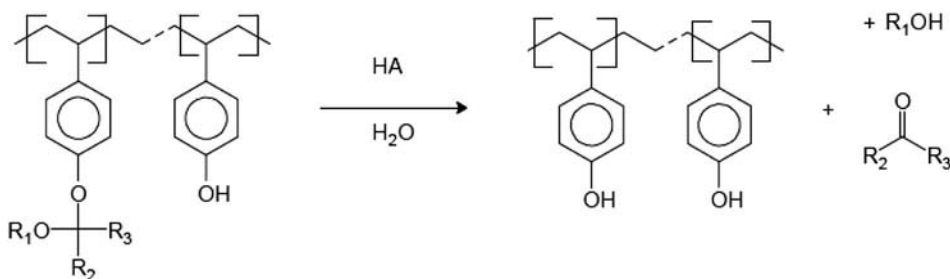


Figure 8.38 Acid-catalyzed hydrolysis of poly(hydroxystyrene): ketal polymer.

without PEBs. This low-temperature processing keeps acid diffusion to a minimum. Wallraff et al.⁷⁵ described the high-resolution capability of a KRS system in terms of reduced image blur due to decomposing acid diffusion. Although acid diffusion will be discussed in more detail in Sec. 8.6.1, it is an important aspect of the KRS resist design. Figure 8.39 shows a dramatic comparison between processing of e-beam exposed films using room temperature versus 110°C processing. Clearly, much better resolution is achieved without the PEB step.

Another interesting characteristic of KRS resists is its interaction with water. Wallraff et al.^{74–76} conducted careful experiments to study the role of water in the lithographic chemistry of these resists. They produced instrumentation that allowed them to expose resists using an EFOS novacure broadband xenon exposure

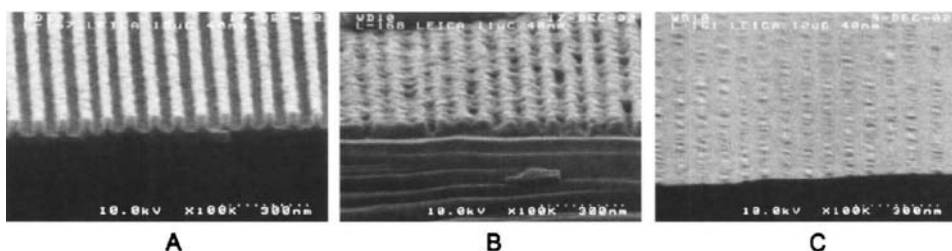


Figure 8.39 Imaging performance and diffusion depth measurements as a function of PEB temperature for KRS: (A) room temperature, (B) 110°C PEB, (C) 120°C PEB. In the absence of a PEB step, 40-nm L/S arrays are resolvable but cannot be printed at PEB temperatures of 110 or 120°C. (Reprinted from Ref. 75 with permission from AVS—The Science & Technology Society.)

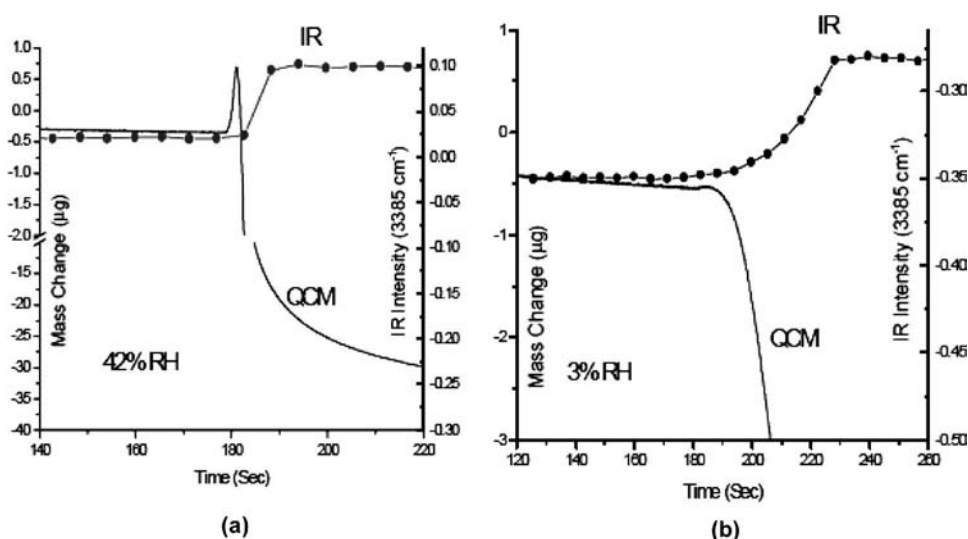


Figure 8.40 Dual IR QCM measurement of exposed KRS films. The film is exposed at 60 s under dry flow conditions, and humid air is introduced at 180 seconds: (a) RH = 42%, (b) RH = 3%. Mass changes in mg are plotted on the left axis and intensity changes in the IR spectra are plotted on the right axis.

tool with a 290- to 450-nm filter⁷⁶ under varying humidity conditions, while independently monitoring the deblocking reaction using infrared spectroscopy (IR) and monitoring water absorption using a quartz crystal microbalance (QCM). The IR spectra followed the deblocking reaction by monitoring the 3385 cm^{-1} phenolic IR band; water absorption followed using a quartz microbalance to monitor changes in resist weight. Figure 8.40 shows three successive steps: Exposure with broadband light (60 s), acquisition of IR data (120 s), and introduction of humid air (180 s). No changes were observed until the humid air was introduced. At this point, a rapid conversion of the ketal protected polymer into poly(hydroxystyrene) was observed by IR. The reaction appears complete within 6 s of the introduction of humid air. Coincident with the onset of the reaction at 180 s, the film mass increased over sev-

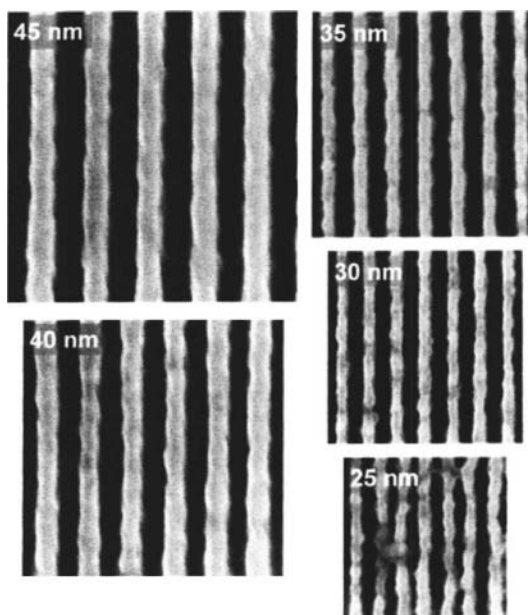


Figure 8.41 Equal line space images ranging from 25- to 45-nm printed in experimental KRS resist provided by IBM. (Reprinted from Ref. 77 with permission from AVS—The Science & Technology Society.)

eral seconds [Fig. 8.40(a)] and then dropped rapidly, losing considerable mass. The small increase in mass is attributed to water absorption by the film, and the subsequent large loss in mass is due to desorption of the ketone and alcohol hydrolysis products. The data in Fig. 8.40(b) were obtained where the relative humidity (RH) was only 3%. At this low value, the hydrolysis reaction clearly slowed and the rate of outgassing was competitive with the rate of water absorption.

Based on these data, the authors concluded that water absorption is rate-limiting, and that at low humidities, the rate of hydrolysis reaction (and consequently the formation of the developable resist image) can be controlled by controlling the humidity in a post-exposure process step.

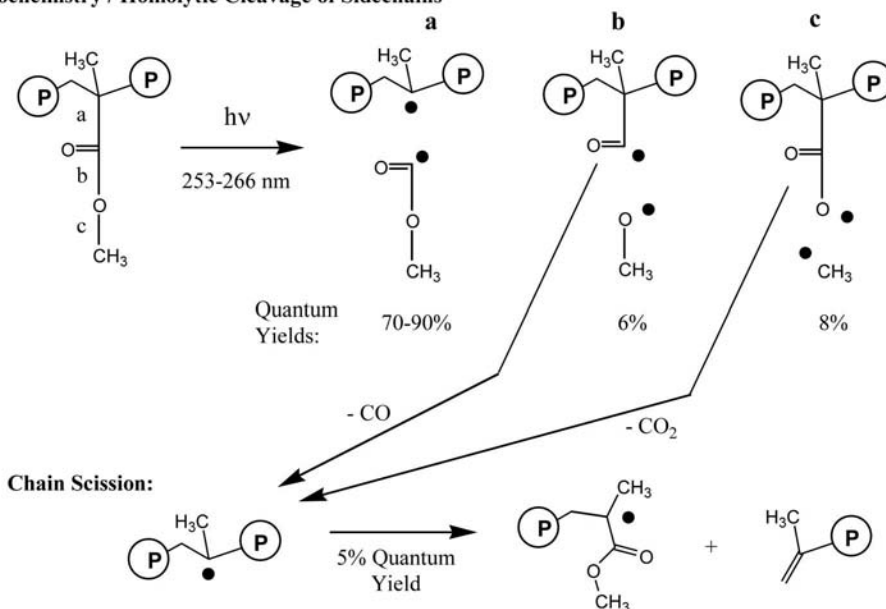
Naulleau et al. printed equal lines and spaces for 25- to 45-nm in an experimental version of KRS using LBNL's 0.3-NA MET (Fig. 8.41).⁷⁷ The authors showed that this was the highest resolution demonstrated on the system as of 2005.

8.5.3 PMMA

Some of the best examples of LER/resolution in combination with e-beam and photon-based lithography have been achieved using the positive chain-scission resist, PMMA.^{78–80} Indeed, the first EUV imaging work of Kinoshita used PMMA.^{11–13} Unfortunately this material has several disadvantages: It has relatively poor sensitivity, outgases significantly, uses solvent development, erodes quickly in the SEM, and has poor etch resistance. Comparison with ESCAP resist

Table 8.4 Comparison between PMMA and ESCAP.

Resist system	Advantages	Disadvantages
PMMA Chain-Scission positive resists	Resolution LER @ Small CD – – –	Pool sensitivity Outgassing Poor etch resistance Poor SEM stability Organic developers
ESCAP	Fast Stable in etch/SEM Aqueous development	Acid diffusion may limit resolution LER not as good as PMMA at small CDs –

Photochemistry / Homolytic Cleavage of Sidechains**Figure 8.42** PMMA exposure mechanism. (Reprinted with permission of the American Chemical Society.)

systems is useful (Table 8.4). ESCAP systems are relatively fast (acid-catalyzed reactions), have excellent etch resistance, and give good resolution and LER. Nonetheless, pure ESCAP systems pale in comparison to PMMA for printing high-resolution imaging with low LER.

Several mechanistic investigations into PMMA imaging have been published,¹⁸ but the most thorough and detailed study was done by Gupta et al. using 253- to 260-nm light.¹⁷ They showed that the photochemical decomposition mechanism of PMMA occurs in two steps (Fig. 8.42). The first step involves the homolytic cleavage of side-chain bonds with remarkably high film quantum yield (100%). The most likely decomposition pathways lead to the formation of methyl formate

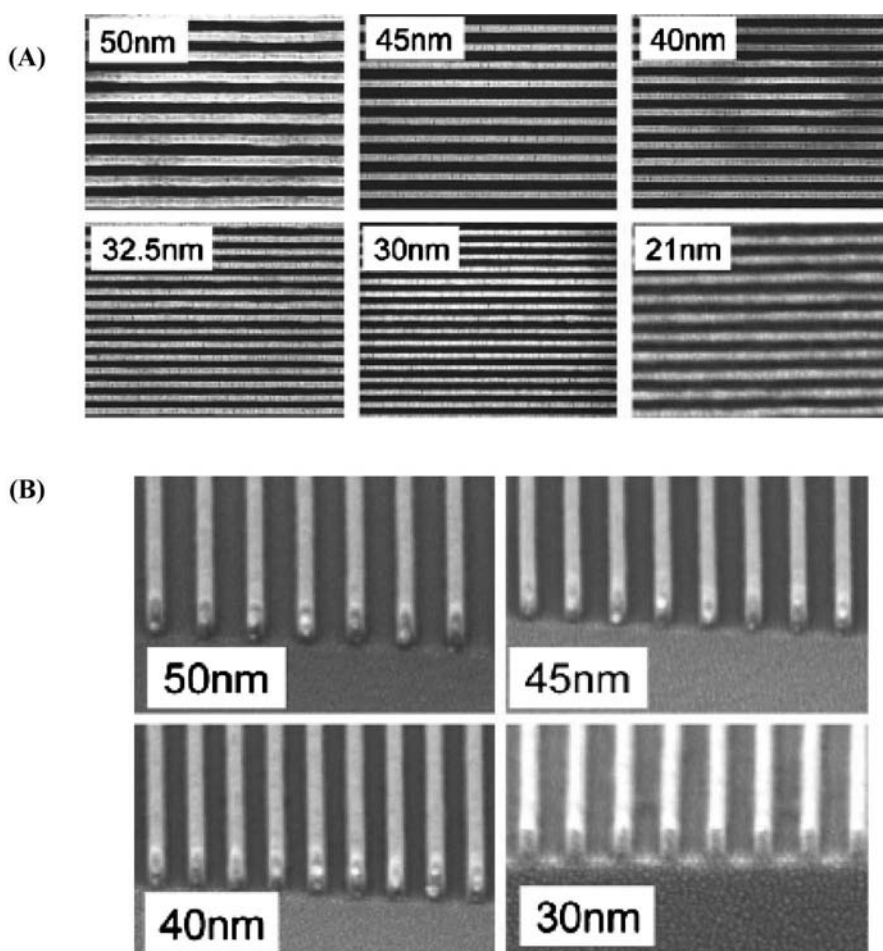


Figure 8.43 (A) Top-down SEM images of dense line patterns in PMMA with indicated half-pitches. (B) Cross-section images of dense line patterns in PMMA with indicated half-pitches. (Reprinted from Ref. 81 with permission from Elsevier.)

and methanol. The chain scission reactions responsible for changes in developer solubility occur with only 5% quantum yield.

Two of the best examples of PMMA imaging were printed using the interference lithography tool at the Paul Scherrer Institut (PSI). Gronheid et al. printed dense lines with half-pitches of 21- to 50-nm and with low LER and straight side walls (Fig. 8.43).⁸¹ More recently, Solak printed 15-nm dense lines and spaces in 25-nm films of PMMA (Fig. 8.44).⁸⁰

8.5.4 Negative resists

In the 1993 paper discussed in Sec. 8.2,²⁴ Early et al. reasoned that negative resists might exhibit steeper sidewalls than positive resists because the highest cross-linking occurs at the top of the film and counteracts the developer

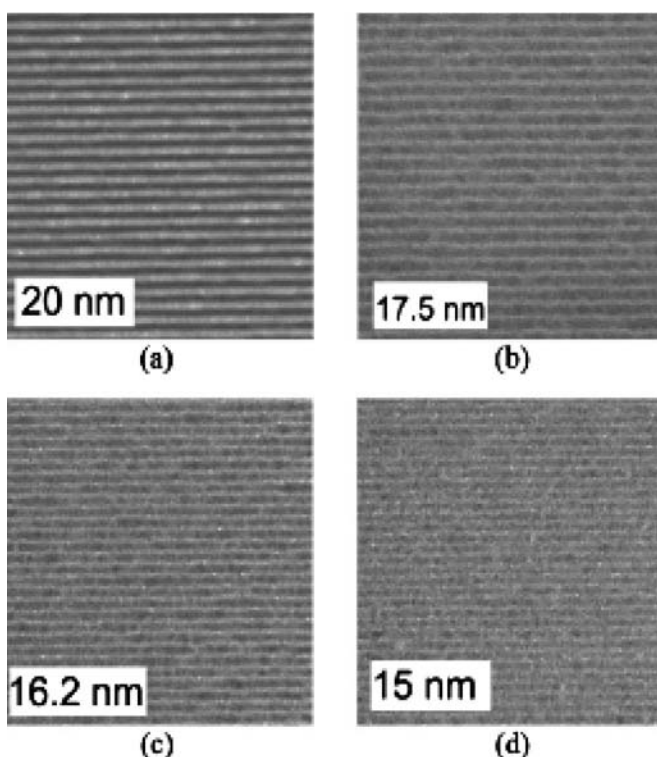


Figure 8.44 Top-down SEM micrographs of L/S patterns in PMMA with half-pitches of (a) 20 nm, (b) 17.5 nm, (c) 16.25 nm, and (d) 15 nm. The thickness of the PMMA film is 25 nm. (Reprinted from Ref. 80 with permission from AVS—The Science & Technology Society.)

gradient with film depth. In fact, many of the earliest papers to examine EUVL evaluated both positive and negative resists.^{24,25,28,29} More recently, however, the development of new negative-tone resists has been limited to three approaches: (1) lactonization polarity switch, (2) calixarenes, and (3) resists with Si or boron.

8.5.4.1 Lactonization polarity switch

Recently, Kojima et al.^{82,83} described the development of a new “molecular” resist made from low-molecular-weight phenolic compounds that uses a novel lactonization reaction as a polarity switch. The design of this system is driven by the observation that conventional negative resists work through cross-linking and a concomitant increase in molecular weight (Mw) at the line edge. The authors reasoned that cross-linking could be a primary source of LER, and that a low-molecular-weight negative resist with a polarity switch could give a much better LER.

Figures 8.45 and 8.46 show the synthesis and imaging chemistry of this lactonization resist system. Figure 8.47 shows the EUV imaging accomplished using

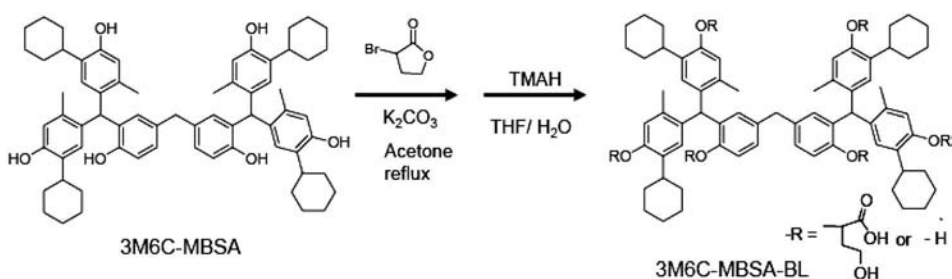


Figure 8.45 Synthetic approach of preparing molecular, lactonization negative resists.

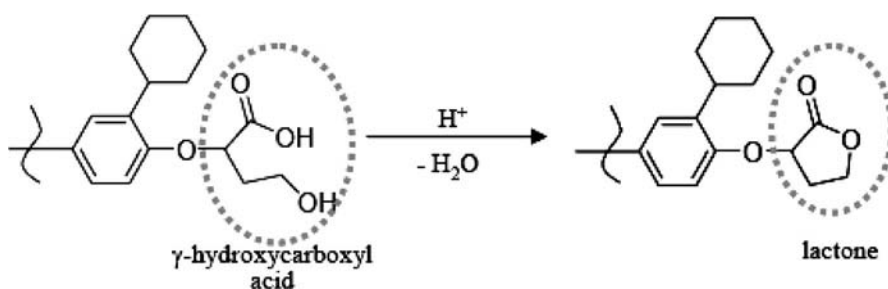


Figure 8.46 Proposed reaction mechanism for lactonization of negative resists based on Fourier transform infrared (FTIR) differential spectra.

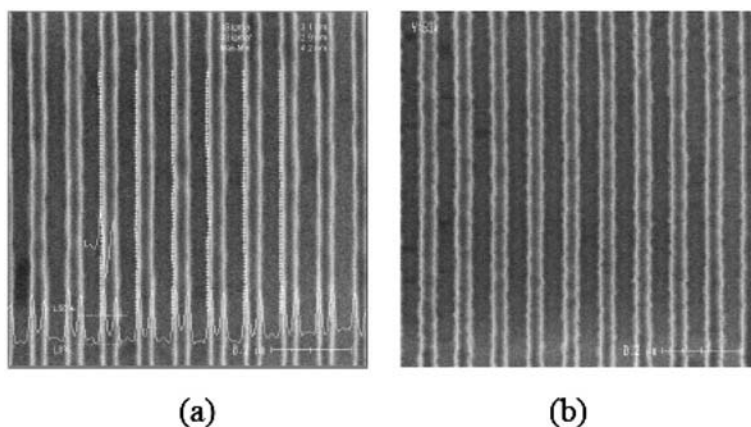


Figure 8.47 Top-view SEM images of resist C exposed to N EUV tool, with 45-nm hp patterns at an exposure dose of 12 mJ/cm². The LER of resist C was (a) 3.1 nm at inspection length $L = 620$ nm, and (b) 3.6 nm at $L = 2000$ nm.

the high-NA (NA = 0.3), small-field EUV exposure tool (HINA) at the Association of Super-Advanced Electronics Technologies (ASET).⁸⁴

8.5.4.2 Calixarenes

Negative resists based on cyclic aromatic ring structures known as calixarenes have demonstrated high-resolution imaging using e-beam lithography.⁸⁵ Recently, Solak et al. used EUV interference lithography to optimize the imaging based on *p*-chloromethyl-methoxy-calix[4]arene [Fig. 8.48(a)] printed 12.5-nm dense lines (Fig. 8.49).⁸⁰ Presumably these resists react via an initial homolytic cleavage of

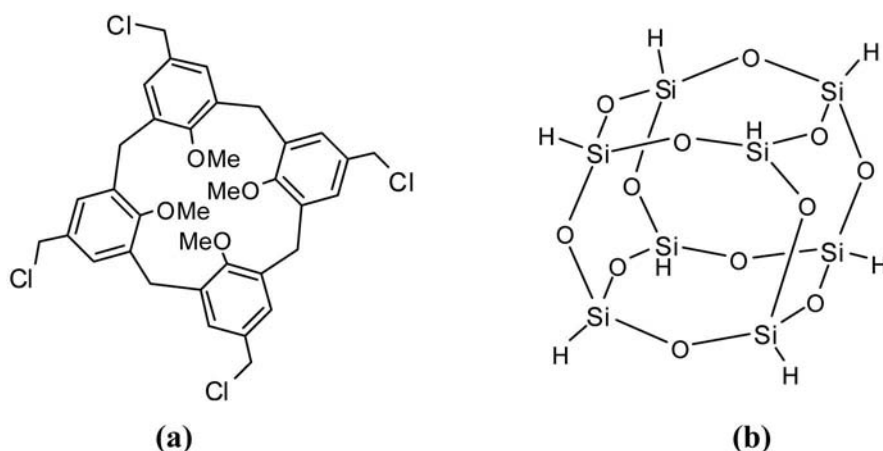


Figure 8.48 (a) Structure of *p*-chloromethyl-methoxy-calix[4]arene single-component resist; (b) molecular structure of eight-corner oligomer of hydrogen silsesquioxane (HSQ).

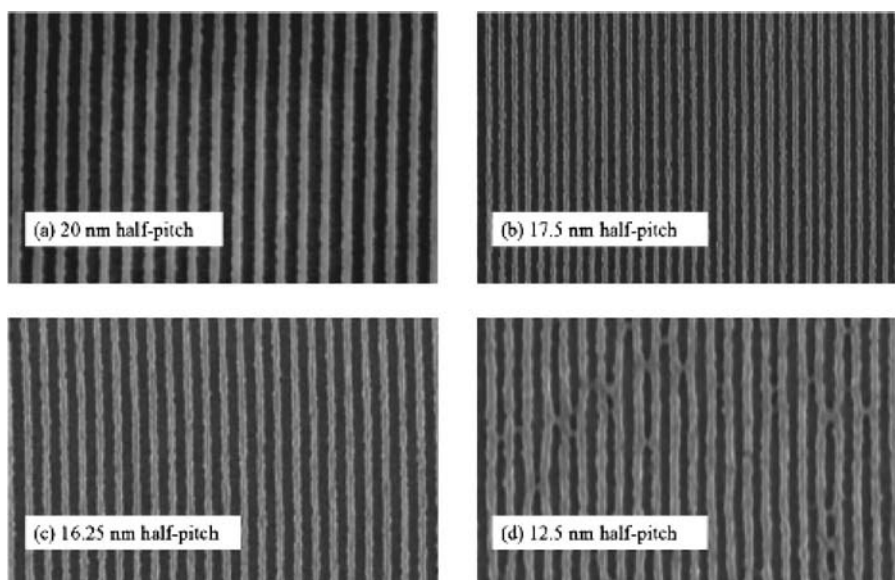


Figure 8.49 Top-down SEM micrographs of L/S patterns in calixarene with half-pitches of (a) 20 nm, (b) 17.5 nm, (c) 16.25 nm, and (d) 12.5 nm. (Reprinted from Ref. 80 with permission from AVS—The Science & Technology Society.)

the benzyl-chlorine bond followed by a series of free radical reactions leading to carbon-carbon bond formation, similar to the free radical reactions studied previously for chloromethylstyrene resists.^{86,87}

8.5.5 Resists with silicon or boron

Figure 8.8 shows the relative absorption coefficients for the first four rows of the periodic table. Both Si and boron stand out as elements with low absorption of EUV light. For this reason, researchers have designed resists with high levels of these elements to increase resist transparency to EUV.

8.5.5.1 Hydrogen silsesquioxane

Hydrogen silsesquioxane (HSQ) is a cube-shaped molecule with the empirical formula of $\text{Si}_8\text{H}_8\text{O}_{12}$ [Fig. 8.48(b)].⁸⁸ Each Si atom is bonded to three oxygen and one hydrogen atom. The postulated mechanism involves the cleavage of the Si–H bonds to form silanols (SiOH) in the presence of water. These silanols disproportionate to form a Si–O–Si bond, thereby decreasing the solubility in an alkaline developer, e.g., tetramethylammonium hydroxide (TMAH) (Fig. 8.50).^{89,90}

Junarsa et al.⁸⁹ printed 26-, 30-, and 40-nm dense lines with LERs of 5.1, 4.5, and 3.3 nm using EUV interference lithography at Wisconsin CNT beamline. More recently, Ekinici et al. printed 20- to 45-nm lines in 35-nm HSQ using interference lithography at PSI.⁹¹ They used 2.6 N TMAH developer ($10\times$ typical normality). Figure 8.51 shows clearly resolved cross sections of these dense lines. The sensitivity of these resists is fairly low, with doses to the mask of 500 mJ/cm^2 and doses to the wafer of $\sim 166 \text{ mJ/cm}^2$ to print 40-nm dense lines.⁹²

Although these HSQ resists show excellent resolution, their performance cannot be attributed to transparency. The high elemental composition of the low absorption element, Si (0.26 versus carbon), is overshadowed by the high absorbance of oxygen (2.77 versus carbon), because there are 1.5 oxygen atoms for each Si atom.

8.5.5.2 Other silicon resists

In 1999, Kessel et al. described their approach of incorporating Si into the acid leaving group.⁹³ They favored this approach because it gave flexibility in designing the backbone and because it allowed the possibility of removing all Si using flood exposure/bake steps to permit stripping of the resist. They developed photoresists based on two polymers that they called PRB and PRC (Fig. 8.52). These

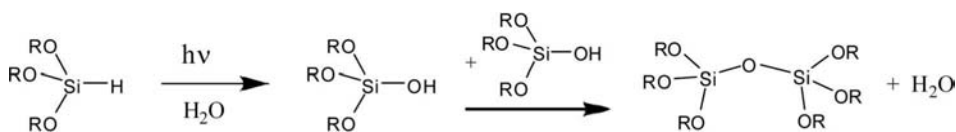


Figure 8.50 Postulated mechanism for cross-linking in HSQ lithography.

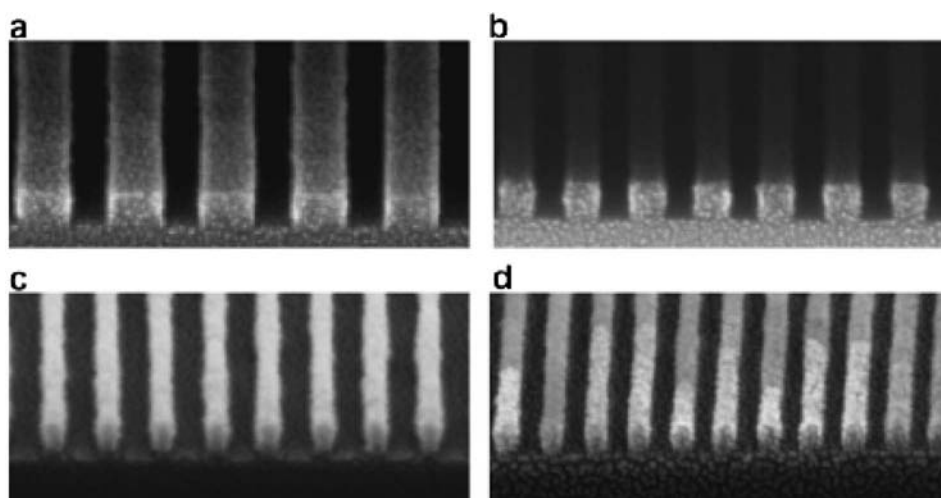


Figure 8.51 Cross-sectional SEM images of 35-nm-thick HSQ lines with (a) 45-nm, (b) 30-nm, (c) 25-nm, and (d) 20-nm half-pitch. The samples are baked at 180°C for 3 min. They are developed in TMAH (2.6 N) solvent for 60 s [(a)–(c)], and for 10 min (d). (Reprinted from Ref. 91 with permission from *Microelectronic Engineering*, Elsevier Limited.)

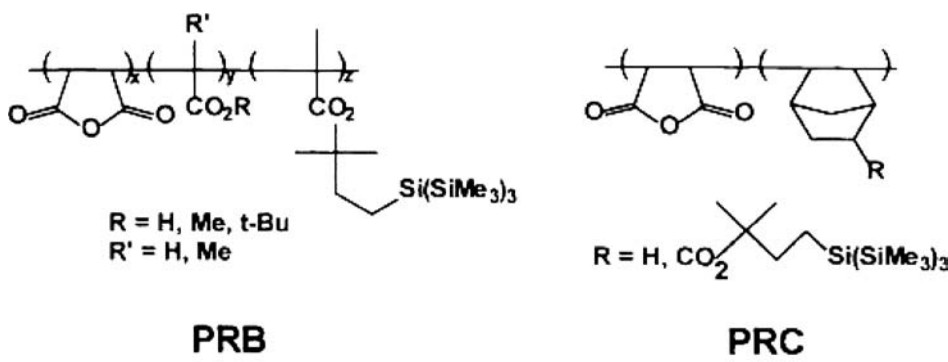


Figure 8.52 Two polymers with Si-containing leaving groups: PRB polymers are random terpolymers of acrylates, methacrylates, and anhydrides in which 15 to 90% of the monomer units contain the Si-containing leaving group. PRC polymers are alternating copolymers of norbornene and maleic anhydride in which some of the norbornene units have the t-butyl silyl ester functional group.

resists were imaged using the 10×1 , 0.088-NA stepper at SNL.⁹⁴ They found that the PRB polymers were hydrophobic with contact angles >90 deg. Increasing levels of polymer groups such as CO_2H , anhydride, and alcohol did not decrease hydrophobicity. Consequently, they struggled to image lines less than 200 nm without adhesion loss to the PRX underlayer.⁹³ The PRC polymer exhibited much better adhesion. The authors speculated that the better adhesion could be attributed to

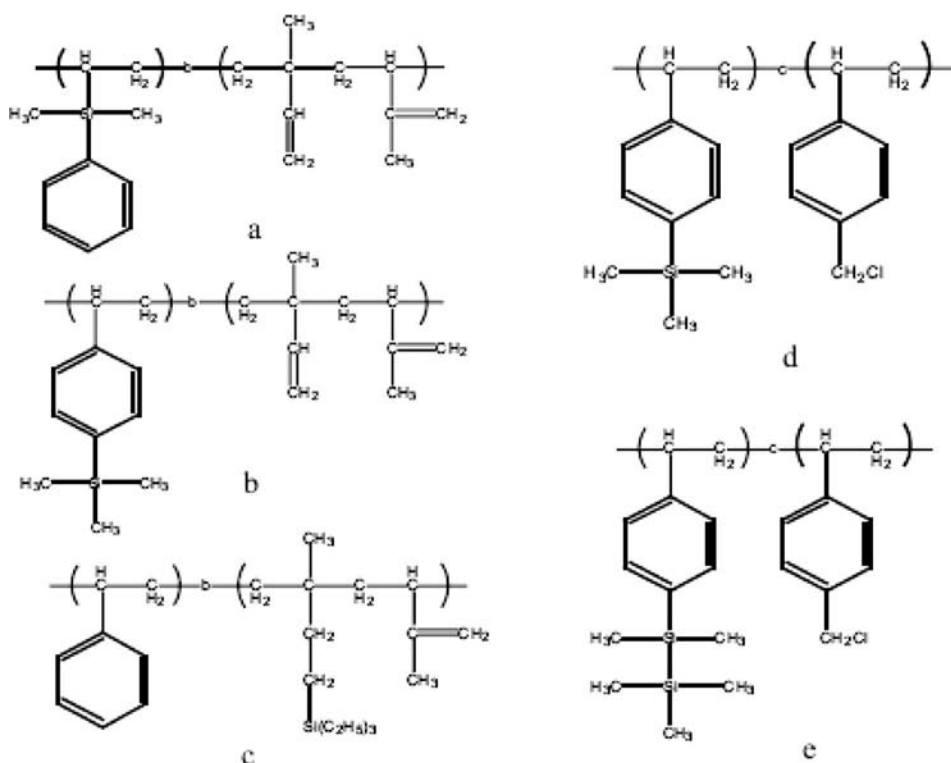


Figure 8.53 Structures of Si-containing polymers. (a) PDMPVS-b-Iso, (b) PTMSS-b-Iso, (c) PSI-Si, (d) PTMSS-co-CMS, and (e) PPMDS-co-CMS.

higher maleic anhydride content. They were able to print 100-nm lines on HMDS-primed Si using PRC resists.

In 2002, Dai et al. described their approach for producing negative EUV resists rich in low-absorbing elements (silicon, carbon, and hydrogen), and low in strongly absorbing elements of oxygen and fluorine (Fig. 8.53).^{95,96} They incorporated Si into the polymer by using trimethylsilyl-styrene or pentamethyldisilyl-styrene and developing the resists with THF/EtOH (40/60). The authors were able to print 180-nm lines using this approach at the Wisconsin CNT beamline.

In 2003, Kwark et al. used ring-opening metathesis polymerization (ROMP) to prepare polymers rich in carbon, hydrogen, and silicon, and low in oxygen and fluorine (Fig. 8.54).⁹⁷ Although the calculated transmittance of the polymer was relatively high (0.68 to 0.71 in 125-nm film), the resists could not be developed in a standard developer. Isopropanol (30%) was added to 0.26 N TMAH to aid in development. This reduced solubility in a purely aqueous developer was probably a result of the low content of oxygen-containing monomers. The authors were able to print 150-nm dense lines using Wisconsin's EUV stepper at CNT.

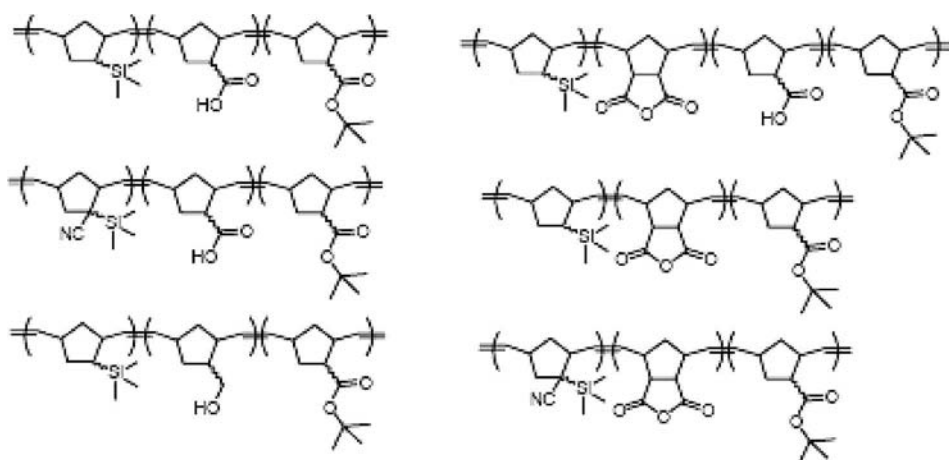


Figure 8.54 Silicon-containing norbornene terpolymers prepared by ROMP.

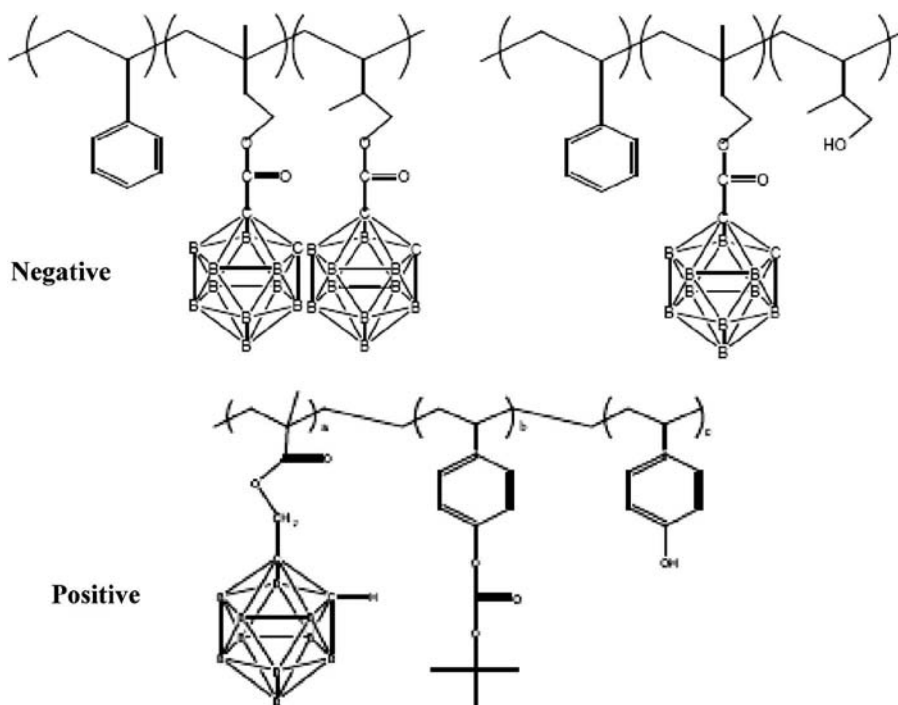


Figure 8.55 Structures of boron-containing polymers for negative and positive EUV resists.

8.5.5.3 Boron-containing resists

Dai et al. published their innovative work in developing relatively transparent polymers containing a carborane group (C_2B_{10}), which were used to prepare both positive- and negative-tone resists (Fig. 8.55).^{96,98} They succeeded in preparing polymers with calculated absorptions of 2.7 to 3.5 μm (base e).⁹⁹ The negative

resists printed 350-nm dense lines and the positive resists printed 250-nm lines using a 0.42-NA DUV stepper.

8.6 PAGs and Acids

8.6.1 Acid diffusion

All prospective lithographic solutions for future 22- and 32-nm nodes involving chemically amplified resists will have to contend with image blur from diffusing acids. Many creative and innovative studies have been performed to characterize and quantify the nature of acid diffusion blur. The most notable work has been that of Willson and his group at the University of Texas,^{100–104} and that of Houle, Hinsberg, et al. at the IBM Almaden Research Center.^{69,105–108} Although all of this work is important, it is beyond the scope of this review other than a few summary statements.

Clearly, acid diffusion blur is an unavoidable consequence of acid-catalyzed resist imaging processes for both positive and negative EUV resists. The challenge to the EUV resist chemist is to design resists that will minimize resolution damage caused by acid diffusion without decreasing the resist sensitivity.

8.6.2 New PAGs for EUV

Little has been published that describes PAG design specifically for EUV applications because PAGs developed for earlier technologies (DUV, 193-nm, e-beam) have been used successfully. Exceptions are the two studies described below.

Gonsalves, Thiagarajan, and Dean^{109–111} prepared ESCAP resists with PAG either bound to the polymer or blended separately (Fig. 8.56). The polymer-bound PAG was faster (5.5 versus 9.3 mJ/cm²) and had a higher contrast than the blended PAG. Imaging experiments conducted at the 0.3-NA MET at LBNL showed that the resist prepared using the polymer-bound PAG (45 nm dense) had better resolution than the resist prepared using the blended PAG (80 nm dense).

Watanabe et al.¹¹² explored the use of new PAGs using cyclo(1,3-perfluoropropanedisulfone) imidate as the counter anion (acid precursor) (Fig. 8.57). The two PAGs with the cyclic anion (A & C) showed higher sensitivity at EUV through the analogous nonaflate PAGs (Table 8.5), but a comparison at DUV and e-beam showed no significant difference between PAGs A and B. Based on outgassing and IR data, the authors concluded that the higher sensitivity of the PAGs with the cyclic imidate anion was due to photodecomposition of the cyclic anion, which created more sulfonic acid.

8.6.3 Exposure mechanisms

PAG photolysis mechanisms have been the subject of careful research over the years. PAG exposure to DUV (248 nm) light has shown that mechanisms generally take two pathways: (1) direct light absorption by the PAG followed by

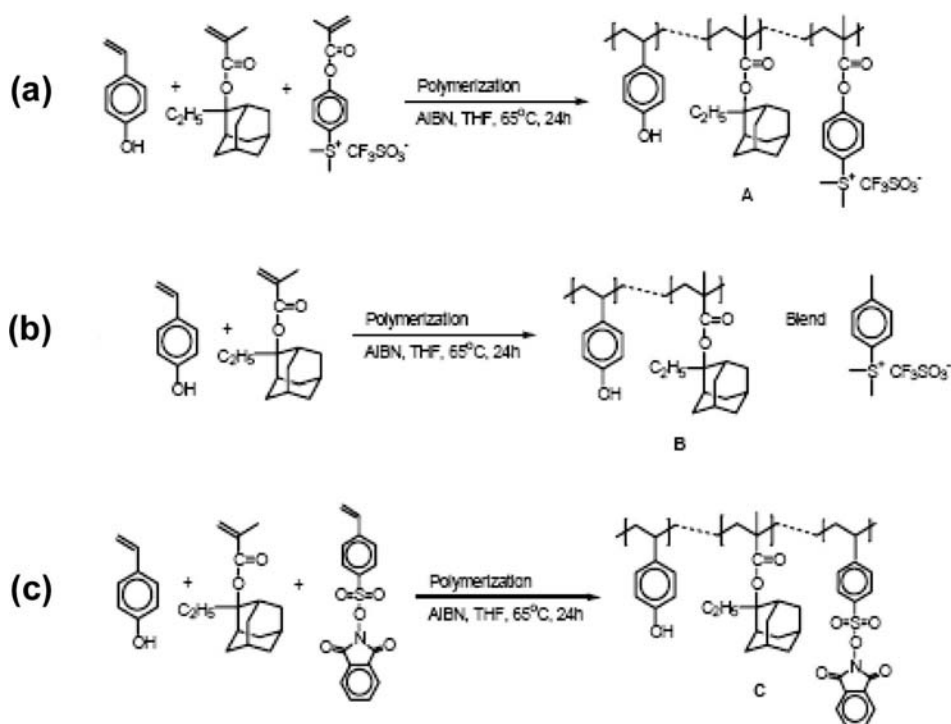


Figure 8.56 Three approaches for incorporating PAGs into EUV photoresists: (a) ionic polymer-bound PAG, (b) blended PAG, and (c) nonionic polymer-bound PAG.

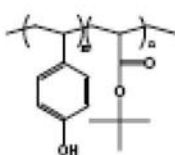
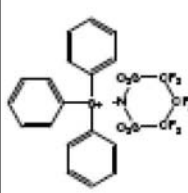
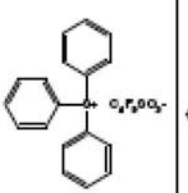
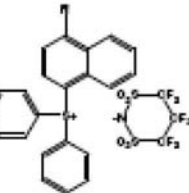
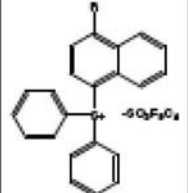
Sample	Resist A	Resist B	Resist C	Resist D
Resin				
PAG				
Solvent	propylene glycol monomethylether acetate (PGMEA)			

Figure 8.57 Four resists prepared with the cyclic anion (A and C) and nonaflate PAGs (B and D). (Reprinted from Ref. 112 with permission from the *Japanese Journal of Applied Physics*.)

Table 8.5 Sensitivity comparison of four PAGs using EUV, DUV, and e-beam exposure.

	Clearing doses (mJ/cm ²)			
	Resist A	Resist B	Resist C	Resist D
EUV Exposure	1.1	3.8	2.0	3.1
DUV Exposure	14.5	14	N/A	N/A
e-Beam Exposure	14.3	14.6	N/A	N/A

NA = not applicable. The authors did not report EUV and e-beam results for resists C and D.

carbon-hetero atom bond cleavage and radical processes that generate acid,^{113,114} or (2) light absorbed by the polymer,^{115,116} which can sensitize the PAG to decomposition. PAG photolysis using 193-nm and 157-nm light is similar to the 248-nm mechanism except the polymer does not participate in sensitizing the PAG.¹¹⁵ The quantum yield of the EUV-2D resist⁴³ in converting absorbed photons to acid using DUV or 193-nm light is 0.33 and 0.14, respectively.¹⁹ Exposure of chemically amplified resists to 13.5-nm (EUV) light occurs by an entirely different mechanism.³³ The energies of EUV photons (92 eV) are 18 and 14 times higher than 248- and 193-nm photons, respectively. These photons interact strongly with the resist components to create photoelectrons. The authors have shown that the EUV-2D resist has a quantum yield of 2.1 acid molecules, or that 2.1 acid molecules are generated for every EUV photon absorbed.¹⁹

Tagawa, Kozawa, et al. actively investigated the mechanisms of photoacid generation by ionizing radiation. They investigated exposure using e-beam, pulse radiolysis, DUV (248 nm), x-ray (~1 nm), as well as EUV light.^{117–122} They described how the trapped hole in the phenolic polymer plays an important role in the production of photoacid,^{117–119} and they demonstrated how subtle changes in polymer structure change the yield of acid generation.¹²¹ Much of their early work was done by exposure in methanol or acetonitrile solutions. More recently, they studied EUV exposure in phenolic matrixes. Much of their work has focused on processes occurring after ionization, including proton-anion recombination reactions. Their work has greatly expanded the general understanding of chemically amplified exposure mechanisms.

8.7 Line Edge Roughness^{1–3}

EUVL will be used to pattern the smallest features on the ITRS roadmap, and therefore must print images with the smallest LER. Current EUV resist targets stipulate that dense lines should have LERs of 1.2 nm (Fig. 8.1). A number of variables are thought to influence the LER of printed images. Some of these include resist processing conditions,¹ acid diffusion,^{123,124} polydispersity of the polymer,^{125,126} shot noise,^{127,128} mask effects, and aerial image contrast. Another aspect to consider in the evaluation of LER at smaller feature sizes is the ability of current image analysis technology to distinguish between LER inherent in the resist image and

that caused by the SEM instrument. A number of advances have been made in this area in an effort to improve SEM and LER processing software capabilities.

LER is an important and active area of research for both EUV and 193-nm lithography, and the topic is too broad to fully cover here. Therefore, this section will be limited to four studies involving the EUV-2D tool test resist: the effect of base loading, polymer Mw, shot noise, and quantum yield.

8.7.1 Added base

Seven resists were prepared identical to EUV-2D resist except with seven levels of base such that the base/PAG ratio spanned 0.0 to 0.75.¹⁹ These seven resists were imaged using dense line patterns at EUV and DUV using the 0.088-NA 10×2 stepper at SNL. Similarly, the clearing doses (E_o 's) of the resists were determined using DUV and EUV exposures. The results of these simple, yet powerful, experiments are the basis of many conclusions about LER, shot noise, film quantum yield, and the mathematical relationship between LER and E_{size} . One reason this base titration method is so powerful is its simplicity. Even very wide ranges of base concentrations have very little effect on resist solubility properties, yet they have a powerful influence on the chemistry of the photo-generated acid. Since the role of this acid is catalytic in these systems, small changes in local acid or base concentrations greatly influence the dissolution rate of the polymer after PEB.

A plot of EUV LER versus EUV E_{size} and DUV LER versus DUV E_{size} shows a dramatic improvement in LER with increasing levels of added base (Fig. 8.58). Both curves show similar shapes: resists requiring low doses have poor LER, whereas the resists requiring high doses have good LER. The authors ruled out the possibility that the LER improvement could be attributed to improved contrast. The plot of relative film thickness versus $\log(\text{dose})$ shows seven curves that differ

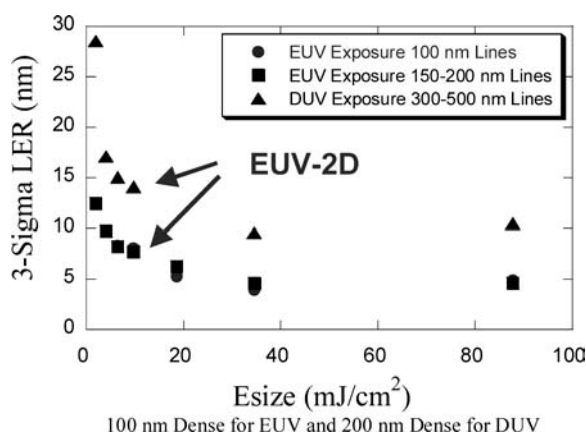


Figure 8.58 LER (3σ) for seven resists after exposure at EUV and DUV.^{142,143} EUV: The LER of 100 nm and an average of 150- and 200-nm dense lines are plotted against E_{size} for 100-nm dense lines. DUV: The LER of average 300-, 400-, and 500-nm dense lines are plotted against E_{size} for 200-nm dense lines.

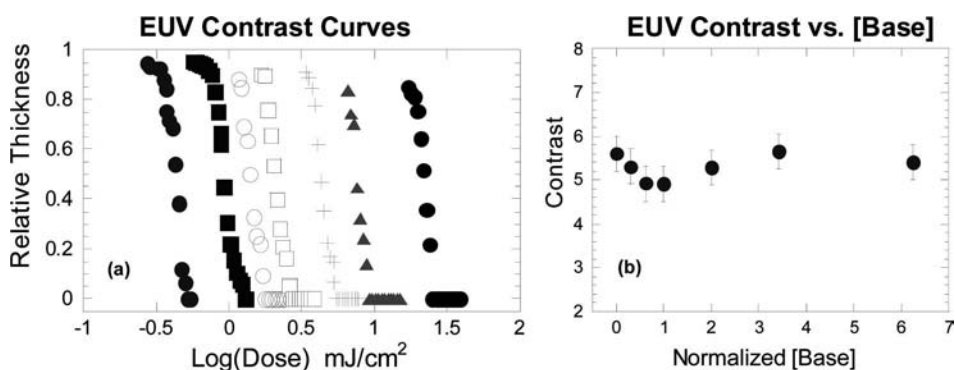


Figure 8.59 (a) EUV contrast curves of seven EUV-2D type resists with seven levels of added base. (b) Contrast as a function of added base.

in sensitivity but have roughly the same shape [Fig. 8.59(a)]. Indeed, a comparison of the contrast shows that there is little change in contrast with base [Fig. 8.59(b)]. Clearly, the bulk resist contrast does not explain the improvement in LER with increasing base.

8.7.2 Polymer size

The LER objective of 1.2 nm is about half of what is currently possible in EUVL and about half the hydrodynamic radius of typical resist polymers. This fact has led many researchers to investigate the role of polymer Mw on LER. The effect of Mw on LER appears to be fundamental. However, the polymer is only one component of a more complex resist system; changes in polymer Mw will drastically alter the dissolution properties of the polymer, and could thereby overwhelm the more subtle contributions of polymer size to resist LER. Therefore, experimentation in this area must be carefully conducted and results critically interpreted to avoid drawing erroneous conclusions.

A number of interesting and valuable studies have addressed the effect of Mw on LER; however, many have been limited to studying polymers of only two or three different Mw's, or polymers over a small Mw range.^{129–131} A portion of this work directly relates the size of the grains or aggregates seen in the atomic force microscope (AFM) surface image of the resist to the magnitude of LER.¹³² Yamaguchi et al.¹³³ examined AFM images of pattern side walls in resists containing partially protected t-Boc-poly(hydroxystyrene) polymers with Mw's of 41, 67, and 102 K. They attributed the cause of the LER to aggregates trapped in the pattern side wall of the resist. Yamaguchi¹³⁴ also linked resist LER directly to aggregate size and reported that grain diameter was seen to increase with polymer Mw. The aggregates trapped in the pattern sidewall were similar to aggregates in the unexposed film regions because the short range order was shown to be independent of the dissolution and exposure processes. However, the “long range” roughness was influenced by dissolution effects and applied dose during resist imaging. Despite

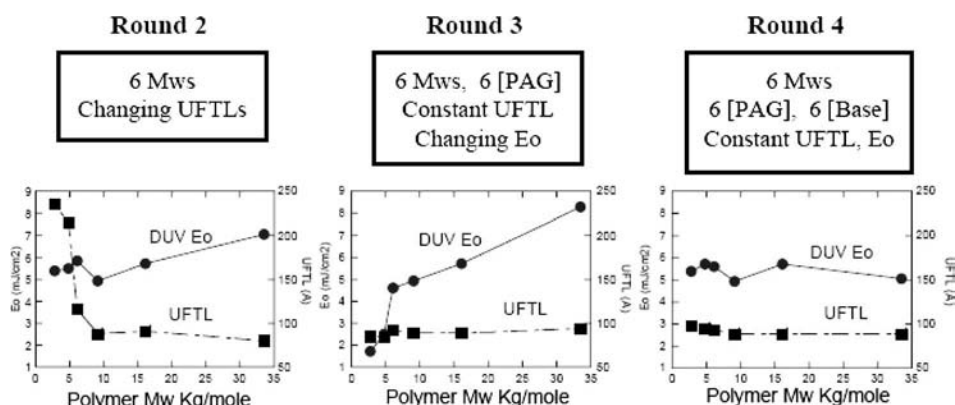


Figure 8.60 UFTL and DUV E_o values for rounds 2, 3, and 4.

some convincing findings, ambiguity still exists in the literature whether Mw really does affect LER.

Cutler et al.⁶⁷ performed a systematic resist study in which they attempted to isolate the variable of polymer size (Mw) and its effect on LER from dissolution rate and sensitivity effects. Six phenolic polymers were prepared with a 12-fold Mw increase from 2.9 to 33.5 Kg/mol. These polymers were incorporated into an EUV-2D type resist matrix, and each resist was exposed at DUV for the E_o and UFTL information, as well as imaged at EUV to determine the LER. The unexposed and developed areas of wafers processed at DUV were also analyzed by AFM to establish the effects of Mw on surface roughness and aggregate size. By taking into account, and compensating for, the impact of changing the polymer Mw on other resist properties such as UFTL, the authors determined the influence of Mw on resist surface characteristics upon LER.

Direct substitution of the six polymers into the same resist formulation (PAG and base held constant) yielded a series of resists (round 2, Fig. 8.60) for which UFTL changed dramatically and E_o changed slightly. The low-Mw polymers had higher dissolution rates and produced resists with higher UFTL. In round 3, the PAG level was adjusted to compensate for the changing polymer Mw and to produce a series of resists with the same UFTL but with changing E_o . The PAG level was increased for resists with 2.9, 4.9, and 6.1 Kg/mol polymers, and decreased for resists with 16.1 and 33.5 Kg/mol polymers. The resist with 9.1 K polymer was a duplicate of the resist with 9.1 Kg/mol polymer in round 2. In round 4, base was added or removed from the round 3 resists to produce a series of resists with constant UFTL and E_o over the 12-fold change in polymer Mw. The resists with 2.9, 4.9, and 6.1 Kg/mol polymers had higher levels of base; the 16.1 and 33.5 Kg/mol resists had lower levels of base; and the resist prepared with the 9.1 Kg/mol polymer was a duplicate of the resists in rounds 2 and 3.

Resists were coated to 140 nm and imaged at EUV. EUV-2D was also imaged before and after each round as a control to give an indication of the baseline performance of the 0.088-NA 10×2 exposure tool at SNL.¹³⁵ LER values are plotted

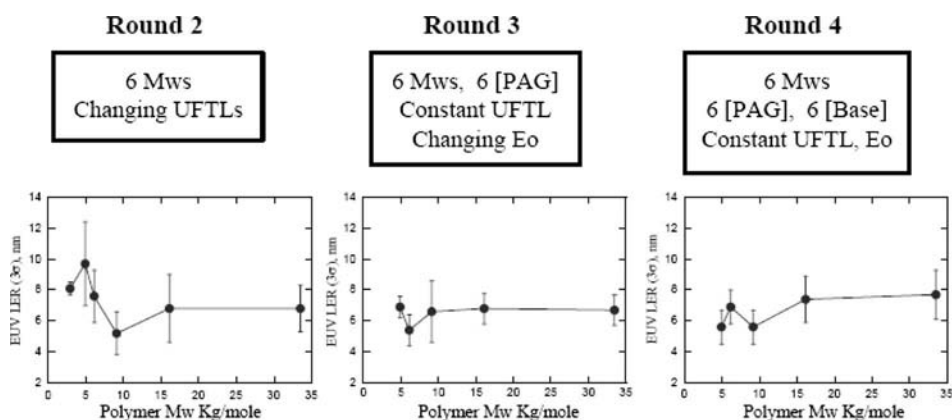


Figure 8.61 EUV 3 σ LER values for rounds 2, 3, and 4.^{142,143}

against polymer Mw for the three rounds (Fig. 8.61). They were measured for 100-nm dense lines imaged at EUV. Low Mw resists in round 2 exhibited a slight increase in LER, but as the Mw increases, the LER becomes more uniform. When UFTL is controlled in rounds 3 and 4, there is little difference in the LER over a 12-fold increase in Mw.

This work studied the effect of changing resist variables such as base level, polymer Mw, and PAG concentration on the LER of EUV resists. The effect of changing Mw was evaluated in three rounds of experiments in which factors such as UFTL and *Eo* were manipulated by removing stronger influences on LER. For the EUV-2D resist chemistry, polymer Mw had no effect on the LER of EUV resists.

8.7.3 Shot noise

Current EUV resist targets stipulate that dense lines should have LERs of ≤ 1.2 nm and E_{size} values of 5 to 15 mJ/cm². Both of these numbers are quite small. While resists having one of these properties have been demonstrated, no images have been printed that show both. In fact, there is concern that photoresists will reach a “shot noise limit” when low doses of high-energy photons cause the number of photons to fall low enough that the statistical variations cause LER to increase beyond an acceptable limit.^{136,137} The shot noise limit is defined as the limit imposed by the statistical probability of underexposing a pixel.¹³⁶

In 1998, Hutchinson developed a theoretical model for comparing the LER of 193-nm resists with that of EUV resists.¹²⁸ Without considering the effects of secondary electrons or acid diffusion, his model predicted that shot noise effects would limit the LER of 193-nm resists to 1 and 5 nm when imaged using doses of 10 and 1 mJ/cm², respectively. At EUV, however, his model predicted that shot noise effects would limit the LER of EUV resists to 8 and 25 nm when imaged using doses of 10 and 1 mJ/cm², respectively. Clearly, if these predictions were to hold true, shot noise generated LER would be a barrier to EUV imaging. More recently,

however, three papers discussed the role that shot noise might play in limiting the manufacturability of contact holes, and the results from these papers were much more optimistic than Hutchinson's theoretical studies.^{137–139} Specifically, Lee et al. concluded that shot noise would not limit the printing of contact holes as small as 30 to 50 nm with acceptable yield.¹³⁹ This section will focus on the effect of shot noise on printing low LER lines, rather than the printing of contact holes.

Brainard et al.¹⁹ presented studies of LER, film quantum yield, and shot noise of EUV resists. Central to these studies was a set of seven resists identical to EUV-2D (XP98248B) that were prepared with seven levels of added base. Much of this paper is directed toward understanding the relationship between LER and E_{size} of these seven resists at DUV and EUV. These experiments led to conclusions about LER, shot noise, film quantum yield, and the mathematical relationship between LER and E_{size} . Poisson statistics were used to better understand these relationships. Exposure of the resists using DUV and EUV light helped to determine the C-parameter of EUV-2D at these wavelengths. Film quantum yields and optical densities were used to determine the concentrations of acid molecules created using both DUV and EUV exposures.

An analytical model was developed to illustrate the scaling behavior of line edge formation in chemically amplified photoresists. The basic assumption was that LER is the result of the inherent statistical nature of the discrete processes of photon absorption, secondary electron generation, PAG excitation, acid-quencher annihilation, and deprotection. For a Poisson process such as photon absorption, the statistical variation in the number of absorbed photons σ_N is equal to the square root of the number of absorbed photons N :

$$\sigma_N = \sqrt{N}. \quad (8.5)$$

The authors showed that the LER is proportional to the relative variation in dose (σ_N/N). This result combined with Eq. (8.5) leads to the conclusion that LER is proportional to dose^{-1/2}, since the number of absorbed photons is proportional to the dose:

$$\text{LER} \propto \frac{\sigma_N}{N} = \frac{1}{\sqrt{N}} \propto \frac{1}{\sqrt{\text{dose}}}. \quad (8.6)$$

Replotting the data shown in Fig. 8.58 as LER versus $(E_{\text{size}})^{-1/2}$ gives curves with excellent linear fits of the DUV and EUV data ($r^2 = 0.94$ and 0.97 , respectively). These linear fits indicate that these resists are following the Poisson statistics of shot noise for exposure at both DUV and EUV (Fig. 8.62). This result is somewhat surprising because there are 18.5 times more photons/mJ in DUV than EUV, yet the LER versus E_{size} relationship is defined by the statistics of shot noise in both cases (i.e., linear plots in Fig. 8.62). Dentinger used a constant ratio of LER between DUV and EUV as evidence that shot noise statistics were not in effect in their study.¹⁴⁰ The work of Brainard et al.¹⁹ led to the conclusion that the LER

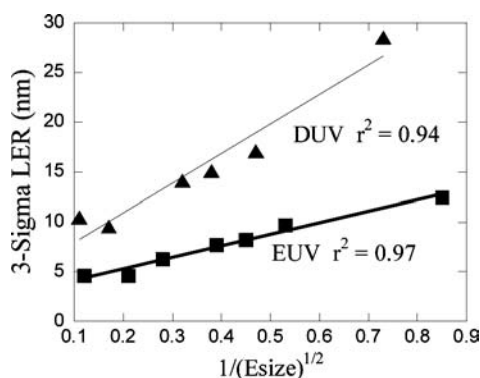


Figure 8.62 LER versus $(E_{size})^{-1/2}$ for DUV and EUV exposure of the seven EUV-2D type resists with seven levels of added base.

versus E_{size} behavior at both DUV and EUV are defined by the Poisson statistics of shot noise.

8.7.4 Film quantum yield

Brainard et al.¹⁹ defined the film quantum yield of photoresists as the ratio between the number of acid molecules generated during exposure and the number of photons absorbed [Eq. (8.7)]. They determined the film quantum yield of EUV-2D so they could better understand the mathematical relationships between the numbers of photons, numbers of acid molecules, and LER. The only two values that are needed to make the calculation are the optical density and the C-parameter. The optical density of EUV-2D has been determined⁴¹ and the C-parameter can be calculated using Szmanda's base titration method.^{64,141} The number of photons absorbed is calculated when a $1\text{ cm} \times 1\text{ cm} \times 125\text{ nm}$ section of EUV-2D is irradiated with 0.1 mJ/cm of EUV light using the absorbance of 125-nm resist film and the number of EUV photons in 0.1 mJ . This result is compared with the number of acid molecules generated when the same section of EUV-2D is irradiated with 0.1 mJ/cm of EUV light using the C-parameter ($0.051\text{ cm}^2/\text{mJ}$) and a dose of 0.1 mJ/cm . The resulting film quantum yield for EUV-2D is 2.08 (Table 8.6).¹⁴²

The film quantum yield for EUV-2D using DUV exposure was also calculated. The product of the first four columns in Table 8.6 gives the number of acid molecules at E_{size} . The values are nearly identical at both wavelengths. In retrospect, it makes sense that the same amount of acid is required to reach sizing when the bake steps and development are the same. Nonetheless, the implications of this result are powerful: it means that the number of acid molecules may be a better indicator of LER than the number of absorbed photons. This result also supports the author's assertion that the LER/sensitivity behavior of both EUV and DUV is defined by

Table 8.6 Film quantum yield comparisons for exposure of EUV-2D, DUV, and EUV.

Wavelength	E_{size} (mJ/cm ²)	# of Photons in 1 mJ/cm ² $\times 10^{13}$	Absorption of 125 nm	Quantum efficiency	Number of acids generated at $E_{\text{size}} \times 10^{13}$
EUV	6.7	6.7	0.41	2.08	38.2
DUV	9.7	125	0.10	0.33	40.6

the Poisson statistics of shot noise: $\text{LER} \propto \text{dose}^{-1/2}$;

$$\text{Film Quantum Yield} = \frac{\text{Number of Acids Generated in the Film}}{\text{Number of Photons Absorbed by the Film}}. \quad (8.7)$$

8.8 Summary and Future Outlook

EUV photoresist technology has progressed significantly since the first experiments conducted by Kinoshita in 1986.^{11–14} Researchers have explored issues related to optical density, thickness, and etch resistance, and are currently using ultrathin (30 to 100 nm) single-layer resist approaches. Novel elements such as silicon and boron have shown to be capable of improving transparency, but the most successful resists used today are primarily composed of the more conventional elements of carbon, hydrogen, oxygen and nitrogen with the use of fluorine, sulfur, and iodine for photoacid generators.⁹ Perhaps the most successful resists at this time are those that give improved resolution by controlling acid diffusion^{100–108} through the use of low E_a polymers such as KRS from IBM.^{74–77} Additionally, PAG-bound polymers show great promise for controlling acid diffusion and improving the homogeneity of PAG distribution.^{109–111}

Ultimately, however, EUV photoresists continue to fall short of the resolution, LER, and sensitivity goals published by the ITRS (Fig. 8.1), and resists remain near the top of the critical issues list presented each fall at the EUV symposium (Table 8.7).¹⁴³ Although EUV resists have made much progress since the first experiments in 1986, the journey is not over, and resist chemists will need to continue to search for new innovations to meet future goals.

Acknowledgments

Thanks to my lovely wife, Lisa, for her help in preparing this manuscript. Thanks to Craig Higgins for his help with permissions. Thanks also to Vivek Bakshi for his expert editing and seemingly inexhaustible patience.

Table 8.7 Critical issues list from the 2007 EUV symposium in Sapporo, Japan.¹⁴³

2003	2004	2005	2006	2007
1. Source power and condenser lifetime	1. Availability of defect-free mask	1. Resist RLS met simultaneously	1. Reliable high-power source and collector module	1. Reliable high-power source and collector module
2. Availability of defect-free mask	2. Lifetime of source components and collector optics	2. Collector lifetime	2. Resist RLS met simultaneously	2. Resist RLS met simultaneously
3. Reticle protection during storage, handling, and use	3. Resist RLS met simultaneously	3. Availability of defect-free mask	3. Availability of defect-free mask	3. Availability of defect-free mask
4. Projection and illuminator optics lifetime	• Reticle protection during storage, handling, and use	4. Source power	4. Reticle protection during storage, handling, and use	4. Reticle protection during storage, handling, and use
5. Resist RLS	• Source power	• Reticle protection during storage, handling, and use	5. Projection and illuminator optics quality and lifetime	5. Projection and illuminator optics quality and lifetime
6. Optics quality for 32-nm half-pitch node	• Projection and illuminator optics lifetime	• Projection and illuminator optics quality and lifetime		

References

1. D. He and F. Cerrina, "Process dependence of roughness in a positive-tone chemically amplified resist," *J. Vac. Sci. Tech. B* **16**(6), 3748–3751 (1998).
2. If the roughness between two edges of a line are uncorrelated, the values of line edge roughness (LER) and line width roughness (LWR) are related by $\sqrt{2}$, or $LWR \cong 1.41 \times LER$.
3. H. B. Cao, Y. Wang, B. J. Rice, et al., "Sources of line-width roughness for EUV resists," *Proc. SPIE* **5376**, 757–764 (2004).
4. R. Brainard, F. Nguyen, G. Lin, P. Kandanarachchi, and K. O'Connell, "Resists for EUV and EPL," in *DARPA Adv. Lith. Review*, San Diego, CA, April 18, 2002; R. L. Brainard, T. Koehler, R. Hemond, and P. Naulleau, "Status of EUV photoresists," in *IEUVI Resist Forum*, 2004 EUV Symposium, Miyazaki, Japan.
5. G. M. Gallatin, "Resist blur and line edge roughness," *Proc. SPIE* **5754**, 38–52 (2005).
6. G. M. Gallatin, P. Naulleau, and R. Brainard, "Fundamental limits to EUV photoresist," *Proc. SPIE* **6519**, 651911/1–651911/10 (2007).
7. D. Van Steenwinckel, R. Gronheid, J. H. Lammers, et al., "A novel method for characterizing resist performance," *Proc. SPIE* **6519**, 65190V/1–65190V/11 (2007).
8. D. Van Steenwinckel, R. Gronheid, and F. Van Roey, "Performance assessment of novel resist approaches for EUV lithography using a single figure of merit," presented at the 2007 International EUV Symposium, Sapporo, Japan.
9. General observations from the 2007 International EUV Symposium, Sapporo, Japan.
10. T. Namioka, "Current research activities in the field of multilayers for soft X-rays in Japan," paper No. 28-AF-15 presented at the 47th Autumn Meeting of the Japan Society of Applied Physics (1986). Published in *Revue Phys. Appl.* **23**, 1711–1726 (1988).
11. H. Kinoshita, K. Kurihara, Y. Ishii, and Y. Torii, "Soft x-ray reduction lithography using multilayer mirrors," *J. Vac. Sci. Tech. B* **7**(6), 1648–1651 (1989).
12. Tungsten-carbon MLs were used before T. W. Barbee Jr. described the use of Mo-Si in Ref. 128. Attempts to print images using 5-nm light were unsuccessful.
13. T. W. Barbee, S. Mrowka, and M. C. Hettrick, "Molybdenum-silicon multilayer mirrors for the extreme ultraviolet," *Appl. Opt.* **24**(6), 883–886 (1985).
14. Personal communication with Rick Uchida (TOK): The two resists supplied by TOK were SPP (silicone-based positive photoresist) and OFPR (Ohka fine pattern resist); personal communication with Hiroo Kinoshita: SPP is a Si-containing resist developed by Dr. A. Tanaka of NTT that exhibits negative-tone behavior at EUV wavelengths; H. Ban, A. Tanaka, Y. Kawai, and S. Ima-mura, "Synthesis of alkaline-soluble silicone resin suitable for resist material in microlithography," *Polymer* **31**(3), 564–568 (1990); A. Tanaka, H. Ban,

- and S. Imamura, "Preparation of novel silicone-based positive photoresist and its application to an image reversal process," *Polym. Mater. Sci. Eng.* **60**, 366–370 (1989); A. Tanaka, H. Ban, S. Imamura, and K. Onose, "Resolution characteristics of novel silicone-based positive photoresist," *J. Vac. Sci. Tech.* **7**(3), 572–575 (1989); H. Ban, A. Tanaka, and S. Imamura, "Alkaline-developable silicone-based positive photoresist for electron beam lithography," *Japan. J. Appl. Phys.* **27**(11), L2137–L2138 (1988).
15. J. E. Bjorkholm, J. Bokor, L. Eichner, et al., "Reduction imaging at 14 nm using multilayer-coated optics: printing of features smaller than 0.1 μm ," *J. Vac. Sci. Tech. B* **8**(6), 1509–1513 (1990).
 16. W. M. Mansfield, et al., "Effects of absorption on resist performance in soft x-ray projection lithography," in *Soft X-Ray Projection Lithography*, Jeffrey Bokor, Ed., Vol. 12, pp. 129–131, Optical Society of America, Washington, D.C. (1991).
 17. A. Gupta, R. Liang, F. D. Tsay, and J. Moacanin, "Characterization of a dissociative excited state in the solid state: photochemistry of poly(methyl methacrylate). Photochemical processes in polymeric systems. 5," *Macromolecules* **13**(6), 1696–1700 (1980).
 18. A. Uhl, J. Bendig, J. Leistner, U. Jagdhold, and J. J. Bauer, "E-beam and deep-UV exposure of PMMA based resists—identical or different chemical behavior?" *Proc. SPIE* **3333**, 1452–1457 (1998); A. Uhl, J. Bendig, U. A. Jagdhold, and J. J. Bauer, "DUV and e-beam chemistry of high-sensitivity positive PMMA-based resist," *Proc. SPIE* **3678**, 1381–1387 (1999); A. Uhl, J. Bendig, J. Leistner, et al., "Nonstatistical degradation and development characteristics of poly(methylmethacrylate) based resists during electron beam exposure," *J. Vac. Sci. Tech. B* **16**(6), 2968–2973 (1998); R. B. Fox, L. G. Isaacs, and S. Stokes, "Photolytic degradation of poly(methyl methacrylate)," *J. Polymer Sci.* **1**(Pt. A), 1079–1086 (1963).
 19. R. L. Brainard, P. Trefonas, J. H. Lammers, et al., "Shot noise, LER, and quantum efficiency of EUV photoresists," *Proc. SPIE* **5374**, 74–85 (2004).
 20. C. M. Berger and C. L. Henderson, "Chemically amplified photoresist characterization using interdigitated electrodes: an improved method for determining the Dill C parameter," *Proc. SPIE* **5376**, 995–1006 (2004).
 21. B. L. Henke, E. M. Gullikson, and J. C. Davis, "X-ray interactions: photoabsorption, scattering, transmission, and reflection at $E = 50\text{--}30,000$ eV, $Z = 1\text{--}92$," *Atomic Data & Nucl. Data Tables* **54**, 181–342 (1993).
 22. The "X-Ray Interaction with Matter" website (http://www-cxro.lbl.gov/optical_constants/filter2.html) has an algorithm for calculating the absorption of EUV by thin films.
 23. Mansfield et al. did not specifically name the absorption value (B-parameter) determined at 37.5-nm light for PMMA, but did state that the C-parameter at this wavelength was determined as a ratio of the B/C constants because the volumetric sensitivity was a constant.

24. K. Early, D. M. Tennant, D. Y. Jeon, et al., "Characterization of AZ PN114 resist for a soft-x-ray projection lithography," *Appl. Opt.* **32**(34), 7044–7049 (1993).
25. K. Early, D. M. Tennant, D. Y. Jeon, et al., "Characterization of AZ PN114 resist for high resolution using electron-beam and soft-x-ray projection lithographies," *J. Vac. Sci. Tech. B* **10**(6), 2600–2605 (1992).
26. J. Grimm, J. Chlebek, T. Schulz, and H. L. Huber, "The influence of post-exposure bake on linewidth control for the resist system RAY-PN (AZ PN 100) in x-ray mask fabrication," *J. Vac. Sci. Tech. B* **9**(6), 3392–3398 (1991); R. Dammel, K. F. Doessel, J. Lingnau, et al., "Negative-tone high-resolution photocatalytic resist for x-ray lithography," *Microelec. Eng.* **9**(1–4), 575–578 (1989); S. Pongratz, R. Demmeler, C. Ehrlich, et al., "Electron-beam application of highly sensitive positive and negative-tone resists for x-ray mask making," *Proc. SPIE* **1089**, 303–316 (1989); C. Eckes, G. Pawlowski, K. Przybilla, et al., "Process latitude for the chemical amplification resists AZ PF514 and AZ PN114," *Proc. SPIE* **1466**, 394–407 (1991).
27. G. D. Kubiak, D. A. Tichenor, W. W. Chow, W. C. Sweatt, and M. D. Himel, "Resist performance in soft x-ray projection lithography," *Proc. SPIE* **1924**, 18–29 (1993).
28. O. R. Wood II, J. E. Bjorkholm, K. F. Dreyer, et al., "Experiments and simulations of EUV lithographic resist patterning at wavelengths from 7 to 40 nm," in *OSA Proc. Extreme Ultraviolet Lithogr., Proc. Top. Meet. 1994*, pp. 83–88 (1995).
29. O. R. Wood II, J. E. Bjorkholm, L. Fetter, et al., "Wavelength dependence of the resist sidewall angle in extreme ultraviolet lithography," *J. Vac. Sci. Tech. B* **12**(6), 3841–3845 (1994).
30. O. R. Wood II, W. T. Silfvast, and T. E. Jewell, "Short-wavelength annular-field optical system for imaging tenth-micron features," *J. Vac. Sci. Tech. B* **7**(6), 1613–1615 (1989).
31. W. R. Hunter, "Design criteria for reflection polarizers and analyzers in the vacuum ultraviolet" *Applied Optics* **17**(8), 1259–1270 (1978).
32. G. D. Kubiak, E. M. Kneidler, R. Q. Hwang, et al., "Characterization of chemically amplified resists for soft x-ray projection lithography," *J. Vac. Sci. Tech. B* **10**(6), 2593–2599 (1992).
33. R. L. Brainard, G. G. Barclay, E. H. Anderson, and L. E. Ocola, "Resists for next generation lithography," *Microelec. Eng.* **61–62**, 707–715 (2002).
34. N. N. Matsuzawa, H. Oizumi, S. Mori, et al., "Theoretical calculation of photoabsorption of various polymers in an extreme ultraviolet region," *Japan. J. Appl. Phys. Pt. 1* **38**(12B), 7109–7113 (1999).
35. N. N. Matsuzawa, H. Oizumi, S. Mori, et al., "Theoretical estimation of absorption coefficients of various polymers at 13 nm," *Microelec. Eng.* **53**(1–4), 671–674 (2000).
36. N. N. Matsuzawa, S. Irie, E. Yano, S. Okazaki, and A. Ishitani, "Theoretical calculations of photoabsorption of polymers in the EUV (extreme ultraviolet) region," *Proc. SPIE* **4343**, 278–284 (2001).

37. J. Bicerano, *Predictions of the Properties of Polymers from Their Structures*, Marcel Dekker, New York (1993).
38. H. Gokan, S. Esho, and Y. Ohnishi, "Dry etch resistance of organic materials," *J. Electrochem. Soc.* **130**(1), 143–146 (1983).
39. S. Irie, M. Endo, M. Sasago, et al., "Study of transmittance of polymers and influence of photoacid generator on resist transmittance at extreme ultraviolet wavelength," *Japan. J. Appl. Phys. Pt. 1* **41**(9), 5864–5867 (2002).
40. S. Irie, M. Endo, M. Sasago, et al., "Measurement of resist transmittance at extreme ultraviolet wavelength using the extreme ultraviolet reflectometer," *Japan. J. Appl. Phys. Pt. 1* **41**(6A), 4027–4030 (2002).
41. M. Chandhok, H. Cao, Y. Wang, et al., "Techniques for directly measuring the absorbance of photoresists at EUV wavelengths," *Proc. SPIE* **5374**, 861–868 (2004).
42. M. Chandrock and R. L. Brainard, EUV-2D absorption poster presented at the 2003 EUV Symposium, Antwerp.
43. R. L. Brainard, C. Henderson, J. Cobb, et al., "Comparison of the lithographic properties of positive resists upon exposure to deep- and extreme-ultraviolet radiation," *J. Vac. Sci. Tech. B* **17**(6), 3384–3389 (1999).
44. G. N. Taylor, L. E. Stillwagon, and T. Venkatesan, "Gas-phase-functionalized plasma-developed resists: initial concepts and results for electron-beam exposure," *J. Electrochem. Soc.* **131**, 1658–1664 (1984).
45. G. N. Taylor, R. S. Hutton, D. L. Windt, and W. M. Mansfield, "Resist schemes for soft x-ray lithography," *Proc. SPIE* **1343**, 258–273 (1990).
46. For a typical focus budget, circuit topography is allocated $\sim 20\%$ of the total focus budget (see H. J. Levinson, *Principles of Lithography, Second Edition*, Chapter 2, pp. 33–43, SPIE Press, Bellingham, WA, 2005). For 0.25 NA at EUV, the Rayleigh DOF $\approx 0.5 \times (l/NA^2) \approx \pm 108$ nm. This yields ~ 200 nm total focus range, which would place a topography top limit of ~ 40 nm for first-generation EUV, assuming that scaling of all contributors to total focus budget is equal (T. I. Wallow, personal communication).
47. D. A. Tichenor, G. D. Kubiak, M. E. Malinowski, et al., "Development of a laboratory extreme-ultraviolet lithography tool," *Proc. SPIE* **2194**, 95–105 (1994).
48. M. Ryoo, S. Shirayone, E. Yano, S. Okazaki, and S. Kang, "Imaging results for resist films exposed to EUV radiation," *Microelec. Eng.* **61–62**, 723–728 (2002).
49. T. Wallow, A. Acheta, Y. Ma, A. Pawloski, S. Bell, B. Ward, C. Tabery, B. La Fontaine, R. Kim, S. McGowan, and H. Levinson, "Line-edge roughness in 193-nm resists: Lithographic aspects and etch transfer," *Proc. SPIE* **6519**, 651919/1–651919/6 (2007).
50. P. K. Montgomery, R. Peters, C. Garza, Sr., et al., "Reduction of line edge roughness and post resist trim pattern collapse for sub 60 nm gate patterns using gas-phase resist fluorination," *Proc. SPIE* **5753**, 1024–1033 (2005).

51. J. L. Cobb, S. Rauf, A. Thean, et al., "Controlling line-edge roughness to within reasonable limits," *Proc. SPIE* **5039**, 376–383 (2003).
52. J. M. Calvert, T. S. Koloski, W. J. Dressick, et al., "Soft x-ray (14 nm) lithography with ultrathin imaging layers and selective electroless metallization," *Proc. SPIE* **1924**, 30–41 (1993).
53. S. W. J. Kuan, C. W. Frank, Y. H. Y. Lee, et al., "Ultrathin polymer films for microlithography," *J. Vac. Sci. Technol. B* **6**(6), 2274–2279 (1988); K. P. Muller and H. S. Sachdev, "Defect studies on single and bilayer resist systems," *J. Vac. Sci. Technol. B* **10**, 2560–2564 (1992); R. R. Kunz, T. M. Bloomstein, D. E. Hardy, et al., "Outlook for 157-nm resist design," *Proc. SPIE* **3678**, 13–23 (1999).
54. U. Okoroanyanwu, J. Cobb, P. Dentinger, et al., "Defects and metrology of ultrathin resist films," *Proc. SPIE* **3998**, 515–526 (2000).
55. V. Rao, J. L. Cobb, C. C. Henderson, et al., "Ultrathin photoresists for EUV lithography," *Proc. SPIE* **3676**, 615–626 (1999).
56. G. F. Cardinale, "Pattern transfer of sub-100-nm features in polysilicon using a single-layer photoresist and extreme ultraviolet lithography," *Proc. SPIE* **3999**, 413–422 (2000).
57. C. Pike, S. Bell, C. Lyons, M. Plat, H. Levinson, and U. Okoroanyanwu, "Lithography using ultrathin resist films," *J. Vac. Sci. Tech. B* **18**(6), 3360–3363 (2000).
58. J. L. Cobb, W. Conley, T. Guenther, et al., "Integration of ultrathin resist processes into MPU IC manufacturing flows," *Proc. SPIE* **4345**, 261–272 (2001).
59. J. L. Cobb, R. L. Brainard, D. J. O'Connell, and P. M. Dentinger, "EUV lithography: patterning to the end of the road," *Mat. Res. Soc. Symp. Proc.* **705**, 91–100 (2002).
60. H. Ito, G. Breyta, D. Hofer, et al., "Environmentally stable chemical amplification positive resist: principle, chemistry, contamination resistance and lithographic feasibility," *J. Photopolymer Sci. Tech.* **7**(3), 433–447 (1994).
61. The two tools used at SNL for resist evaluation (10×1 and 10×2) were in operation from 1998 to 2004. These tools had NAs of 0.088.
62. Dose calibration for several tools were defined based on printing 100-nm dense-line sizing dose ($E_{\text{size}} = 6.8 \text{ mJ/cm}^2$) of EUV-2D (XP98248B) using 125-nm-thick films coated over primed silicon wafers, soft bake = $130^\circ\text{C}/60 \text{ s}$, PEB = $130^\circ\text{C}/90 \text{ s}$, and 45 s development in CD-26 developer at room temperature.
63. T. Kozawa, S. Nagahara, Y. Yoshida, et al., "Radiation-induced reactions of chemically amplified x-ray and electron-beam resists based on deprotection of t-butoxycarbonyl groups," *J. Vac. Sci. Technol. B* **15**, 2582–2586 (1997); T. Kozawa, Y. Yoshida, M. Uesaka, and S. Tagawa, "Radiation-induced acid generation reactions in chemically amplified resists for electron-beam and x-ray lithography," *Japan. J. Appl. Phys. Pt. 1* **32**, 4301–4306 (1992).

64. C. R. Szmanda, R. L. Brainard, J. F. Mackevich, et al., "Measuring acid generation efficiency in chemically amplified resists with all three beams," *J. Vac. Sci. Tech. B* **17**(6), 3356–3361 (1999).
65. T. Koehler, R. L. Brainard, P. P. Naulleau, et al., "Performance of EUV photoresists on the ALS micro exposure tool," *Proc. SPIE* **5753**, 754–764 (2005).
66. D. van Steenwinckel, J. H. Lammers, T. Koehler, R. L. Brainard, and P. Trefonas, "Resist effects at small pitches," *J. Vac. Sci. Tech. B* **24**(1), 316–320 (2006).
67. C. A. Cutler, J. F. Mackevich, J. Li, et al., "Effect of polymer molecular weight on AFM polymer aggregate size and LER of EUV resists," *Proc. SPIE* **5037**, 406–417 (2003).
68. J. P. Cain, P. Naulleau, E. Gullikson, C. Spanos, "Lithographic characterization of the flare in the Berkeley 0.3 numerical aperture extreme ultraviolet microfield optic," *J. Vac. Sci. Tech. B* **24**(3), 1234–1237 (2006).
69. W. D. Hinsberg, F. A. Houle, M. I. Sanchez, et al., "Extendibility of chemically amplified resists: another brick wall?" *Proc. SPIE* **5039**, 1–14 (2003).
70. W. D. Hinsberg, F. A. Houle, J. A. Hoffnagle, et al., "Chemistry and physics of the post-exposure bake process in a chemically amplified resist," *Microlith. World* **9**(2), 16–22 (2000).
71. V. N. Golovkina, P. F. Nealey, F. Cerrina, et al., "Exploring the ultimate resolution of positive-tone chemically amplified resists: 26 nm dense lines using extreme ultraviolet interference lithography," *J. Vac. Sci. Tech. B* **22**(1), 99–103 (2004).
72. J. M. Roberts, R. Meagley, T. H. Fedynyshyn, et al., "Contributions to innate material roughness in resist," *Proc. SPIE* **6153**, 61533U/1–61533U/11 (2006).
73. A. Jouve, J. Simon, J. Foucher, et al., "Overcoming pattern collapse of ultra high resolution dense lines obtained with EUV resists," *Proc. SPIE* **5753**, 720–731 (2005).
74. G. M. Wallraff, D. R. Medeiros, C. E. Larson, et al., "Studies of acid diffusion in low Ea chemically amplified photoresists," *Proc. SPIE* **5753**, 309–318 (2005).
75. G. M. Wallraff, D. R. Medeiros, M. Sanchez, et al., "Sub-50 nm half-pitch imaging with a low activation energy chemically amplified photoresist," *J. Vac. Sci. Tech. B* **22**(6), 3479–4023 (2004).
76. S. D. Burns, D. R. Medeiros, H. F. Johnson, et al., "Effect of humidity on deprotection kinetics in chemically amplified resists," *Proc. SPIE* **4690**, 321–331 (2002).
77. P. Naulleau, J. P. Cain, E. Anderson, et al., "Characterization of the synchrotron-based 0.3 numerical aperture extreme ultraviolet microexposure tool at the advanced light source," *J. Vac. Sci. Tech. B* **23**(6), 2840–2843 (2005).
78. M. D. Shumway, E. L. Snow, K. A. Goldberg, et al., "EUV resist imaging below 50 nm using coherent spatial filtering techniques," *Proc. SPIE* **5374**, 454–

- 459 (2004); M. D. Shumway, S. H. Lee, C. H. Cho, et al., "Extremely fine-pitch printing with a $10\times$ Schwarzschild optic at extreme-ultraviolet wavelengths," *Proc. SPIE* **4343**, 357–362 (2001); H. H. Solak, D. He, W. Li, and F. Cerrina, "Nanolithography using extreme ultraviolet lithography interferometry: 19 nm lines and spaces," *J. Vac. Sci. Tech. B* **17**(6), 3052–3057 (1999); H. H. Solak, D. He, W. Li, et al., "EUV interferometric lithography for resist characterization," *Proc. SPIE* **3676**, 278–282 (1999).
79. S. Yasin, D. G. Hasko, and H. Ahmed, "Fabrication of <5 nm width lines in poly(methyl methacrylate) resist using a water: isopropyl alcohol developer and ultrasonically-assisted development," *Appl. Phys. Lett.* **78**, 2760–2762 (2001); S. Yasin, D. G. Hasko, and H. Ahmed, "Comparison of MIBK/IPA and water/IPA as PMMA developers for electron beam nanolithography," *Microelectron. Eng.* **61–62**, 745–753 (2002).
80. H. H. Solak, Y. Ekinici, P. Kaser, and S. Park, "Photon-beam lithography reaches 12.5 nm half-pitch resolution," *J. Vac. Sci. Tech. B* **25**(1), 91–95 (2007).
81. R. Gronheid, H. H. Solak, Y. Ekinici, A. Jouve, and F. van Roey, "Characterization of extreme ultraviolet resists with interference lithography," *Microelec. Eng.* **83**(4–9), 1103–1106 (2006).
82. K. Kojima, T. Hattori, H. Fukuda, et al., "Negative-tone polyphenol resist based on chemically amplified polarity change reaction with sub-50 nm resolution capability," *Proc. SPIE* **6153**, 1–8 (2006).
83. K. Kyoko, M. Shigeki, S. Daiju, H. Hideo, and J. Onodera, "Material design of negative-tone polyphenol resist for EUV and EB lithography," *Proc. SPIE* **6519**, 65193U/1–65193U/6 (2007).
84. H. Oizumi, et al., "Lithographic performance of high-numerical-aperture ($NA = 0.3$) EUV small-field exposure tool (HINA)," *Proc. SPIE* **5751**, 102–109 (2005).
85. J. Fujita, Y. Ohnishi, Y. Ochiai, and S. Matsui, "Ultrahigh resolution of calixarene negative resist in electron beam lithography," *Appl. Phys. Lett.* **68**, 1297–1299 (1996); M. Ishida, J. Fujita, T. Ogura, et al., "Sub-10-nm-scale lithography using p-chloromethyl-methoxy-calix[4]arene resist," *Japan. J. Appl. Phys. Pt. 1* **42**, 3913–3916 (2003); S. Hosaka, H. Sano, K. Itoh, and H. Sone, "Possibility to form an ultrahigh packed fine pit and dot arrays for future storage using electron-beam writing," *Microelec. Eng.* **83**, 792–795 (2006).
86. S. J. Holder, R. G. Jones, and J. J. Murphy, "Evaluation of halomethylated poly(methylphenylsilane)s as electron-beam resists," *J. Mat. Chem.* **7**(9), 1701–1707 (1997).
87. K. Tanigaki, M. Suzuki, Y. Saotome, Y. Ohnishi, and K. Tateishi, "Radiation-induced reactions of chloromethylstyrene-based resist materials analyzed from radiolysis of low molecular model compounds," *J. Electrochem. Soc.* **132**(7), 1678–1683 (1985).

88. M. J. Loboda, C. M. Grove, and R. F. Schneider, "Properties of a-SiO_x:H thin films deposited from hydrogen silsesquioxane resins," *J. Electrochem. Soc.* **145**(8), 2861–2866 (1998).
89. I. Junarsa, M. P. Stoykovich, P. F. Nealey, et al., "Hydrogen silsesquioxane as a high resolution negative-tone resist for extreme ultraviolet lithography," *J. Vac. Sci. Tech. B* **23**(1), 138–143 (2005).
90. H. Namatsu, Y. Takahashi, K. Yamazaki, et al., "Three-dimensional siloxane resist for the formation of nano-patterns with minimum linewidth fluctuations," *J. Vac. Sci. Tech. B* **16**, 69–76 (1998).
91. Y. Ekinici, H. H. Solak, C. Padeste, et al., "20 nm line/space patterns in HSQ fabricated by EUV interference lithography," *Microelec. Eng.* **84**(5–8), 700–704 (2007).
92. The dose to the wafer is typically three times less than the dose to the mask on the PSI interference tool (H. Solak, unpublished results).
93. C. R. Kessel, L. D. Boardman, S. J. Rhyner, et al., "Novel silicon-containing resists for EUV and 193-nm lithography," *Proc. SPIE* **3678**, 214–220 (1999).
94. D. A. Tichenor, G. D. Kubiak, and R. H. Stulen, "Extreme ultraviolet lithography for circuit fabrication at 0.1 mm feature size," *Proc. SPIE* **2523**, 23–28 (1995), and references therein.
95. J. Dai, C. K. Ober, S.-O. Kim, et al., "Synthesis and evaluation of novel organo-element resists for EUV lithography," *Proc. SPIE* **5039**, 1164–1172 (2003).
96. J. Dai, C. K. Ober, L. Wang, F. Cerrina, and P. F. Nealey, "Organoelement resists for EUV lithography," *Proc. SPIE* **4690**, 1193–1202 (2002).
97. Y. J. Kwark, J. P. Bravo-Vasquez, C. K. Ober, et al., "Novel silicon-containing polymers as photoresist materials for EUV lithography," *Proc. SPIE* **5039**, 1204–1211 (2003).
98. J. Dai and C. K. Ober, "Novel resists with non-traditional compositions for EUV lithography," *Proc. SPIE* **5376**, 508–516 (2004).
99. Transmittance at 13.4 nm was calculated assuming a density = 1.0. The actual transparency was probably lower since typical densities for resists are somewhat higher.
100. K. E. Mueller, W. J. Koros, C. A. Mack, and C. G. Willson, "Diffusivity measurements in polymers, part IV: acid diffusion in chemically amplified resists," *Proc. SPIE* **3049**, 706–711 (1997).
101. G. M. Schmid, M. D. Stewart, C.-Y. Wang, et al., "Resolution limitations in chemically amplified photoresist systems," *Proc. SPIE* **5376**, 333–342 (2004).
102. M. D. Stewart, H. V. Tran, G. M. Schmid, et al., "Acid catalyst mobility in resist resins," *J. Vac. Sci. Tech. B: Microelec. Nan. Struct.* **20**(6), 2946–2952 (2002).
103. M. D. Stewart, M. H. Somervell, H. V. Tran, S. V. Postnikov, and C. G. Willson, "Study of acid transport using IR spectroscopy and SEM," *Proc. SPIE* **3999**, 665–674 (2000).

104. P. L. Zhang, A. R. Eckert, C. G. Willson, S. E. Webber, and J. Byers, "Acid diffusion through polymer films," *Proc. SPIE* **3049**, 898–909 (1997).
105. F. A. Houle, W. D. Hinsberg, and M. I. Sanchez, "Acid-base reactions in a positive tone chemically amplified photoresist and their effect on imaging," *J. Vac. Sci. Tech. B* **22**(2), 747–757 (2004).
106. F. A. Houle, W. D. Hinsberg, M. I. Sanchez, and J. A. Hoffnagle, "Influence of resist components on image blur in a patterned positive-tone chemically amplified photoresist," *J. Vac. Sci. Tech. B* **20**(3), 924–931 (2002).
107. F. A. Houle, W. D. Hinsberg, M. Morrison, et al., "Determination of coupled acid catalysis-diffusion processes in a positive-tone chemically amplified photoresist," *J. Vac. Sci. Tech. B* **18**(4), 1874–1885 (2000).
108. W. Hinsberg, et al., "Reactive dissolution kinetics of lithographic copolymers," *Proc. SPIE* **5376**, 352–359 (2004).
109. K. E. Gonsalves, M. Thiagarajan, and K. Dean, "Newly developed polymer bound photoacid generator resist for sub-100-nm pattern by EUV lithography," *Proc. SPIE* **5753**, 771–777 (2005).
110. K. E. Gonsalves, M. Thiagarajan, and K. Dean, "New resists for nanometer scale patterning by extreme ultraviolet lithography," *J. Microlith. Microfab. Microsyst.* **4**(2), 029701/1–029701/6 (2005).
111. M. Thiagarajan, K. E. Gonsalves, K. Dean, and E. C. H. Sykes, "Design and performance of EUV resist containing photoacid generator for sub-100 nm lithography," *J. Nanosci. Nanotech.* **5**(7), 1181–1183 (2005).
112. T. Watanabe, H. Hada, S. Y. Lee, et al., "Development of fast-photospeed chemically amplified resist in extreme ultraviolet lithography," *Japan. J. Appl. Phys. Pt. 1* **44**(7B), 5866–5870 (2005).
113. S. P. Pappas, B. C. Pappas, L. R. Gatechair, and W. Schnabel, "Photoinitiation of cationic polymerization. II. Laser flash photolysis of diphenyliodonium salts," *J. Polymer Sci.* **22**(1), 69–76 (1984).
114. J. L. Dektar and N. P. Hacker, "Photochemistry of triarylsulfonium salts," *J. Amer. Chem. Soc.* **112**(16), 6004–6015 (1990); J. L. Dektar and N. P. Hacker, "Photochemistry of diaryliodonium salts," *J. Org. Chem.* **55**(2), 639–647 (1990).
115. J. F. Cameron, N. Chan, K. Moore, and G. Pohlers, "Comparison of acid-generating efficiencies in 248 and 193-nm photoresists," *Proc. SPIE* **4345**, 106–118 (2001).
116. N. P. Hacker, D. C. Hofer, and K. M. Welsh, "Photochemical and photophysical studies on chemically amplified resists," *J. Photopolymer Sci. Tech.* **5**(1), 35–46 (1992); K. M. Welsh, J. L. Dektar, M. A. Garcia-Garibaya, N. P. Hacker, and N. J. Turro, "Photo-CIDNP and nanosecond laser flash photolysis studies on the photodecomposition of triarylsulfonium salts," *J. Org. Chem.* **57**(15), 4179–4184 (1992).
117. T. Kozawa and S. Tagawa, "Basic aspects of acid generation processes in chemically amplified resists for electron beam lithography," *Proc. SPIE* **5753**, 361–367 (2005); T. Kozawa and S. Tagawa, "Basic aspects of acid generation

- processes in chemically amplified electron beam resist,” *J. Photopoly. Sci. Tech.* **18**(4), 471–474 (2005).
118. S. Tagawa, S. Nagahara, T. Iwamoto, et al., “Radiation and photochemistry of onium salt acid generators in chemically amplified resists,” *Proc. SPIE* **3999**, 204–213 (2000).
119. A. Nakano, K. Okamoto, Y. Yamamoto, et al., “Deprotonation mechanism of poly(4-hydroxystyrene) and its derivative,” *Proc. SPIE* **5753**, 1034–1039 (2005).
120. T. Kozawa, A. Saeki, and S. Tagawa, “Modeling and simulation of chemically amplified electron beam, x-ray, and EUV resist processes,” *J. Vac. Sci. Tech. B* **22**(6), 3489–3492 (2004).
121. H. Yamamoto, T. Kozawa, A. Nakano, et al., “Dependence of acid generation efficiency on the protection ratio of hydroxyl groups in chemically amplified electron beam, x-ray and EUV resists,” *J. Vac. Sci. Tech. B* **22**(6), 3522–3524 (2004).
122. T. Kozawa, A. Saeki, A. Nakano, Y. Yoshida, and S. Tagawa, “Relation between spatial resolution and reaction mechanism of chemically amplified resists for electron beam lithography,” *J. Vac. Sci. Tech. B* **21**(6), 3149–3152 (2003).
123. T. Itani, H. Yoshino, S. Hashimoto, et al., “Acid and base diffusion in chemically amplified DUV resists,” *Microelec. Eng.* **35**, 149–152 (1997).
124. T. Itani, H. Yoshino, and M. Fujimoto, “Photoacid bulkiness effect on dissolution kinetics in chemically amplified deep ultraviolet resists,” *J. Vac. Sci. Tech. B* **13**(6), 3026–3029 (1995).
125. T. Yoshimura, H. Shiraishi, J. Yamamoto, and S. Okazaki, “Correlation of nano edge roughness in resist patterns with base polymers,” *Japan. J. Appl. Phys.* **32**, 6065–6070 (1993).
126. T. Itani, H. Yoshino, S. Hashimoto, et al., “Polymer structure effect on dissolution characteristics and acid diffusion in chemically amplified deep ultraviolet resists,” *J. Vac. Sci. Tech. B* **15**(6), 2541–2544 (1997).
127. J. M. Hutchinson, “Shot noise impact on resist roughness in EUV lithography,” *Proc. SPIE* **3331**, 531–536 (1998).
128. N. Rau, F. Stratton, C. Fields, et al., “Shot-noise and edge roughness effects in resists patterned at 10 nm exposure,” *J. Vac. Sci. Tech. B* **16**(6), 3784–3788 (1998).
129. S. Mori, T. Morisawa, N. Matsuzawa, et al., “Reduction of line edge roughness in the top surface imaging process,” *J. Vac. Sci. Tech. B* **16**(6), 3739–3743 (1998); W. Hinsberg, F. Houle, G. Wallraff, et al., “Factors controlling pattern formation in chemically amplified resists at sub-100 nm dimensions,” *J. Photopolymer Sci. Tech.* **12**(4), 649–662 (1999).

130. V. Rao, J. Hutchinson, S. Holl, et al., "Top surface imaging process and materials development for 193 nm and extreme ultraviolet lithography," *J. Vac. Sci. Tech. B* **16**(6), 3722–3725 (1998).
131. S. Mori, N. Matsuzawa, Y. Kaimoto, et al., "Study of high photo-speed top surface imaging process using chemically amplified resist," *J. Photopolymer Sci. Tech.* **11**(4), 613–618 (1998).
132. H. Namatsu, M. Nagase, T. Yamaguchi, K. Yamazaki, and K. Kurihara, "Influence of edge roughness in resist patterns on etched patterns," *J. Vac. Sci. Tech. B* **16**(6), 3315–3321 (1998).
133. T. Yamaguchi, H. Namatsu, M. Nagase, K. Kurihara, and Y. Kawai, "Line-edge roughness characterized by polymer aggregates in photoresists," *Proc. SPIE* **3678**, 617–624 (1999).
134. T. Yamaguchi, H. Namatsu, M. Nagase, K. Yamazaki, and K. Kurihara, "Nanometer-scale linewidth fluctuations caused by polymer aggregates in resist films," *Appl. Phys. Lett.* **71**(16), 2388–2390 (1997).
135. In rounds 2, 3, and 4, the 9K-polymer resist was the same in all three rounds and an EUV-2D control resist was imaged in-between each round at EUV to monitor imaging consistency within the three rounds. It was found that the combined uncertainty, taking into account the variation in the $\times 10$ stepper over four days of imaging and SEM instrumentation, was approximately ± 1.6 nm.
136. A. R. Neureuther and C. G. Willson, "Reduction in x-ray lithography shot noise exposure limit by dissolution phenomena," *J. Vac. Sci. Tech. B* **6**(1), 167–173 (1988).
137. S. C. O'Brien and M. E. Mason, "Exposure latitude requirements for high yield with photon flux-limited laser sources," *Proc. SPIE* **4346**, 534–543 (2001).
138. J. Cobb, F. Houle, and G. Gallatin, "Estimated impact of shot noise in extreme-ultraviolet lithography," *Proc. SPIE* **5037**, 397–405 (2003).
139. S. H. Lee, R. Bristol, and J. Bjorkholm, "Shot noise and process window study for printing small contact holes using EUV lithography," *Proc. SPIE* **5037**, 890–899 (2003).
140. P. M. Dentinger, L. L. Hunter, D. J. O'Connell, et al., "Photospeed considerations for extreme ultraviolet lithography resists," *J. Vac. Sci. Tech. B* **20**(6), 2962–2967 (2002).
141. C. R. Szmanda, et al., "Simple method for measuring acid generation quantum efficiency at 193 nm," *Proc. SPIE* **3678**, 857–866 (1999).
142. Quantum efficiencies greater than 1 for photoacid generation have previously been reported by T. H. Fedynyshyn, R. F. Sinta, W. A. Mowers, and A. Cabral, "Quantum efficiency of PAG decomposition in different polymer matrices at advanced lithographic wavelengths," *Proc. SPIE* **5039**, 310–321 (2003).
143. Critical Issues List from the 2007 EUV Symposium in Sapporo, Japan.



Robert Brainard received his BS in chemistry from the University of California, Berkeley, and his PhD from the Massachusetts Institute of Technology in 1985, following his graduate studies with Prof. George Whitesides. Following his postdoctoral studies with Prof. Robert Madix at Stanford University, he worked for Polaroid (1987–1990) and Shipley/RHEM (1990–2005) in the areas of color filter DUV, EUV, e-beam, and x-ray photoresists. Robert is now an Associate Professor at the College of Nanoscale Science and Engineering, investigating new materials for use in EUV and 193-nm lithography. His specific research interests include EUV photoresist exposure mechanisms, high quantum efficiency EUV photoresists, the chemistry of thin films, and acid amplifiers.

Chapter 9

High-Resolution EUV Imaging Tools for Resist Exposure and Aerial Image Monitoring

Malcolm Gower

Contents

9.1	Introduction	450
9.2	EUV Tool Design Considerations	450
9.3	EUV Microstepper	453
9.3.1	MS-13 tool concept	453
9.3.2	EUV source	453
9.3.3	EUV optics	453
9.3.3.1	EUV imaging objective	453
9.3.3.2	EUV collection and illumination system	455
9.3.4	Tool subsystems	459
9.3.4.1	Tool body and platform	459
9.3.4.2	Reticle-objective-wafer mounting assembly	459
9.3.4.3	Wafer and reticle stages	459
9.3.4.4	Wafer and reticle chucks	461
9.3.4.5	Wafer and reticle loading	461
9.3.4.6	EUV radiation monitoring	463
9.3.4.7	Vacuum system and control	464
9.3.4.8	Tool control	464
9.3.4.9	Tool enclosure	466
9.3.4.10	Tool assembly	466
9.3.5	Tool subsystems testing	467
9.3.5.1	Vacuum conditions	467
9.3.5.2	Autofocus repeatability	467
9.3.5.3	Illumination uniformity	468
9.3.5.4	Exposure dose control	469
9.3.6	Resist exposure results	470
9.4	Reticle Imaging Microscope	470
9.4.1	RIM-13 tool architecture	471
9.4.2	EUV source	472
9.4.3	EUV illumination	473

9.4.4 Reticle imaging	475
9.4.5 EUV microscope	475
9.4.6 Visible microscope	477
9.4.7 Tool subsystems	479
9.4.7.1 Tool core	479
9.4.7.2 Vibration isolation system	479
9.4.7.3 Reticle stages and chuck	479
9.4.7.4 Vacuum system	483
9.4.7.5 Reticle loader	483
9.4.8 EUV reticle aerial image capture results	485
9.4.9 Software	485
9.4.9.1 Interface	485
9.4.9.2 Example analysis sequence	486
9.5 Summary and Future Outlook	488
Acknowledgments	490
References	490

9.1 Introduction

Two types of high-resolution EUV imaging tools have been developed by Exitech for commercial use by the semiconductor industry. The MS-13 Microstepper is a small-field, high-resolution imaging tool designed for early learning on resist exposures at an imaging numerical aperture (NA) similar to that adopted for production scanners at the 32-nm node. This tool enables R&D in areas such as resist development and reticle defect printability.^{1,2} It also provides crucial general early learning on EUVL potential technology blockages, hardware, tool infrastructure, and the economics thereof. The first MS-13 Microstepper tools have been installed at the RP1 fab of Intel Corporation in Hillsboro, Oregon, and at the EUV Resist Test Center in the NanoFab North facility of SEMATECH North in Albany, New York. The RIM-13 is a reticle imaging actinic microscope capable of capturing aerial images from EUV reticles with illumination and imaging characteristics that emulate full-field production scanner tools. This tool, part of a joint development agreement (JDA) between Exitech and SEMATECH, fulfills an essential requirement for actinic inspection and printability studies of amplitude and phase defects on blank and patterned EUV reticles.³

9.2 EUV Tool Design Considerations

Since all solids, liquids, and gases are highly opaque to EUV radiation at 13.5 nm, the source, beam delivery, imaging objective, reticle, wafer handling, and stages of EUV tools must all operate in a high-vacuum environment. Reflective rather than refractive optics must be used for optical beam transport, shaping, and imaging. Normal incidence mirrors are fabricated using phase-additive reflections from up to 100 layers of silicon (Si) and molybdenum (Mo) (magnetron, ion, or electron-

beam deposited), each only 3 nm, or about 15 atoms, thick. Reticles themselves must be reflective with circuit features defined by patterning a thin absorbing layer on top of the reflective multilayers (MLs). To replace the vacuum chucking methods used in more traditional atmospheric pressure deep ultraviolet (DUV) steppers, new techniques for wafer and reticle stage clamping must be developed that are compatible with an overall vacuum environment.

Because EUV radiation is aggressive at cracking most molecular species—the products of which can contaminate and erode sensitive optical coatings—any hydrocarbons or water vapor in the vacuum chamber must be minimized. This requirement means that the tool chamber must be as clean as an ultrahigh vacuum (UHV) system. Since all high-power EUV sources are currently based on plasmas (laser-produced or gas-discharge pinches), the potential for further optics contamination can also arise from the inherent heavy-particle and charged-ion debris produced by such sources. Source debris must be contained by trap arrangements and kept well away from the imaging section of the tool. This is particularly difficult since an EUV source must be engineered to be integral to the tool body rather than remote from it like an excimer laser source is with a DUV stepper. With most of their input energy converted to waste heat, incoherent EUV plasma-based sources are much less efficient radiation generators than DUV excimer lasers. If the ultimate imaging performance of the tool is to be achieved, excess heat from the source in both its radiative and conductive forms must be efficiently managed, and any source of mechanical vibration must be effectively damped. Unlike DUV tools operating at atmospheric pressure, the high-vacuum chambers required for EUV stepper operation make subsystems inaccessible for simple maintenance and servicing. A high degree of subsystem automation of appropriate vacuum, radiation, position, and motion control, together with their diagnostics, are required to maintain tool functionality and serviceability. Compared to 248-, 193-, and 157-nm DUV exposure tools, the EUV spectral region at the 13.5-nm wavelength presents many complex challenges to the exposure tool builder that require the development of entirely new engineering concepts.

As illustrated in Fig. 9.1, the architecture common to the two types of high-resolution imaging tools described in this chapter is the incorporation of a rigid, vibration-isolated, stiff structure from which the imaging objective, mask, and wafer stages are mounted in strict registration.

The tools are essentially passive to minimize potential sources of internal vibration during exposure. This passive design also minimizes thermal inputs, the effects of which are further reduced by the use of low-thermal-expansion materials such as invar and Zerodur. For EUV exposure tools, an additional design requirement is to strictly control the choice of materials used inside the vacuum chamber in order to minimize outgassing and achieve acceptable optics lifetimes in the presence of relatively large fluxes of EUV radiation.³ Masks and wafers are loaded and removed from the tools through automated load-locks from/to standard mechanical interface (SMIF) boxes and/or a wafer track. Both types of EUV tools share many common features and components. Designers of the RIM-13 EUV tool adopted a

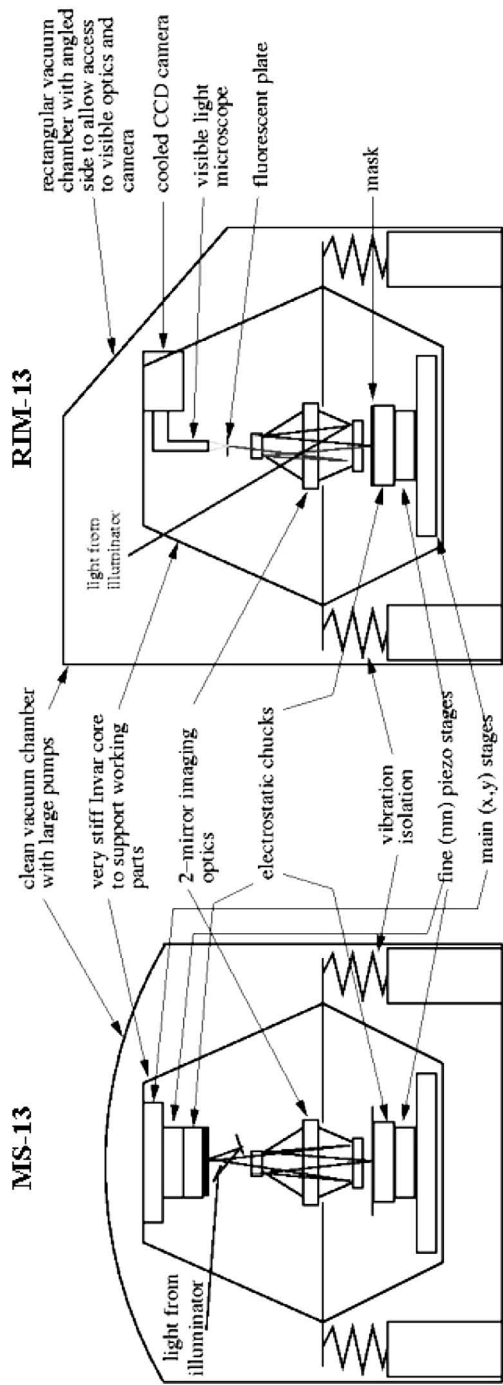


Figure 9.1 Schematic of the MS-13 and RIM-13 Microstepper architectures illustrating the similarities between the two EUV tools.

clear evolutionary path based on the lessons learned from the design, manufacturing, and operational use of the MS-13 Microstepper.

9.3 EUV Microstepper

9.3.1 MS-13 tool concept

The architecture of the MS-13 Microstepper tool developed for EUV resist testing, technology evaluation, and early learning at the 32-nm node and beyond is shown in Fig. 9.2. Operating in a step-and-repeat exposure mode, the MS-13 is capable of printing $5\times$ demagnified high-resolution features from 6-in. EUV reflective reticles onto 200- or 300-mm-diameter wafers over an image field die size of 0.6×0.2 mm. Exposure times for a 10 mJ/cm^2 sensitivity photoresist are around 0.25 sec/die. Details of the tool design architecture, module layouts, high-vacuum chamber, and major subsystems, including performance specifications, are presented in the following sections.

9.3.2 EUV source

Figure 9.3(a) shows the xenon (Xe) based discharge produced plasma (DPP) EUV source manufactured by Xtreme Technologies GmbH that is used in the MS-13. Its Z-plasma pinch electrode structure is shown in Fig. 9.3(b). At a 1-kHz repetition rate, approximately 3 kW of radiation at all wavelengths is emitted by the source into 2π sr, of which 35 W is contained within a 2% bandwidth of the EUV wavelength at 13.5 nm. Bursts of pulses with a duty cycle typically between 2 and 10% are used for resist exposures. The pulse-to-pulse stability of the EUV radiation from the source as measured at the reticle plane in the MS-13 is shown in Fig. 9.3(c). As can be seen, after relaying to the reticle by the collection and relay optics in the tool, the $3\times$ standard deviation (3σ) of the EUV pulse intensity is 18.0%.

9.3.3 EUV optics

9.3.3.1 EUV imaging objective

The 0.3-NA, $5\times$ reduction, 0.6×0.2 mm field EUV objective for the microexposure tool (MET) was designed by the EUV Limited Liability Company (EUV LLC) under a contract from SEMATECH^{4,5} and manufactured by Carl Zeiss SMT. The figure, mid- and high-spatial-frequency roughnesses (MSFR and HSFR) of sets 3 and 4 of the MET objective mirrors used in these tools were between 0.2- and 0.3-nm rms. The wavefront error of the assembled objectives after alignment was ~ 0.7 -nm rms with the single largest contribution of ~ 0.26 nm arising from astigmatism.⁶ The lens and its key parameters are shown in Fig. 9.4.

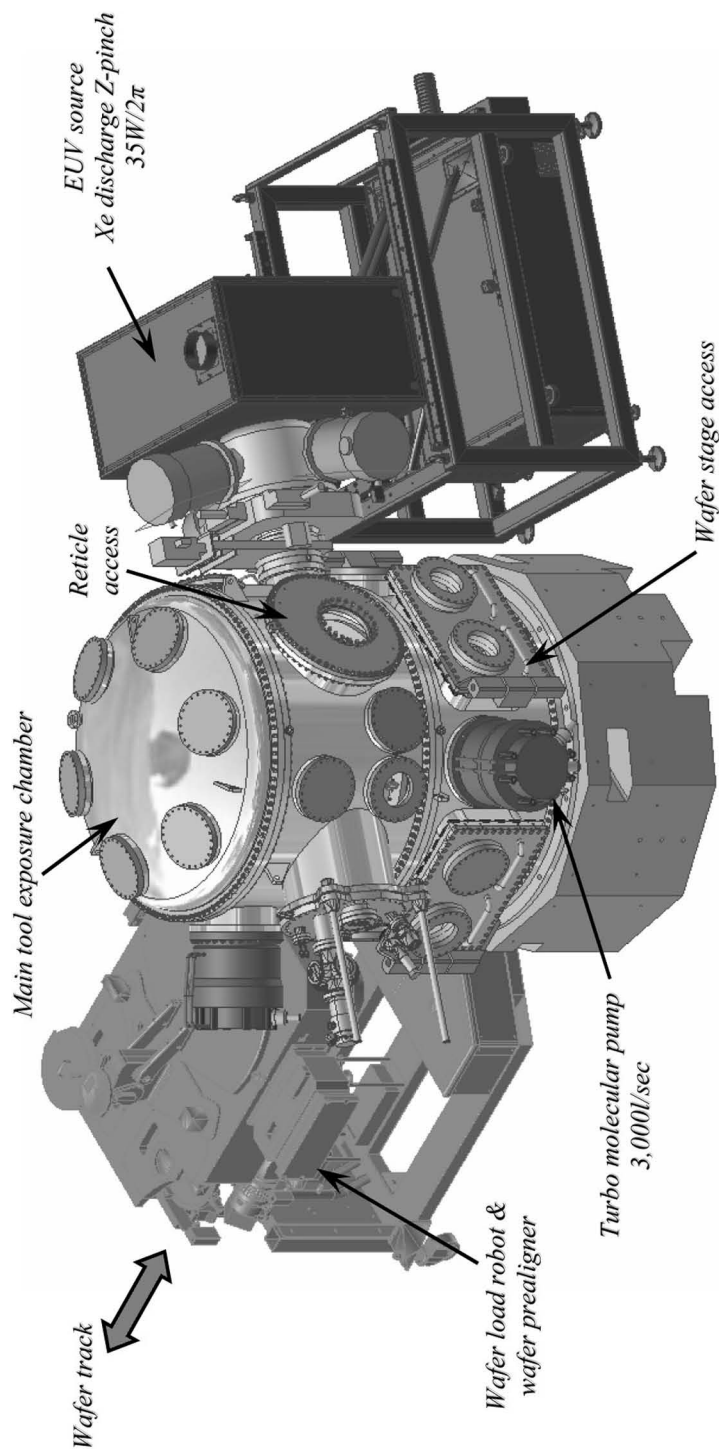


Figure 9.2 MS-13 EUV Microstepper architecture.

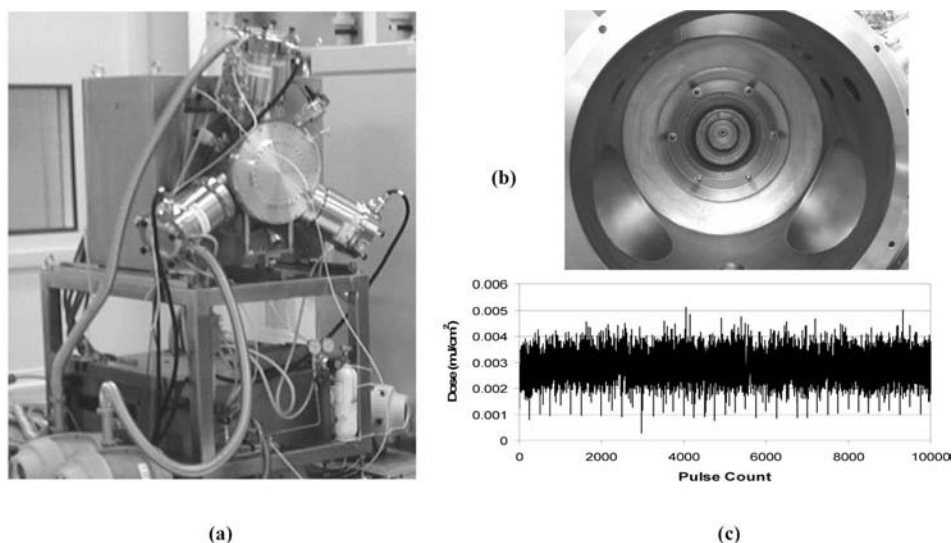


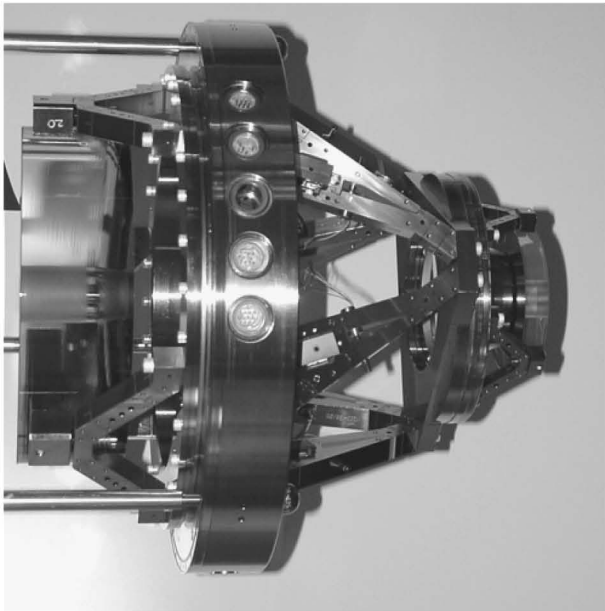
Figure 9.3 (a) EUV Z-pinch Xe gas plasma source. (b) Electrode structure of pinch. (c) Pulse-to-pulse EUV power measured for 10,000 pulses at the MS-13 reticle plane, with repetition rate = 1 kHz, 2% duty cycle, bursts of 250 pulses, and 3σ deviation is 18.0%.

9.3.3.2 EUV collection and illumination system

The quasi-critical EUV illumination system with four nested Wölter ellipsoid collector shells was also designed and manufactured by Carl Zeiss SMT⁶ and is shown in the concept layout in Fig. 9.5. A magnified defocused image of the source illuminates the reticle field plane, while a demagnified image of the output plane of the collector shells provides annular illumination of an intermediate pupil plane at which partial coherence apertures can be positioned. A demagnified image of this pupil plane is then relayed into the entrance pupil of the objective. This design allows relatively simple high-reflectivity mirrors (two spherical normal incidence and two plane folding) to be used within the beam delivery system and provides easy access to both pupil and field stop positions.

The four nested reflective collector shells that collect radiation over a solid angle of 0.55 sr from the source are shown in Fig. 9.6(a). The outer three shells are used for reticle illumination while the innermost shell provides a secondary monitor of the EUV power for dose control and source diagnostic purposes. As shown in Fig. 9.6(b), a water-cooled lamella structure mounted on the front of the collector shells is used to contain migration of particulate debris caused by electrode erosion from the plasma source.

Figure 9.7(a) shows the EUV illumination at the pupil plane taken with an off-axis CCD camera viewing the fluorescence from a scintillator screen. The EUV intensity distribution at this plane, which is a demagnified image of the collector exit plane, consists of three uniformly illuminated concentric rings that are further relayed into the entrance pupil of the centrally obscured objective. The picture in Fig. 9.7(a) shows the shadowing caused by the spider mounting structure of the



Wavelength	13.54nm. Fit to 6° CRA reticles @ 13.5nm
Numerical aperture	0.3
Form	2 mirror aspheric design
Field size at wafer	0.6 x 0.2mm
Demagnification	5x
Mag anisotropy	10 ⁻³ due to reticle tilt
Track length	474.165 mm
Wavefront error - design	≤ 0.031 rms (0.42nm)
- manufactured	< 1.0nm rms
Stray light	< 10% including DUV
Minimum CD	30nm dense lines & spaces
Usable DOF	80nm for 30nm isolated lines 150nm for 50nm dense lines
CD uniformity	< 5nm TIR
H-V bias	< 3nm
Linearity	< 12%
TFPD	< 120nm
Astigmatism	< 50nm worse point
Outgassing rates	< 10 ⁻⁵ mbar l /sec; < 10 ⁻⁷ mbar l/sec C-H

Figure 9.4 EUV MET objective.

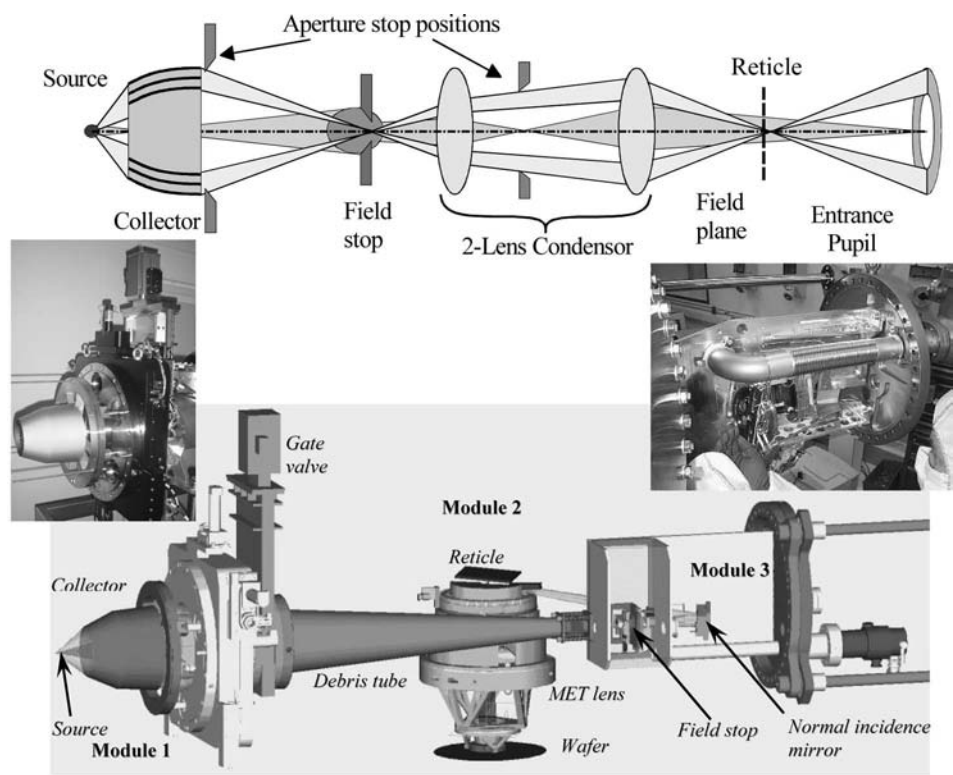


Figure 9.5 Quasi-critical EUV illumination scheme used in the MS-13. (Courtesy of Carl Zeiss SMT.)

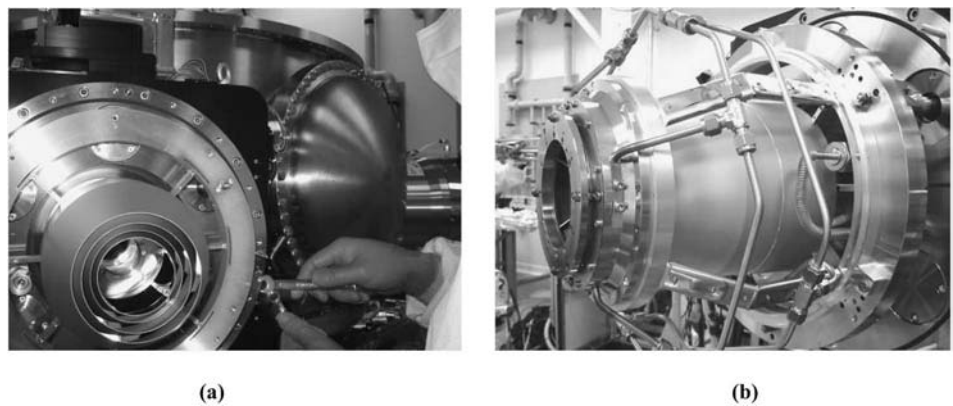


Figure 9.6 (a) Four-shell nested Wölter collector, front view. (b) Debris mitigation device mounted on collector.

collector rings, the source debris mitigation lamella structure, and obscuration by the deflection mirror used to pick off light in the inner ring used for source power monitoring. By inserting apertures at the pupil plane using the motorized wheel

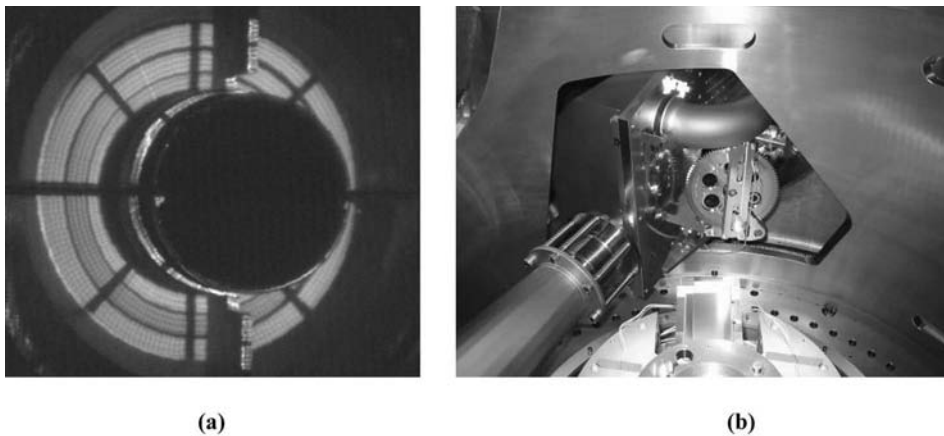


Figure 9.7 (a) EUV intensity distribution at the pupil plane. The apparent slight ring ellipticity is caused by viewing it with an off-axis camera. (b) Pupil wheel structure used to control illumination partial coherence factor.

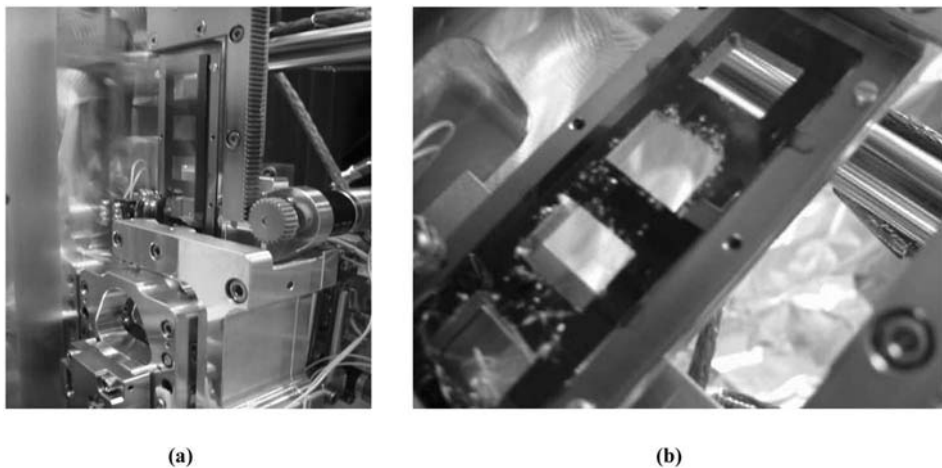


Figure 9.8 (a) Silicon membrane SPF window strip. (b) Burst SPFs caused by excessive radiation-induced thermal loading.

assembly shown in Fig. 9.7(b), the partial coherence of the tool illumination can be varied. Five of the six positional settings on the wheel can be used to provide annular, quadrupole, or dipole illumination with inner and outer coherence factors ranging between 0.36 and 0.55. An EUV scintillator screen used to monitor the pupil plane intensity distribution is located at the sixth wheel position.

A thin Si membrane spectral purity filter (SPF) positioned at the intermediate field stop is used to absorb out-of-band visible and DUV radiation emitted by the source. In addition to filtering the EUV radiation, the SPF also isolates the source vacuum chamber and its operating conditions from the main tool exposure vacuum

chamber, and it isolates the exposure chamber and the optics contained therein from heavy and charged particle debris produced by the source.

As shown in Fig. 9.8(a), these membranes are built into a motorized moveable window strip for ease of replacement. Early experiments showed that if the thickness and material of the SPF are not commensurate with the thermal loading caused by absorption of out-of-band radiation from the source, the membrane windows can easily burst [see Fig. 9.8(b)].

9.3.4 Tool subsystems

9.3.4.1 Tool body and platform

To achieve low mechanical vibrations of the reticle-lens-wafer assembly during exposures, both active and passive vibration control systems are integrated with the tool chamber and subsystems. The exposure chamber, source, and wafer loader are mounted on a common massive polymer concrete base. The exposure chamber is mounted on its own polymer concrete plinth that has a low Q , high stiffness, and damping. Designed for low stage forces and short settle times, the exposure chamber itself is also very stiff. Relatively “quiet” magnetic-levitation turbo-molecular pumps are used to establish and maintain the high vacuum in the chamber.

9.3.4.2 Reticle-objective-wafer mounting assembly

As shown in Fig. 9.9, a stiff invar conic shell structure isolated by three active vibration isolation mounts from the vacuum chamber is used as a common core structure to mount the imaging objective and the wafer and reticle stages. The active isolator mounts use air-spring and linear forcers to achieve an attenuation of -30 dB at 10 Hz. Detailed modeling by finite element analysis (FEA) was used to engineer the structural modes and dynamics of this “tool core” to provide a high-resonant-frequency (175 Hz) structure with low displacements, high stiffness, light weight, and very low thermal expansion properties. Its high gas conductance allows for efficient pumping and easy access to mounted subsystems.

9.3.4.3 Wafer and reticle stages

Coarse and fine motion control of the reticle and wafer positions is achieved using two stacked sets of piezoelectric-driven stage assemblies. The vacuum-compatible wafer stages in Fig. 9.10 use multiple driver blocks, each containing eight piezoceramic “finger walkers” to achieve 450×200 mm of travel and 20-nm positional resolution. Fine six-axis control with 2-nm resolution over a 100- μ m range of the wafer and reticle motion is made using piezo-driven flexure stages mounted on top of these stages. Stage vibrations in the static exposure position were measured to be ≤ 3 nm.

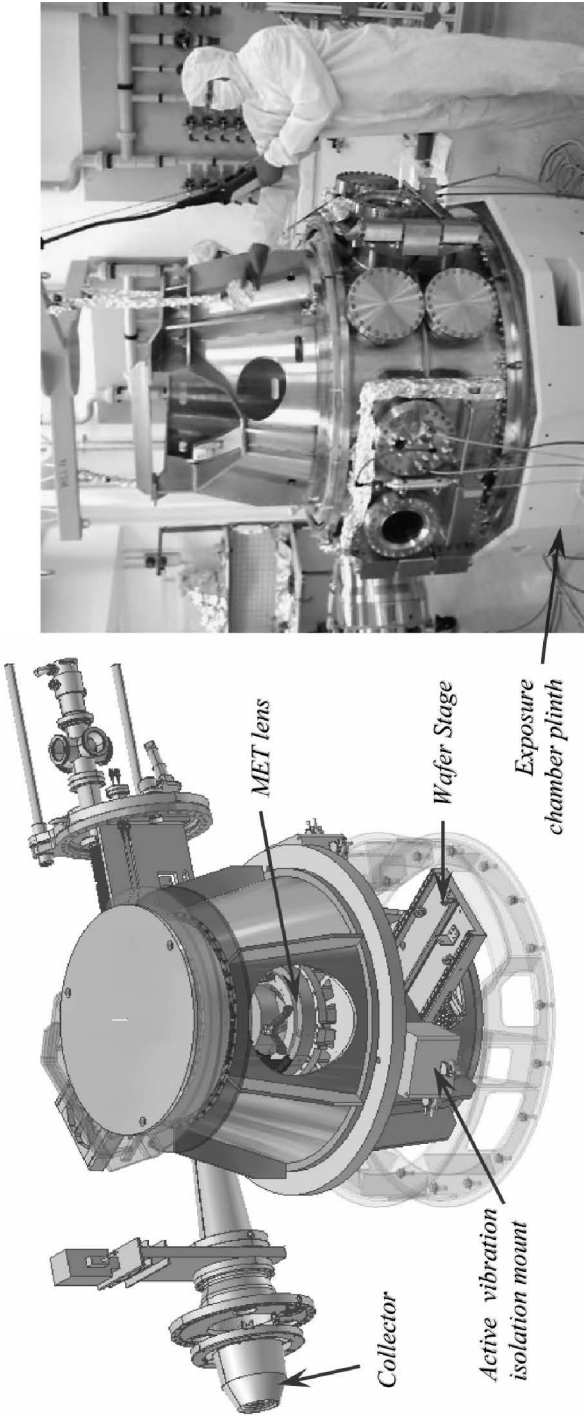


Figure 9.9 Tool core used for lens, reticle, and wafer stage mounting.

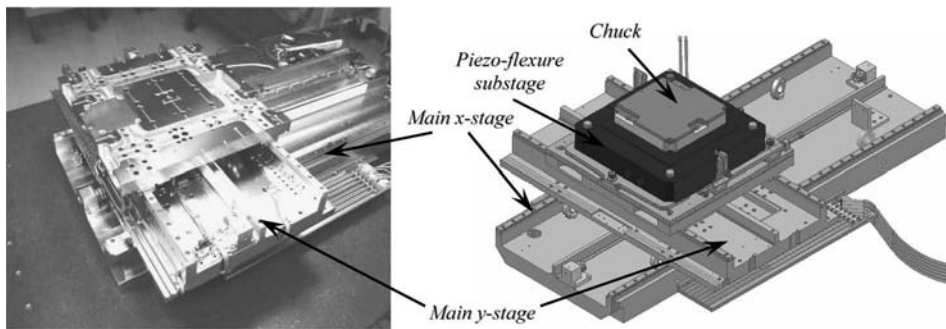


Figure 9.10 Coarse- and fine-stage assemblies for wafer motion.

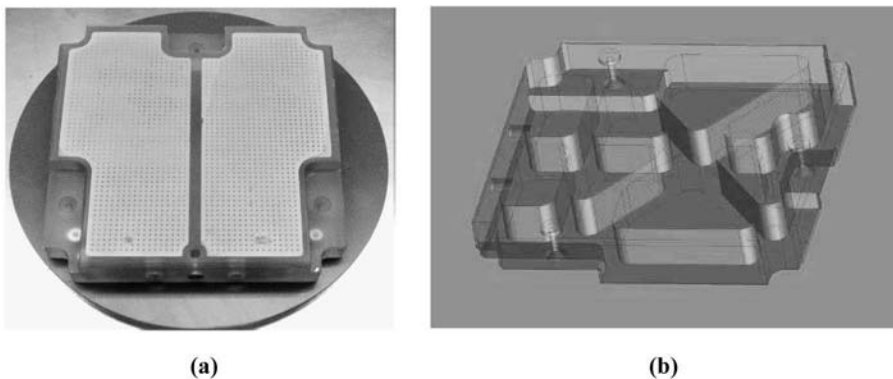


Figure 9.11 (a) Electrostatic 6-in. reticle chuck. (b) FEA-optimized light-weighted ULE chuck-mounting structure.

9.3.4.4 Wafer and reticle chucks

Because most vacuum chuck designs are incompatible with operation in a vacuum environment, the MS-13 uses electrostatic chucks of a bipolar design to hold the wafers and reticles. Advanced sensor electronics monitor the proximity of the substrate to the surface so the grip voltage is optimized, and residual charge canceling methods allow substrate release in a few seconds. Over 40 mm, the ultra-low-expansion (ULE) light-weighted chucks shown in Fig. 9.11 had a surface flatness of 250 nm. Pin elevators were used to lift wafers from the chuck.

9.3.4.5 Wafer and reticle loading

As shown in Fig. 9.12, 200- or 300-mm wafers are loaded from a TEL Model ACT 12 wafer track into and out of the MS-13 using a vacuum cluster tool robot supplied by Brookes Automation. To enable tool testing without the use of a track, an additional load lock was developed to allow separate manual loading of wafers. An in-vacuum wafer prealigner orientates wafers prior to loading into the load lock of the exposure chamber.

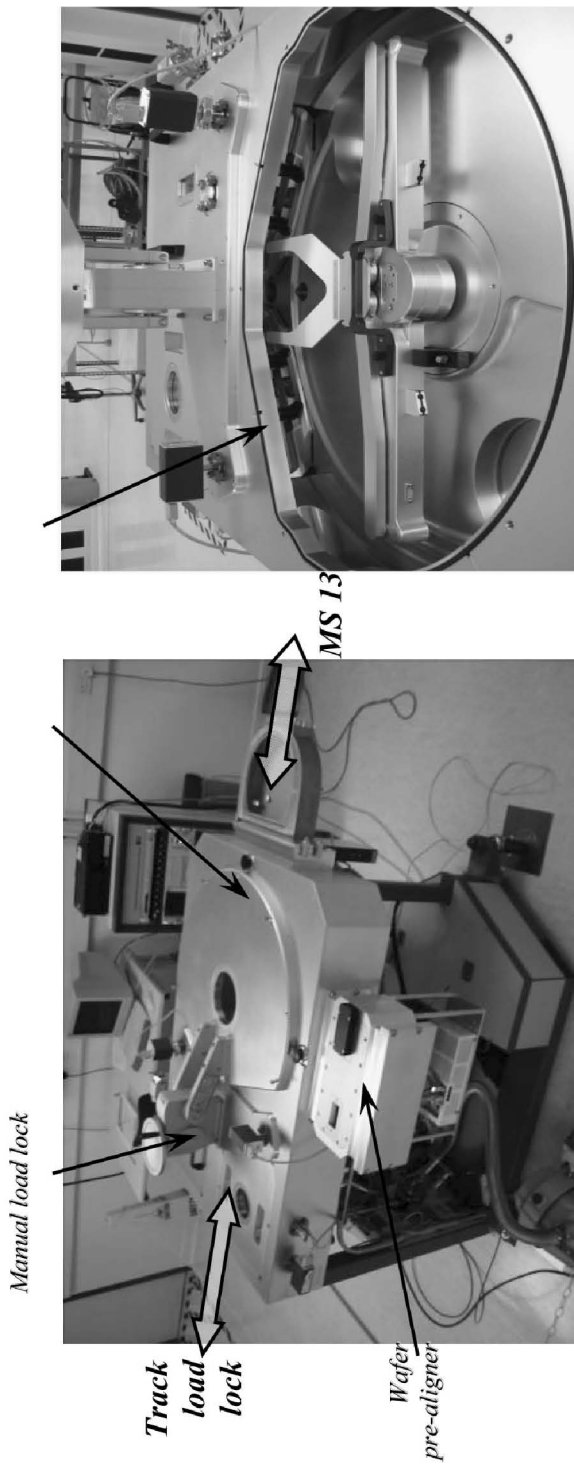


Figure 9.12 Wafer loading robot.

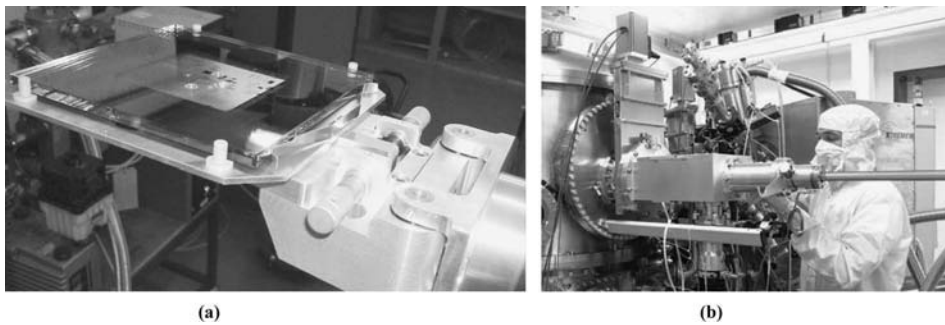


Figure 9.13 (a) Reticle loader arm with EUV reticle. (b) Loader arm interface to the vacuum load lock and exposure chamber.

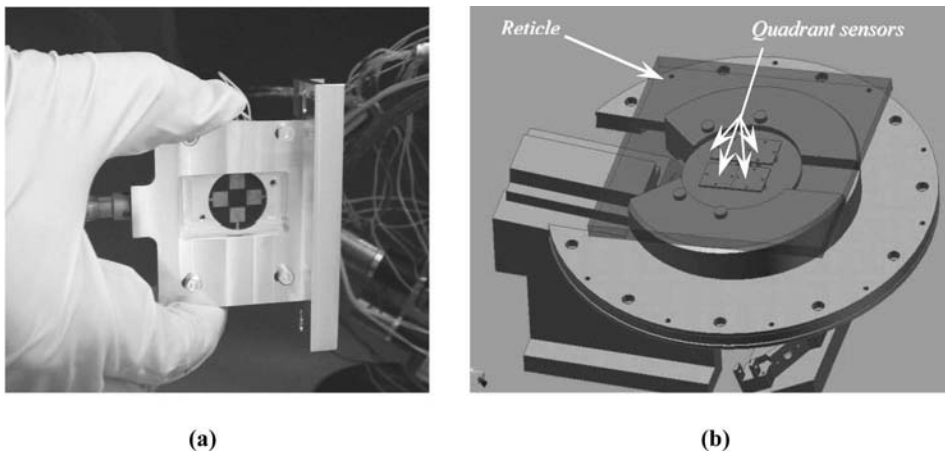


Figure 9.14 Quadrant sensors at (a) intermediate focus for aligning the source and collector, and (b) a reticle for dose monitoring.

Because of the reduced image field size of the objective, the tool is designed to be used with reticles containing up to a 5×3 array of subfield patterns that can be moved on precision stages into the exposure field. This secondary use, coupled to the tool's primary use for EUV resist testing, ensures that users must change the reticles infrequently. Hence, early in the design of the MS-13 the designers decided to implement manual reticle loading. The arm for loading reticles into the vacuum load lock, then into the tool chamber for release onto the electrostatic chuck, is shown in Fig. 9.13.

9.3.4.6 EUV radiation monitoring

Specially developed EUV-radiation-hardened Si photodiodes with a thin deposited layer of zirconium (Zr) to act as a spectral filter were used to monitor the EUV beam intensity at key positions throughout the tool. As shown in Fig. 9.14(a), a quadrant diode sensor was used at the intermediate focus position to align the source and collector.

Illumination uniformity at the reticle is measured using a scanning diode with a pinhole-restricted aperture. As shown in Fig. 9.14(b), another quadrant sensor, situated immediately below the reticle monitoring overspill EUV radiation immediately outside the object field, is used for primary dose control. Another diode located near the pupil plane that monitors the EUV light collected by the collector's inner shell is used for secondary dose control and source diagnostics. Detectors are cross-calibrated for exposure dose settings at the wafer level using another diode mounted at the edge of the wafer chuck.

9.3.4.7 Vacuum system and control

Wherever possible, UHV practices were adopted in the design and assembly of the tool to minimize the risk of optics contamination by EUV-induced cracking of background hydrocarbons and water vapor.⁷ The tool is designed to operate at a base pressure of $<10^{-6}$ mbar with partial pressures of hydrocarbons $<10^{-9}$ mbar. Extensive outgassing tests were carried out on all subassemblies integrated inside the chamber. TransCalc (BOC-Edwards), VacTran, StarD, and Monte Carlo software codes were used to carry out extensive modeling of all aspects of the vacuum system during its design.

To contain any potential optics contamination arising from, for example, resist and cable insulation outgassing products, the main exposure chamber is divided by baffles into three zones—reticle, imaging objective, and wafer, each of which is differential-pumped with a 3,000 l/sec turbo-molecular pump backed by a scroll pump. This design is shown in Fig. 9.15. Three additional 1300 l/sec turbo pumps are used to pump the source gases [Xe with an argon (Ar) buffer] from the source vacuum chamber, which is physically isolated from the exposure chamber by the SPF. The vacuum system controller for the tool was manufactured by BOC-Edwards. A touch-screen interface provides full automation, interfacing, and sequencing control of gauges, pumps, and valves.

For simplicity of manufacture, ease of assembly, and access, the main exposure chamber itself was constructed in four sections. During its design, FEA was carried out to address issues such as modal response, stiffness, safety, and pump-down distortion.

9.3.4.8 Tool control

Tool control uses a specially developed man-machine interface based on Visual Basic software. Touch screens and keyboards operate the tool and provide diagnostics of all relevant process information. The processing parameters, including the exposure dose at each site and wafer location, are selected by the operator using exposure editor graphical user interfaces (GUIs). Basic software routines are provided for exposure tests such as step and repeat, focal position, and exposure dose matrix scans, raster scans, etc. The GUI allows dose and focal scans to be set up easily, with all information stored in separate databases for later reference. The screen allows exposure sites to be “dragged and dropped” and shows the most relevant process parameters alongside a graphical display of sites on the wafer.

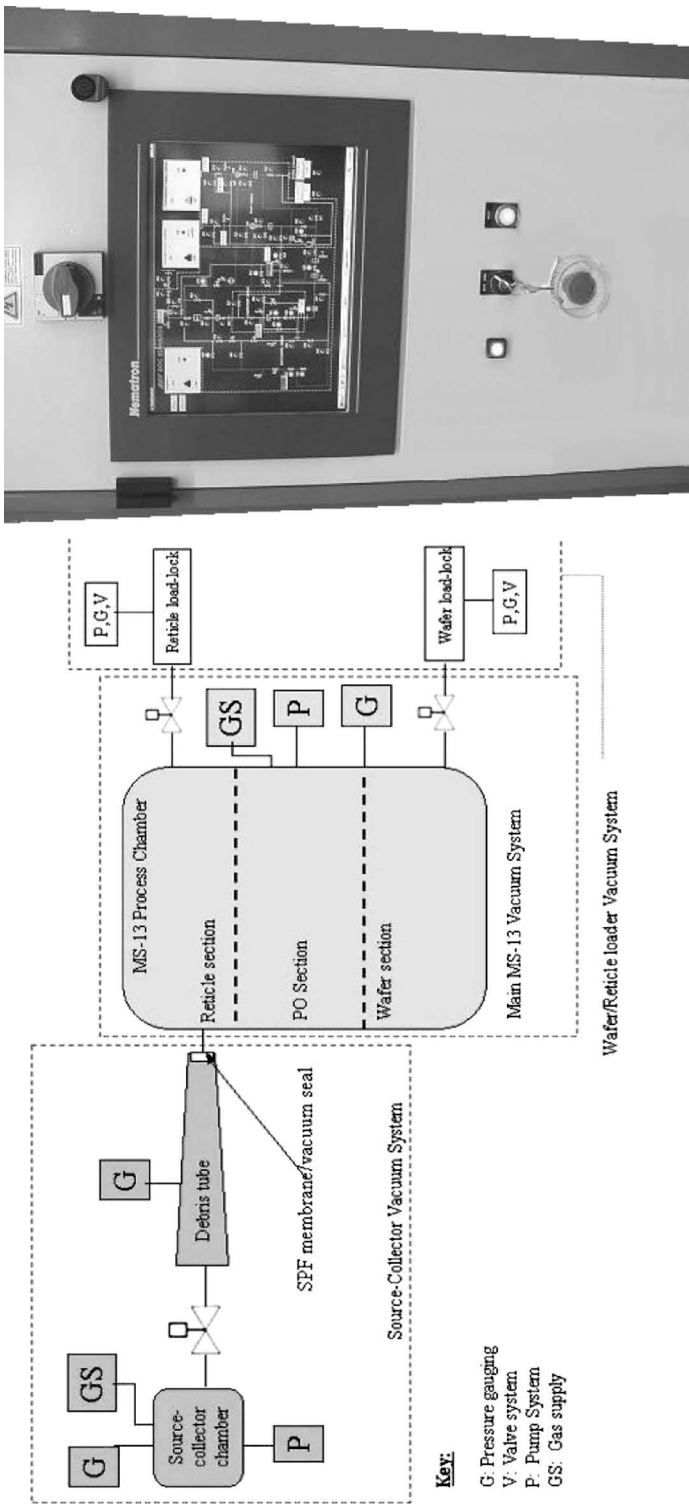


Figure 9.15 Vacuum layout of the tool and touch-screen vacuum system control.

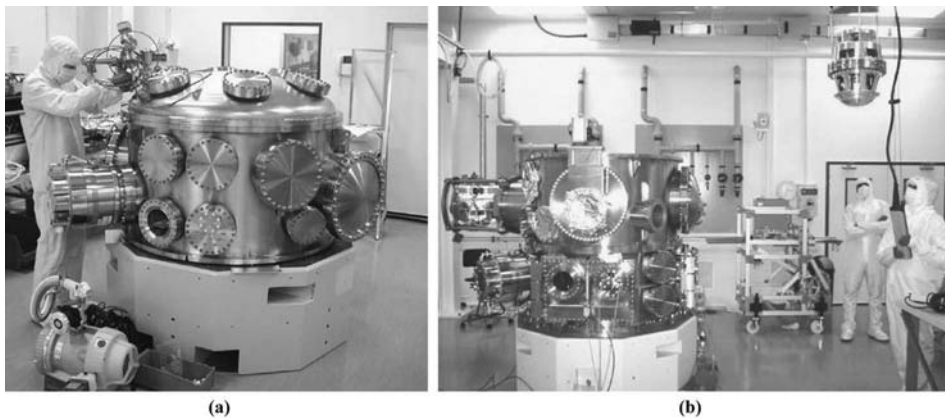


Figure 9.18 (a) Middle and top sections of the exposure chamber. (b) Installation of the surrogate lens into the exposure chamber.

chemical, ultrasonic, and thermal heat treatment cleaning procedures. The middle and top sections of the exposure chamber are shown in Fig. 9.18(a).

A surrogate MET lens was fabricated that was identical to the real imaging objective other than the actuators not being installed and the mirror blanks not having any aspheric departure. This surrogate, shown being loaded into the tool in Fig. 9.18(b), was used to ensure good mechanical fit of the lens inside the tool and to enable separate opto-electro-mechanical subsystem testing to be performed without the risk of contaminating the real imaging objective.

9.3.5 Tool subsystems testing

9.3.5.1 Vacuum conditions

The complete chamber integrated with the source, subsystem assemblies, and diagnostics is shown in Fig. 9.19(a).

Although the risk of optics contamination and the composition of other subsystem assemblies do not allow the populated chamber to be baked, the chamber reached a pressure of 5×10^{-8} mbar after only a few days of pumping. After approximately two weeks of pumping, the individual hydrocarbon partial pressures of masses >44 amu was $<10^{-10}$ torr, as shown by the residual gas analyzer spectrum in Fig. 9.19(b). This is further proof of the cleanliness and vacuum tightness of the chamber.

9.3.5.2 Autofocus repeatability

The repeatability and error of the wafer autofocus system was measured by moving the wafer through focus in 50-nm increments over a range of $0.7 \mu\text{m}$, then using the z -axis wafer stage encoder to measure the difference between the wafer height set and the value taken from the Si position-sensitive-detector used to detect the

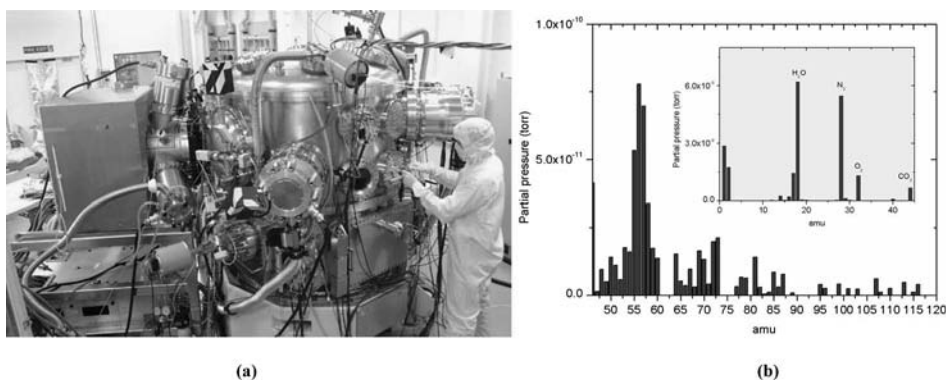


Figure 9.19 (a) Assembled MS-13 chamber and source. (b) Residual gas analyzer spectrum of atomic masses >44 amu after ~ 2 weeks of pumping the fully populated exposure chamber.

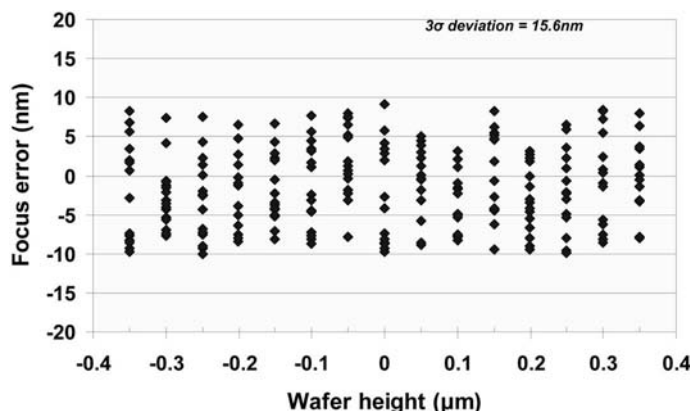


Figure 9.20 Measurements of the wafer autofocus repeatability error.

wafer surface height. A typical data set is shown in Fig. 9.20. As can be seen, with a 3σ deviation of only 15.6 nm, this autofocus repeatability error is very small.

9.3.5.3 Illumination uniformity

A high degree of illumination uniformity at the reticle and wafer planes is crucial for achieving the ultimate imaging performance of exposure tools. The time-averaged uniformity of the EUV radiation illuminating the reticle in the MS-13 is measured by scanning an EUV-sensitive photodiode across the illumination area with a 200- μm -diameter pinhole obscuring its area of detection. In the quasi-critical illumination scheme, the illumination at the reticle is a magnified image of the source emission. The isometric plot of the intensity distribution in Fig. 9.21 shows that, over the restricted 1×3 mm object field of the objective, uniformity is very good: $< \pm 2.7\%$ for the case shown.

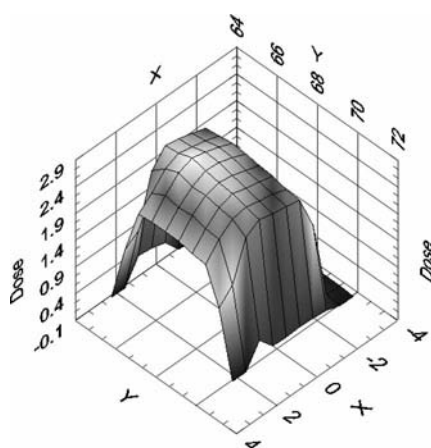


Figure 9.21 EUV intensity distribution measured at the reticle object field: 3×3 mm field with 10×10 sites, 200- μm pinhole, 500 pulses/site (2 bursts of 250 pulses), 500 Hz, 10% duty cycle, uniformity $< \pm 2.7\%$.

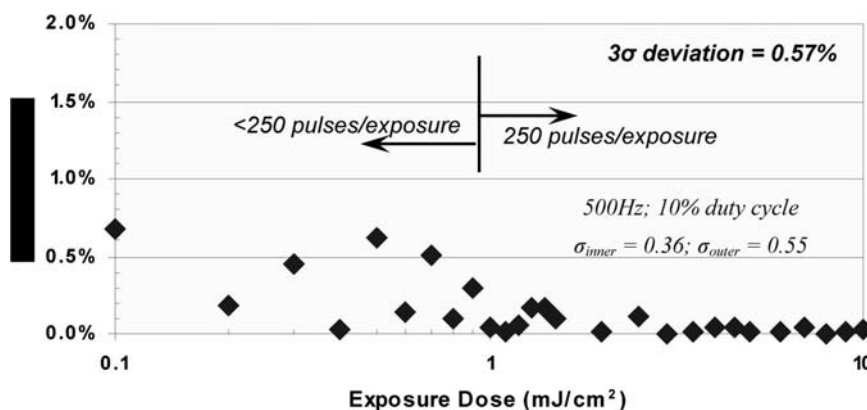


Figure 9.22 Measurements of the error between exposure dose set and delivered.

9.3.5.4 Exposure dose control

Accurate setting, control, and reproducibility of the exposure dose are critical features for any photolithography exposure tool. Primary dose detection in the MS-13 is provided by Si diode quadrant detectors that monitor EUV radiation overspill outside the object field at the reticle. Dose control at the exposure site is then provided by measuring the integrated dose accumulated on a pulse-by-pulse basis. Firing of the source is automatically commanded to stop when the dose set is achieved. Doses at the reticle in the range 0.1 to 10 mJ/cm^2 correspond to doses of approximately 1 to 100 mJ/cm^2 at the wafer. Figure 9.22 shows the error between the set dose and the dose delivered, which is very small. For the data shown, the 3σ deviation is only 0.57%. As expected, larger errors are encountered at lower doses when fewer pulses are used for the integration, in this case below 1 mJ/cm^2 .

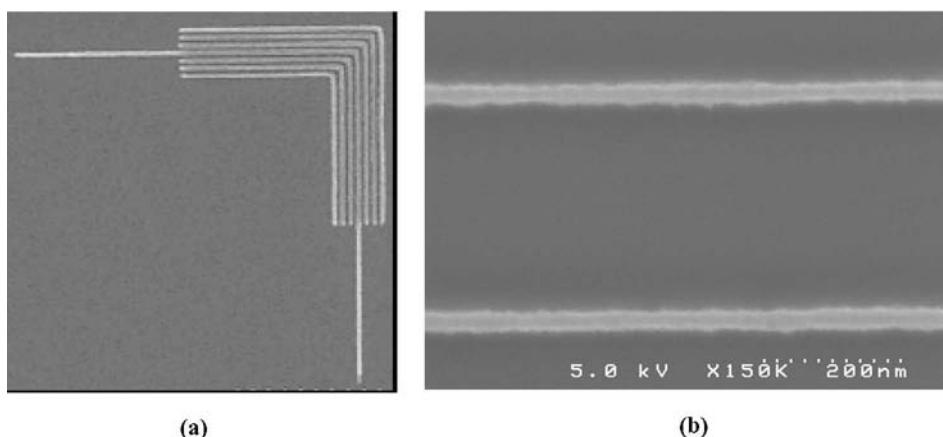


Figure 9.23 Sample images taken from the first MS-13 tool installed at Intel Corp. (a) 50-nm L/S elbow structures. (b) 27-nm isolated lines, 7 mJ/cm² dose.

9.3.6 Resist exposure results

Figure 9.23 shows some sample images taken from the first MS-13 tool installed at Intel Corp.^{8–10} These pictures show images of dense 50-nm and isolated 27-nm structures. The critical dimension (CD) variation of 50-nm features over a $160 \times 500 \mu\text{m}$ image field was measured to be $\pm 3.3\%$. Using a modified Kirk resist exposure test, the flare level at the wafer for this two-mirror objective was measured to be $\sim 5\%$.¹⁰ Further evidence of the high optical resolution performance and opto-mechanical stability of the tool was provided by successfully printing 50-nm lines and spaces using exposure times as long as 15 sec/die.

The MS-13 Microstepper has achieved imaging performance well beyond its 50-nm lines and spaces (L/S) imaging specification. Currently, the tool's ultimate imaging resolution appears limited by the performance of EUV photoresists rather than the tool's opto-mechanical properties. Naulleau et al. described the performance of an experimental facility that uses the synchrotron at the Advanced Light Source, Lawrence Berkeley National Laboratory (LBNL), as the EUV source, and an earlier version (set 2) of the MET imaging objective.^{10–12} Their imaging results in resist appear similar to those presented here for the MS-13 tool with its Xe-based DPP EUV source and a very different illumination scheme.

9.4 Reticle Imaging Microscope

The RIM-13 is a reticle imaging actinic microscope tool capable of capturing aerial images from EUV reticles with illumination and imaging characteristics that emulate full-field production scanner tools.^{13,14} This tool, developed as part of a JDA with SEMATECH, fulfills an essential requirement for actinic inspection and printability studies of amplitude and phase defects on blank and patterned EUV reticles.³

Because EUV reticles use reflective ML coatings to achieve bright areas and absorber coatings on top to define dark areas of integrated circuit (IC) features, both amplitude and phase types of defects can be present on the wavefront of the reflected light. Due to errors in the absorber patterning, amplitude defects will arise from particles that land on top of the reticle—which for EUV reticles is exacerbated by the lack of a protective pellicle. In addition, particles or other defects on the mask blank before or during coating of the ML or absorber coatings can lead to phase defects that are observable only by inspection at actinic wavelengths. In developing strategies to find, assess, and repair such mask defects, it is essential to understand *a priori* how such defects may eventually print in the exposure tool. The RIM-13 reticle aerial image microscope tool provides a magnified electronic image of patterns on a reticle that emulates its demagnified counterpart image on the wafer as it would print in a resist exposure tool. The optical design of the RIM-13 was validated by carrying out aerial image modeling simulations of reticle defects and showing signatures to be identical with those modeled for an idealized EUVL full-field scanner.

9.4.1 RIM-13 tool architecture

Like the MS-13, the RIM-13 tool is essentially passive so that during aerial image capture, potential sources of internal vibration are minimized. Masks are loaded and removed from the tool through automated load locks from/to SMIF boxes.

Figure 9.24 shows the mechanical design of the tool with its reticle loader robot and load lock. During measurement, the reticle is orientated face up in the RIM tool below the magnifying EUV imaging objective. The imaging objective has the same NA (0.0625) as that used in the first full-field scanner tools, which are currently in development (0.25 NA at the wafer with $4\times$ image demagnification of the reticle to the wafer). The illumination coherence properties of the RIM-13 reticle are also identical to those adopted in lithography exposure tools. The tool's imaging train uses a two-stage image converter: an EUV objective provides a $10\times$ magnified image of the reticle, which is then faithfully replicated into an optical image using a scintillator plate comprising a thin crystal of cerium (Ce)-doped yttrium aluminum garnet (YAG). The visible image transmitted through the plate is then further magnified with a cover slip-corrected custom optical microscope objective-tube lens combination having a magnification that can be varied between $25\times$, $50\times$, and $75\times$. The overall $250\times$, $500\times$, or $750\times$ magnified image of the reticle is then relayed onto a low-noise CCD camera detector. Splitting the optical magnification between the EUV and visible in this way enables a much more compact tool design with fewer complex and expensive EUV optical components than would otherwise be the case if the full magnification were all carried out in the EUV.

At a given defect site, the tool automatically finds the best focus position and then, with user-selectable defocus steps between images, captures a series of through-focus images through the $\sim 3\text{ }\mu\text{m}$ depth of focus (DOF) of the EUV image. Each image exposure is accurately controlled, and images are normalized

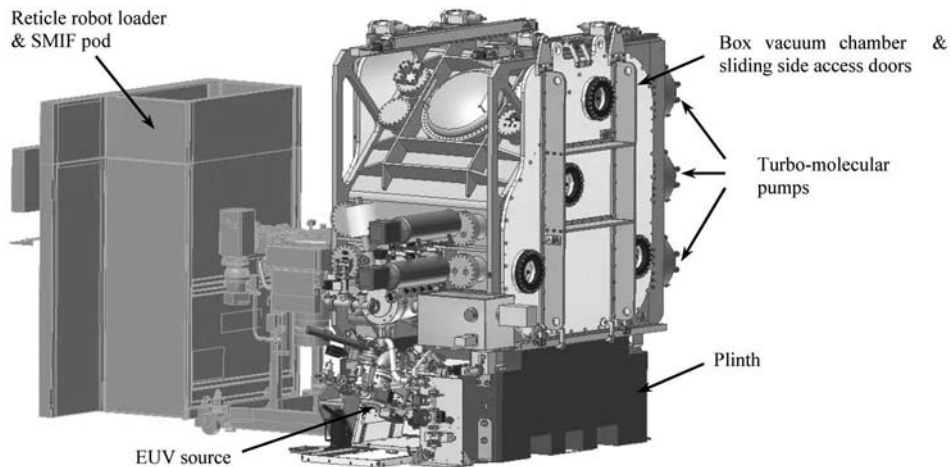


Figure 9.24 RIM-13 reticle aerial image microscope tool chamber with reticle loader.

using bright and dark reference images. Software analysis of through-focus images allows data to be presented in the form of Bossung plots, exposure-dose latitude, DOF, CD variability, image thresholds, normalized image log-slope (NILS), etc., and then input into lithography simulation packages. High-speed defect inspection tools provide coordinate locations of likely defect sites to the RIM-13.

The RIM-13 and MS-13 Microstepper tools are similar in concept since both are subject to similar tight requirements for vibration and temperature stability. However, the designs diverge greatly in their details due to their different EUV source and optical arrangements as well as the RIM-13 tool's requirement for much greater levels of particle control. Furthermore, because the RIM-13 is used in manufacturing operations, the ease of maintenance and serviceability were major drivers in its design. Some of the most critical subsystems of the RIM-13 are described in more detail in the following sections.

9.4.2 EUV source

Modeling of the tool's optical design indicates that a source brightness of at least $0.5 \text{ W/mm}^2/\text{sr}$ is necessary to carry out aerial image measurements to the required accuracy. Furthermore, the overall étendue or light gathering power of the tool is constrained by the very small $6.5 \times 10^{-6} \text{ mm}^2/\text{sr}$ value inherent to its EUV imaging objective. Ideally, incoherent EUV source diameters that best match this étendue would be very small—perhaps in the 10- to 50- μm range. A first EUV source to be integrated with α and β versions of the tool, shown in Fig. 9.25, was supplied by AIXUV GmbH and is a modified version of their standard Xe gas-based DPP EUV source.¹⁵

With this source, the étendue mismatch caused by its relatively large $\sim 400\text{-}\mu\text{m}$ diameter means that only $\sim 0.03\%$ of the light at the 13.5-nm wavelength emitted in $2\pi \text{ sr}$ and 2% bandwidth can be passed through the optical system and used effectively. When operating at 250 Hz with a 20% duty cycle, the source generates



Figure 9.25 EUV Xe DPP source during brightness testing.

0.125 W/sr (compared to 5.6 W/sr for the MS-13 source). When averaged over its diameter, it has an in-band brightness at 13.5 nm of $0.5 \text{ W/mm}^2/\text{sr}$. Preventing the reticles that pass through the tool from becoming contaminated by adder particles is critical to the tool's success in actinic inspection. To mitigate the possibility of contaminants produced by the plasma source entering the tool chamber as well as to achieve the maximum lifetime for all the EUV optics in the tool, a thin EUV transmissive Si membrane filter is used to isolate the source from the chamber. The filter, situated between the source and the collection optics, provides a protective barrier from bombardment by heavy, neutral, or charge particle source debris for components situated downstream.

9.4.3 EUV illumination

Figure 9.26 shows the concept of transmission of the Köhler pupil-relayed condenser illumination optical arrangement used to emulate the illumination characteristics of lithography exposure tools. In this scheme, the source is first imaged to an intermediate pupil plane at which coherence apertures can be placed, which is then relayed into the entrance pupil of the imaging objective. Simultaneously, the highly uniform intensity distribution at the exit pupil of the condenser collection optics is imaged onto the reticle.

The actual EUV reflective components are comprised of six mirrors. The one grazing incidence and five normal incidence mirrors, together with their layout in the tool, are shown in Fig. 9.27. For simplicity and lower cost, the illumination mirrors were designed to be planar or spherical without any aspheric departure. The total number of EUV mirrors required by the design was kept to the minimum

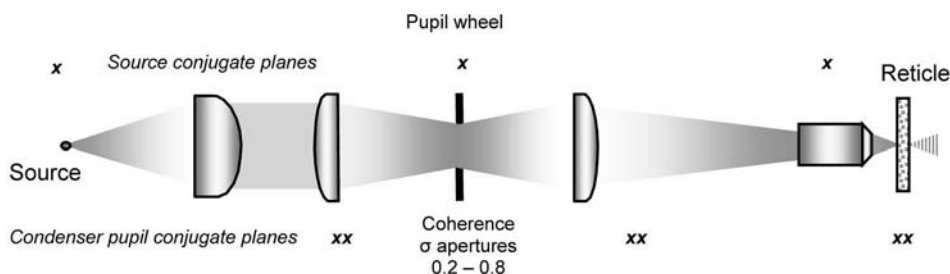


Figure 9.26 Concept of the RIM-13 EUV Köhler pupil-relayed illumination scheme (not to scale).

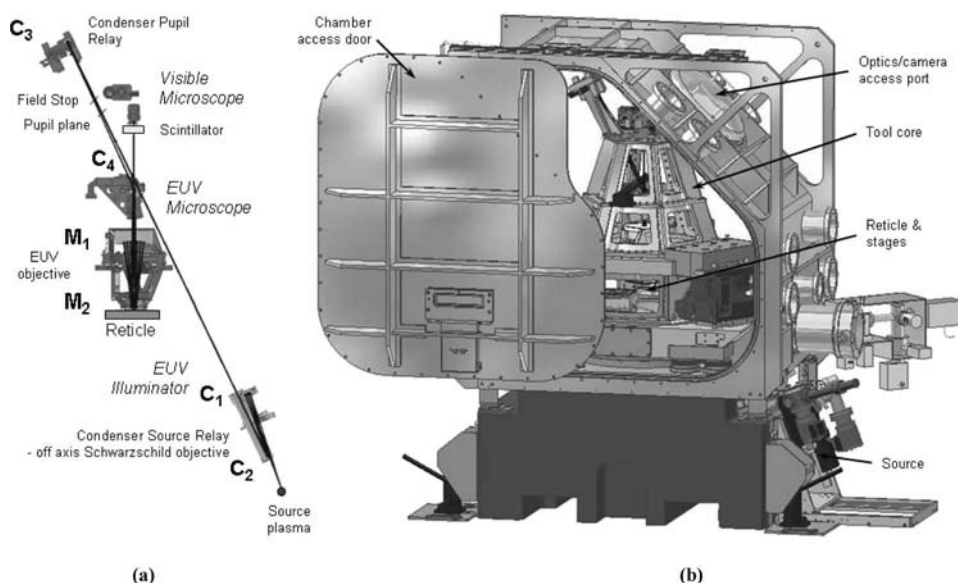


Figure 9.27 RIM-13 tool layout: (a) optical system, and (b) cross section of mechanical design showing tool core and light path.

to maximize the throughput of EUV light through the system. Only two folding mirrors, C_3 and C_4 , are used, and the $10\times$, 0.0625-NA objective itself is used to both illuminate and image the reticle in a double-pass arrangement.

As shown in Fig. 9.27(a), light is collected from the source using an off-axis Schwarzschild objective comprising Zerodur mirrors C_1 and C_2 that relay the central $\sim 100\text{-}\mu\text{m}$ diameter of the source to the pupil plane, where apertures can be selected to change the partial coherence σ settings of the illumination between 0.2 and 0.8. This pupil plane is then relayed onward by C_3 and the grazing incidence turning mirror C_4 into the entrance pupil of the imaging lens. The uniform intensity distribution at a field stop position close to the mirror C_2 is relayed to the reticle to produce uniform illumination over a diameter of $\sim 60\text{ }\mu\text{m}$. Two small subapertures limit the aperture of the imaging objective, one of which forms part of the illumination system that provides a 6-deg angle of incidence for illuminating the reticle.

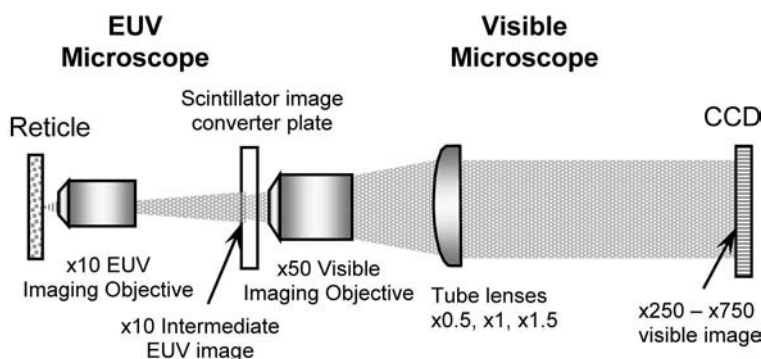


Figure 9.28 Concept of two-stage RIM-13 reticle imaging microscope (not to scale).

The mechanical design and manufacture of the illumination system was provided by SSG Precision Optronics Inc.

9.4.4 Reticle imaging

High-magnification imaging of features on the reticle is accomplished using a two-stage image converter and separate EUV and visible imaging objectives, as depicted in Fig. 9.28. The EUV objective provides a $10\times$ magnified image of the reticle, which is then faithfully replicated into an optical image using a scintillator plate.

9.4.5 EUV microscope

The projection optics (PO) box design of the $10\times$, 0.0625-NA EUV objective used in the RIM-13 tool shown in Fig. 9.29 is somewhat similar to the design used for the MET lens in the MS-13 tool.⁴ Like the MET lens, the objective is an “equal radii” Cassegrain-type built into an invar hexapod PO box structure. However, the smaller NA of the RIM EUV objective makes it physically smaller. While the full aperture of the RIM lens is <0.2 NA compared to 0.3 NA for the MET objective, as mentioned above it is used with two off-axis subapertures that limit the NA used for imaging to 0.0625 NA.

It is important for the performance of the RIM tool that the aerial images of reticle patterns and defects captured by the tool faithfully emulate those produced in full-field lithography scanner tools. The reticle features shown in Fig. 9.30(a)—70-nm bright field lines on a 140-nm pitch with a 35-nm subresolution, 45-deg ($\lambda/8$) phase-shift defect—are shown (square dots) in Fig. 9.30(b) as the modeled cross-section of the aerial image produced by the EUV microscope in the RIM-13 tool.

For comparative purposes, this image is then overlaid (diamond dots) with that predicted for a six-mirror objective in an idealized full-field, 0.25-NA, $4\times$ demagnification lithography scanner.¹⁶ The aerial images predicted for both tools are identical for these features.

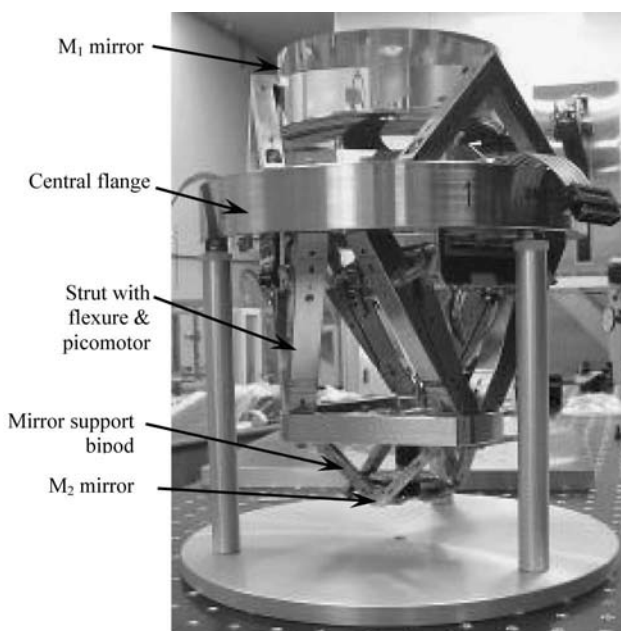


Figure 9.29 The 0.0625-NA, 10 $\times$ EUV imaging objective used in the RIM-13 tool.

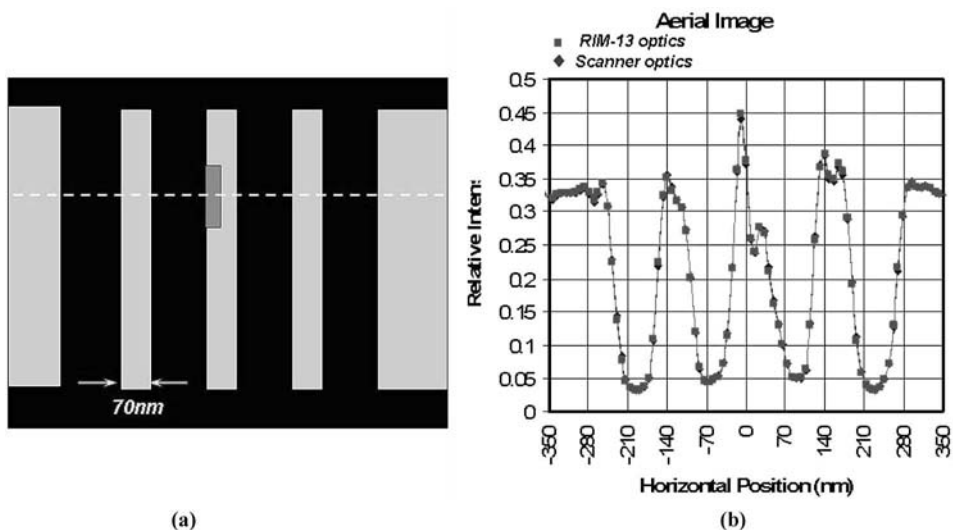


Figure 9.30 (a) Simulation of reticle pattern of 70-nm bright lines on a 140-nm pitch with a 35-nm-wide subresolution, 45-deg ($\lambda/8$) phase-shift defect. (b) Aerial image of EUV microscope in RIM-13 and six-mirror, 0.25-NA, 4 $\times$ EUV scanner objective.

The EUV objective is mechanically designed and manufactured by Tinsley Laboratories with PO box design and analysis contributions from Layton Hale of Lawrence Livermore National Laboratories (LLNL). Analysis of the PO box structure shows that the first rigid body resonance of the objective loaded only by gravity has a frequency of 370 Hz, while the lowest non-rigid body mode occurs at

Table 9.1 First objective M₁ and M₂ mirror polishing showing figure, MSFR, and HSFR rms values.

Uncoated Mirror Data (rms values)	M1	M2
		
Figure (CA ⁻¹ -1mm ⁻¹)	0.25nm	0.38nm
MSFR (1mm ⁻¹ -1μm ⁻¹)	0.34nm	0.34nm
HSFR (1μm ⁻¹ -50μm ⁻¹)	Not measured	0.37nm

606 Hz. Table 9.1 summarizes the polishing results of the first M₁ and M₂ objective mirrors over the imaging subapertures.

Figure 9.31 shows the performance of the assembled EUV objective after ML coating of the mirrors and alignment on an interferometer. As can be seen, the rms wavefront error over the imaging subaperture of the first objective used in the RIM-13 alpha tool was 0.78 nm, which is comparable to the wavefront errors measured for sets 3 and 4 of the MET lens.⁶

The five normal incidence mirrors used in the illuminator and imager are coated with MLs of Mo/Si while the grazing incidence mirror is coated with a single layer of ruthenium (Ru). Figure 9.32 shows the calculated throughput efficiency and bandwidth of the complete EUV optical train from source to image (scintillator) plane using the measured reflectivity performance of the coatings of each optical element. Different curves are for radiation arising on-axis and at the edges of the object field as collected from the source. A peak optical throughput efficiency of ~1.4% is obtained at 13.54 nm with a full width half-maximum (FWHM) bandwidth of ~0.28 nm.

9.4.6 Visible microscope

The EUV objective forms a 10× magnified image of the reticle on the surface of a thin scintillator plate comprising a single crystal of Ce-doped YAG. Within <100 nm of the surface, this EUV image is converted to a green visible image at a 540-nm peak wavelength with a spectral width of 108-nm FWHM.^{17,18} As shown in Fig. 9.33, the visible image transmitted through the plate is then viewed with an in-vacuum custom-designed 0.85-NA cover slip-corrected microscope objective.

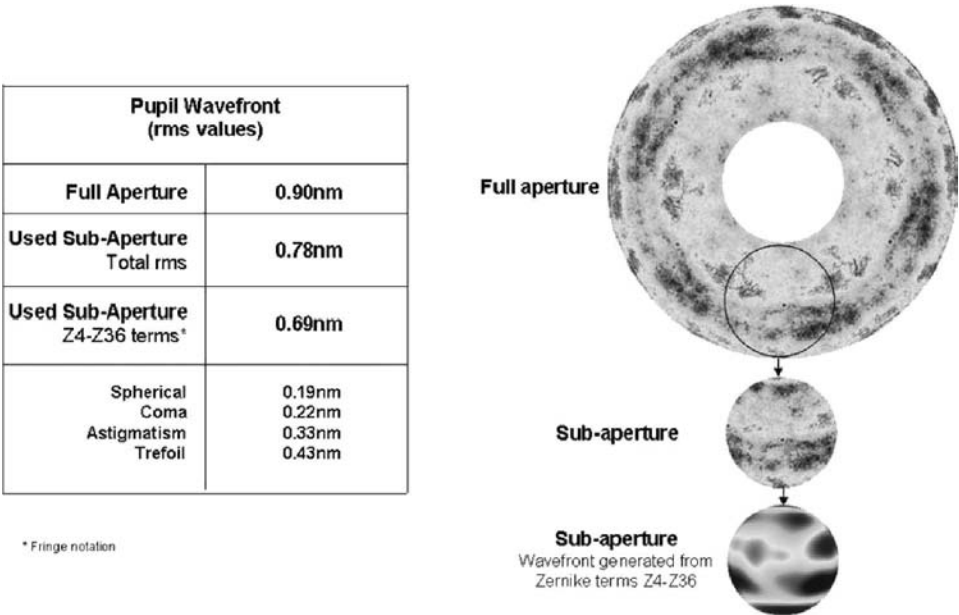


Figure 9.31 Measured full and imaging subaperture rms wavefront errors with fitted fringe Zernike coefficients.

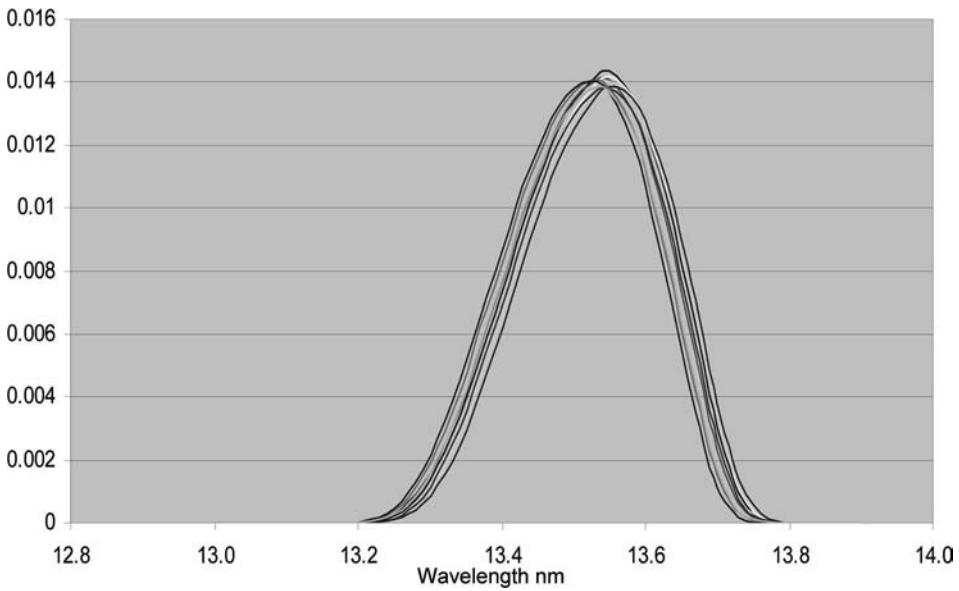


Figure 9.32 Throughput efficiency versus wavelength of nine reflections from the EUV source to the image (scintillator) plane. Data were taken from measured ML coatings of the EUV collection, illumination, and imaging optics.

In contrast to standard commercially available objectives, this objective manufactured by Leica Microsystems GmbH provides diffraction-limited image quality and low distortion over its entire 500- μm image field diameter.

As shown in Fig. 9.34, tube lenses inserted by motor into the optical path allow the magnification of the visible microscope to be changed between $25\times$, $50\times$, and $75\times$. The overall $250\times$, $500\times$, or $750\times$ magnified image of the reticle is relayed onto a low-noise CCD camera detector.

9.4.7 Tool subsystems

9.4.7.1 Tool core

Figure 9.35 shows the tool core mounted inside the vacuum chamber. Like the structure used in the MS-13, this core is a large, extremely stiff structure from which the imaging objective, the majority of the optics, the detection system, and the reticle stages are rigidly mounted. For ease of manufacture, it consists of several invar subassemblies bolted together and holds all key components in strict registration to each other. Its design and construction render it insensitive (as much as possible) to temperature fluctuations and external sources of vibration. A FEA of the one-ton structure showed a first resonant frequency at 184 Hz. The core itself does not introduce any significant object-image movement.

9.4.7.2 Vibration isolation system

The core of the RIM-13 is supported on an in-vacuum active system that isolates it from vibrations in the walls of the vacuum chamber, the floor, and external sources of acoustic vibration. This development of the system was used successfully in the MS-13. The core is supported on three units located at the vertices of an equilateral triangle. Each unit contains an air spring with linear motors to provide damping. In addition, inductive sensors in the units detect perturbations in the x , y , and z directions and operate motors to oppose them, which substantially improves the low-frequency performance over passive systems. As shown by the data in Fig. 9.36, the low-frequency performance is significantly improved over a passive system.

The second function of this system is to maintain registration between the optical elements mounted on the core and those mounted with the source on the vacuum chamber. All optics in the tool are mounted on the core apart from the source and Schwarzschild condenser. The core maintains the relative positions of the illumination mirrors. Figure 9.37 shows that the position recorded by the vertically mounted inductive sensor on one of the isolators over an eight-hour period varied by about $5\text{ }\mu\text{m}$, which is well within the positional tolerance provided by the collection and illumination optical design.

9.4.7.3 Reticle stages and chuck

Relatively coarse control of the reticle position and motion in the RIM-13 tool is provided by vacuum-compatible, x - y linear, motor-driven bearing, rail substages, which for positional accuracy and stability are actively servoed by feedback from glass position encoders. As shown by the data in Fig. 9.38, its position and stability are controlled to $\sim \pm 1\text{ nm}$. The x - y stage can translate the reticle to allow

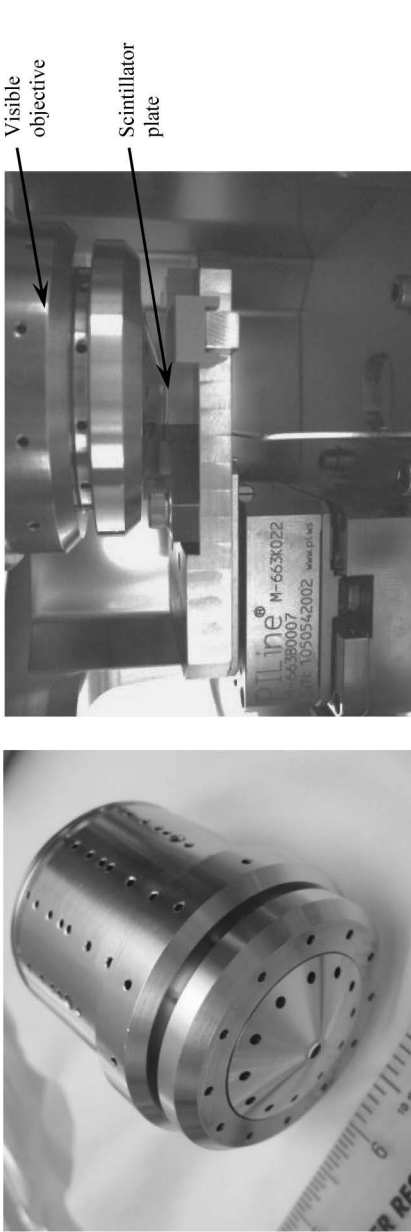


Figure 9.33 A 0.85-NA, UHV-compatible, 540-nm microscope objective.

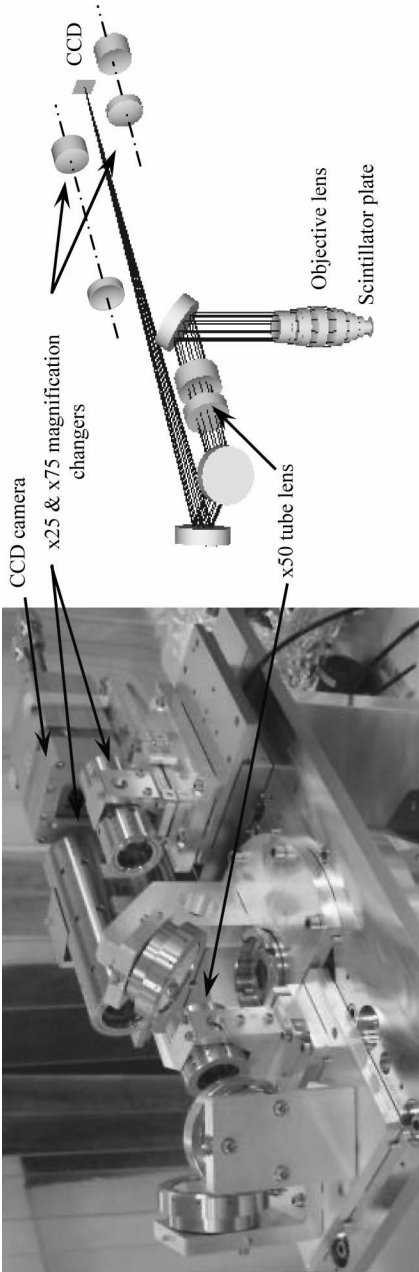


Figure 9.34 In-vacuum visible microscope configuration with magnification changers.

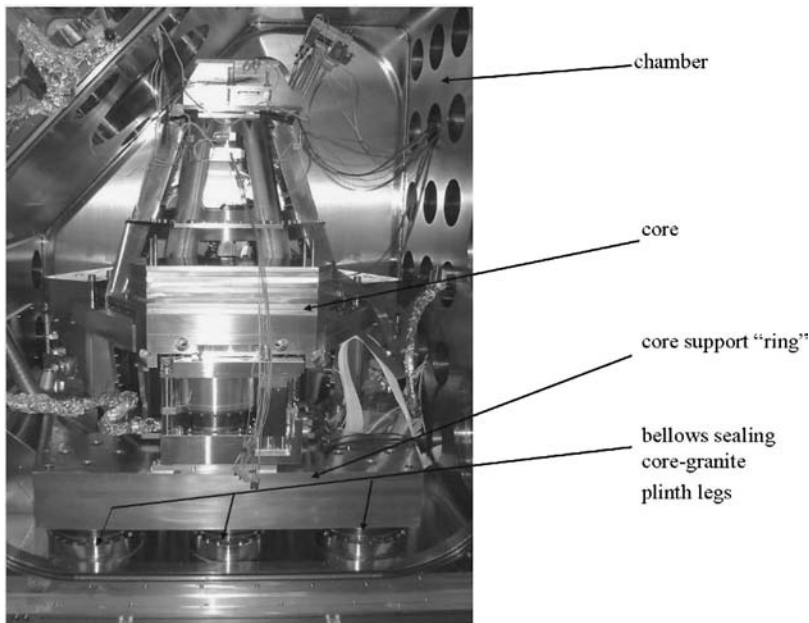


Figure 9.35 Common tool core structure from which the EUV and visible microscopes, illumination optics, reticle stages, and detection system are rigidly mounted.

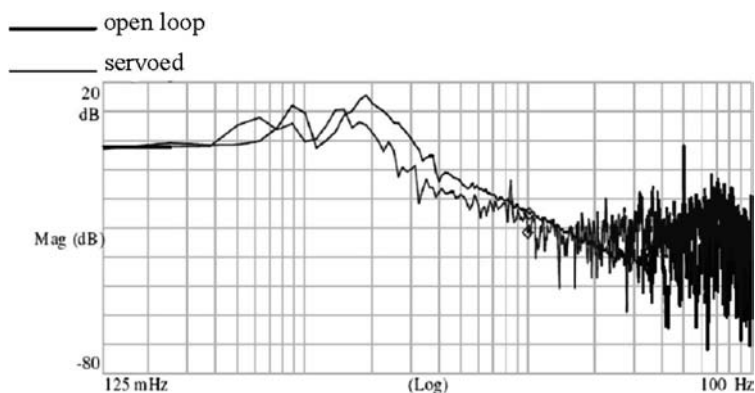


Figure 9.36 Measured transmission (vertical direction) of the vibration isolation system. Note the improvement at low frequencies with the active system engaged.

inspection of any part of its surface and to access the load position over a travel of 160×260 mm. A three-axis piezo-flexure stage mounted on top is used for focus adjustment and field leveling.

Figure 9.39 shows the chuck/stage stack, fitted to the core, viewed from the reticle load position. The main stage and piezo-flexure stage are both indicated. Since the working distance of the EUV objective is only a few mm, in the load position the reticle is moved clear of the objective when accessing the loading/unloading robot. The vertical travel is sufficient to accommodate any thickness variations in

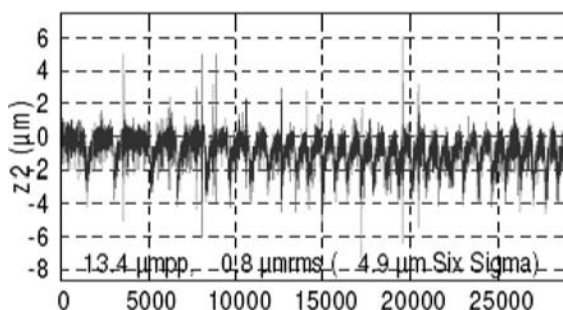


Figure 9.37 Vertical position stability over 30,000 s (~8 hours).

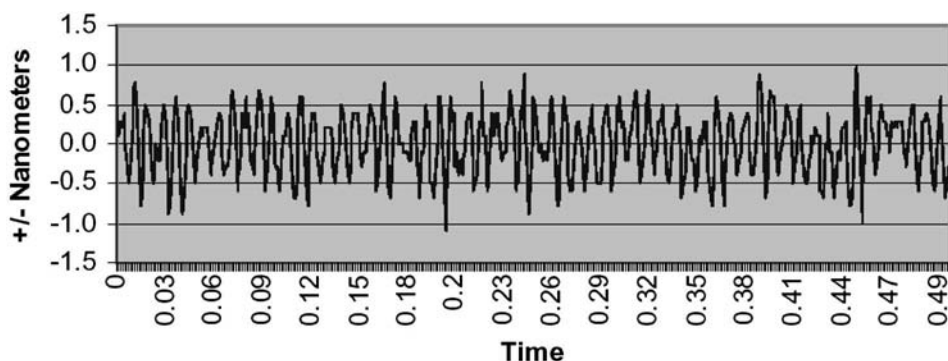


Figure 9.38 Reticle x -stage (top of stack) position as a function of time (500-ms sampling period at center of travel).

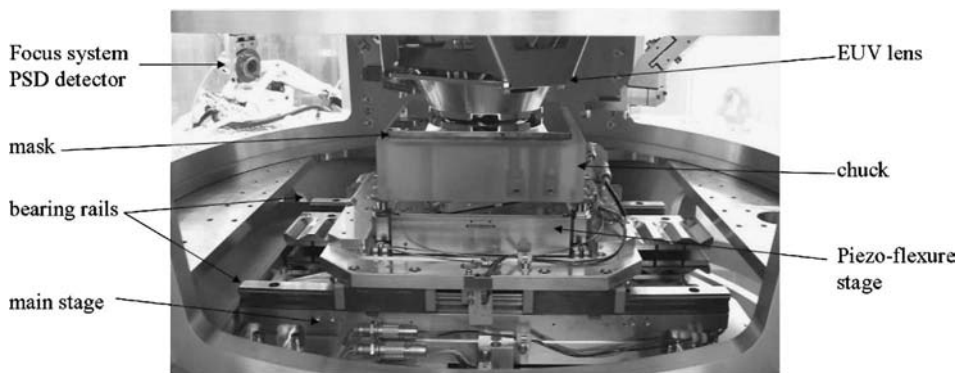


Figure 9.39 Reticle stage stack on the core viewed from the reticle load position.

EUV reticles allowed by the SEMI P37 standard.¹⁹ To minimize particle generation during motion, all moving frictional parts of the stages are baffled.

On the top of the stages shown in Fig. 9.39 is an electrostatic chuck holding the reticle. This is one of the first applications to require a chuck that meets the SEMI P40 specification¹⁹ of a 15-kPa grip pressure and flatness specification of

50-nm peak to valley (P-V). The Zerodur chuck has had considerable material removed from its backside to reduce the load on the piezo-flexure stage to ~ 2 kg. The 15-kPa (0.15-bar) grip pressure is high for an electrostatic chuck. The chuck manufacturer, ElectroGrip, used the Johnsen-Rabek effect²⁰ and their proprietary, semiconducting dielectric to facilitate strong grip at moderate (few kV) voltages.

9.4.7.4 Vacuum system

The MS-13 tools demonstrate that with large pumps and careful screening of all materials in the vacuum system, it is possible to achieve total base pressures of $<10^{-7}$ mbar, with water partial pressures of $<10^{-8}$ mbar, and the integrated sum of all the (hydrocarbon) partial pressures for mass numbers between 45 and 100 of $<10^{-10}$ mbar. These vacuum pressures, together with the EUV intensities used in the tool, are believed to be compatible with optics lifetimes of >2 years.⁷

The RIM-13 vacuum system is an evolution of that used in the MS-13 tool. As shown in Fig. 9.40, the main departure from the MS-13 chamber design is the use of a box chamber rather than a more traditional cylindrical shape. Such a box design allows the core to be fully assembled and instrumented, and for the optics to be aligned in air in a Class 10 or better clean environment and then placed into the chamber. Such a strategy provides a much cleaner and more straightforward tool-build procedure than that adopted for the MS-13—a critical requirement because the RIM-13 tool has an extremely strict specification on particulates and their potential for contaminating reticles. Furthermore, since the RIM-13 will be used in mask manufacturing operations, a box chamber design allows greater ease of access with less downtime for service and maintenance operations of the tool's internal subassemblies.

As shown in Fig. 9.41, complete fail-safe operation of the full automation, interfacing, and sequencing control of all gauges, pumps, and valves, together with data logging and error limit setting, is provided by a GUI interface of the vacuum control system.

9.4.7.5 Reticle loader

Since the RIM-13 tool is designed for defect inspection, it is critically important that the tool itself does not add defects to the reticle during the inspection cycle. Assuming that a $4\times$, 0.3-NA scanner is used with a resist process having k_1 values <0.44 , particles larger than ~ 80 -nm diameter will print if they are present on the reticle surface during exposure. This emphasizes the requirement that the RIM-13 tool must meet an extremely stringent particle contamination specification. A critical operation for the tool process cycle is the clean transfer of EUV reticles from a SMIF pod storage box at ambient gas pressure to the UHV-like conditions of the RIM-13 main chamber.

A vacuum transfer load lock can provide fully automated, ultra-clean transfer and alignment of the reticle into the RIM tool. The reticle handler for the RIM-13 tool is provided by Brooks Automation and is equipped with specialized end

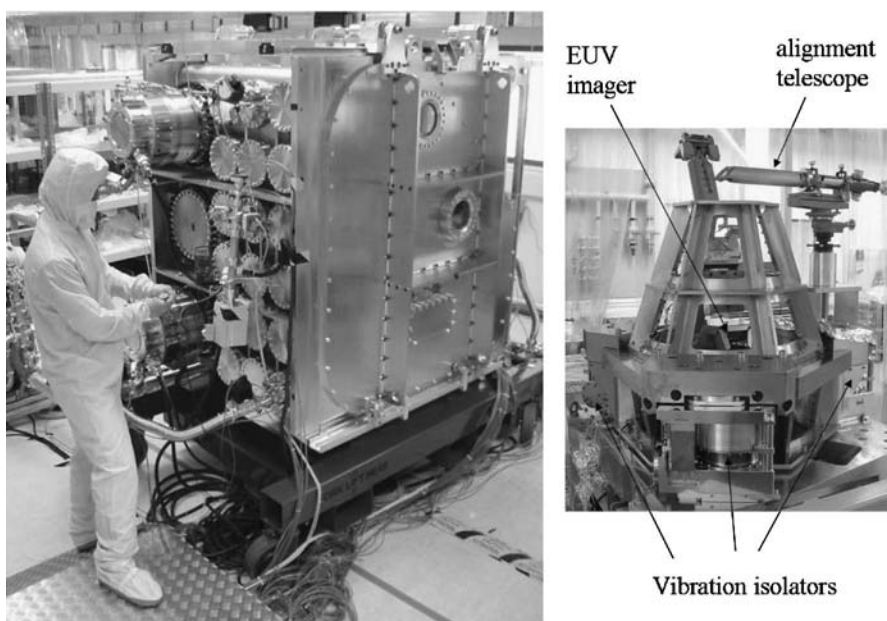


Figure 9.40 RIM-13 tool chamber and tool core prior to integration. The autocollimator telescope for visible alignment of the EUV optical train is mounted in place of the visible microscope.



Figure 9.41 Vacuum control system interface.

effectors and aligner hardware designed to minimize contact with the EUV reticle backside during handling and alignment operations. Reticle extraction from the SMIF pod is carried out by a four-axis atmospheric robot under ISO Class 2

laminar flow conditions. It is then transferred into a two-chamber load lock with the transfer chamber vacuum back end housing a three-axis vacuum robot and customized substrate aligner. The loader system was tested by loading and unloading a mask between the SMIF pod and the in-vacuum aligner via the load lock and the transfer chamber 250 times. The mask was inspected for particle defects before and after the test with a KLA Tencor Surfscan that is sensitive to particle sizes of 200 nm and larger located in the Class 10 assembly area. Inspection revealed that only 16 particles of >200 nm had been added by the 250 load/unload cycles.

The system provides reticle placement accuracies on the chuck of ± 75 μm (3σ). Given the small 50- μm field of view of the imaging objective, this high accuracy helps to expedite fiducial mark acquisition by the imaging system. The system is fully SEMI standard compliant and is tuned to handle EUV reticles with minimal risk of particulate contamination.

9.4.8 EUV reticle aerial image capture results

Figure 9.42 shows sample aerial images captured from an EUV reticle in the RIM-13 tool. The ability to clearly resolve the dense 88-nm lines and spaces features in Fig. 9.42(b) demonstrates well the theoretical resolution limit of the 0.0625-NA EUV imaging capability of the tool.

9.4.9 Software

9.4.9.1 Interface

While the electro-opto-mechanical design of the RIM-13 is complex, the operator user interface is a simple image analysis GUI that can be operated from a remote

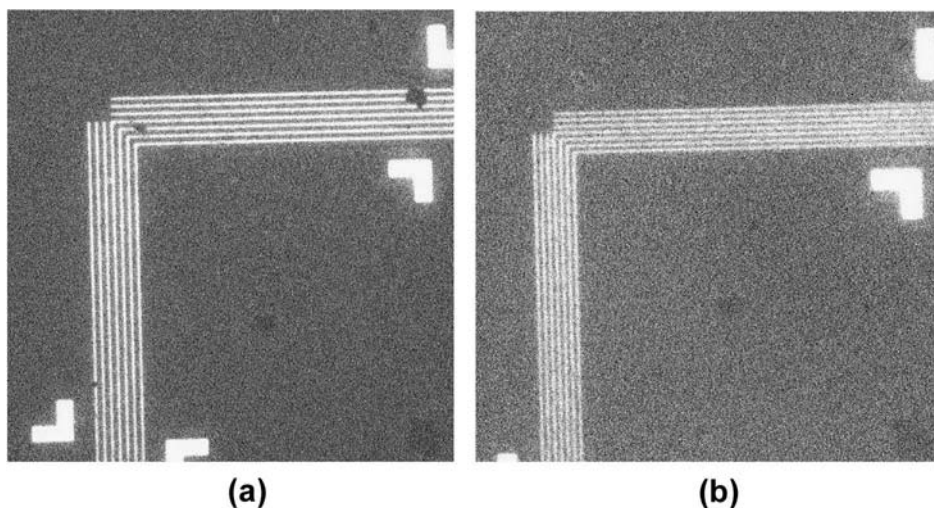


Figure 9.42 Approximately 15- μm square fields on an EUV reticle with bright line elbows captured on a dark field: (a) 120-nm 1:1 L/S, (b) 88-nm 1:1 L/S. Exposure time = 150 sec operating the pulsed source continuously at 50 Hz.

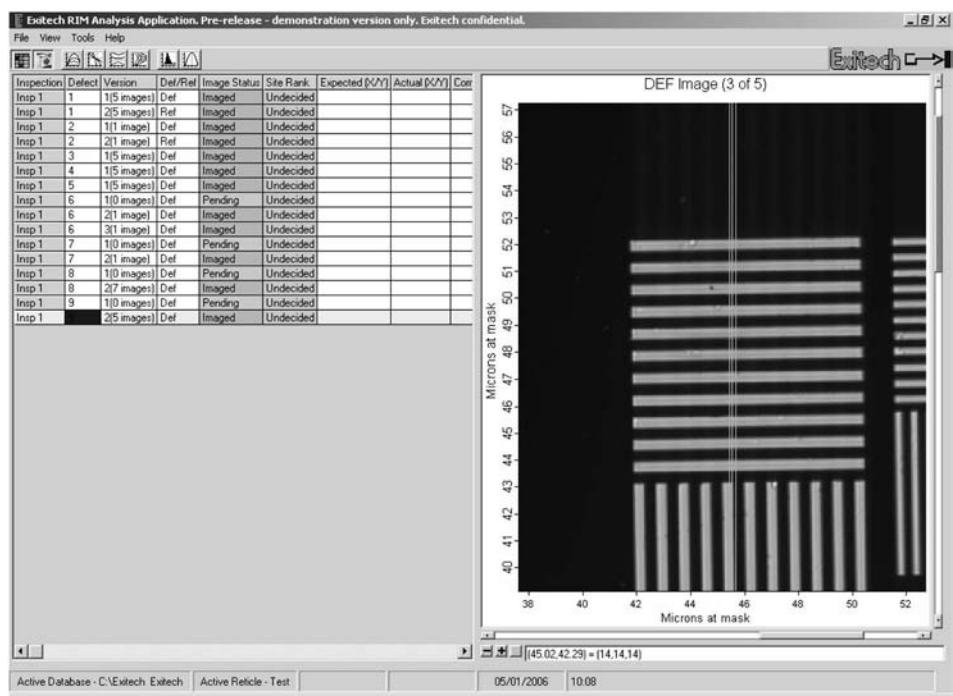


Figure 9.43 Database and sample image ready for analysis.

computer with a network connection to the tool. Reticles are first loaded into the tool by an operator. All the necessary tool hardware functions such as position moves, fiducial acquisition, image acquisition, through focus image capture, etc. can be performed automatically with little or no input from the operator. Indeed, while data are being analyzed from one defect on the reticle, the tool may be acquiring images in automatic mode from another site. Defects selected for analysis from archive databases of reticle features also can be analyzed in a similar fashion.

9.4.9.2 Example analysis sequence

The purpose of reticle defect analysis in the RIM-13 tool is to establish how defects whose locations have been identified by a different defect location tool may print when the photoresist is exposed by the aerial image generated. As explained earlier, to perform this function the optical system must closely emulate that of an EUV exposure tool (scanner).

For a typical defect analysis, several images of the defect are acquired automatically, one at best focus and others at symmetric intervals on either side of best focus. Figure 9.43 shows well-resolved images of horizontal and vertical 500-nm lines and spaces obtained during setup and testing of the 50× visible microscope prior to its installation inside the vacuum chamber. These images were obtained by using white light to illuminate a scintillator that had a calibration test mask in contact with its front surface to simulate 50-nm L/S on the reticle. Also shown in

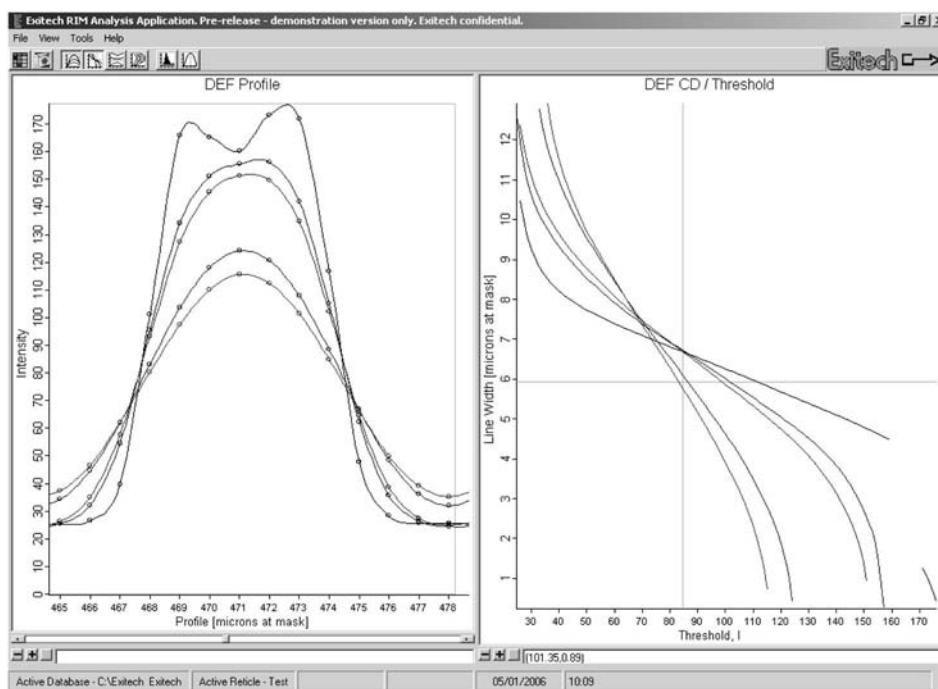


Figure 9.44 Smoothed profiles and CD versus threshold plots.

Fig. 9.43 is a screenshot from the analysis application showing the database entry for a given defect.

For each image in a data set, the likely first analysis step is a plot of the profile and CD against a user-settable exposure intensity “threshold” level normalized to the peak pixel value for the feature under investigation—analogue to dose in a resist exposure. A mouse click selects a location on the image and generates the plots. The left panel of Fig. 9.44 shows the profile indicated by the rectangle in the right panel of Fig. 9.43. Data points from the through-focus data set are plotted along with the fitted line calculated by the software.

In this data set there is actually a defect in the line that leads to the dip in the top of the best-focus profile. This subtlety demonstrates the value of this type of aerial image analysis, since the defect is not visible in either of the pairs of defocused profiles (which show reduced contrast related to their separation from the best-focal plane). The RIM-13 software allows all plots to be compared to similar plots from a known good location, either contained in a database or acquired from the reticle as a reference image set.

The next analysis step might be a plot of CD versus defocus for various thresholds (Bossung plots). Again, the software automatically performs the necessary fits and interpolations. The Bossung plot is shown in the left panel of Fig. 9.45. Finally, as shown in the right panel of this figure, the software generates a graph of defocus against threshold for a given CD. Here, three lines of constant CD are shown. The range of CDs plotted can be selected to correspond to the allowable CD range in

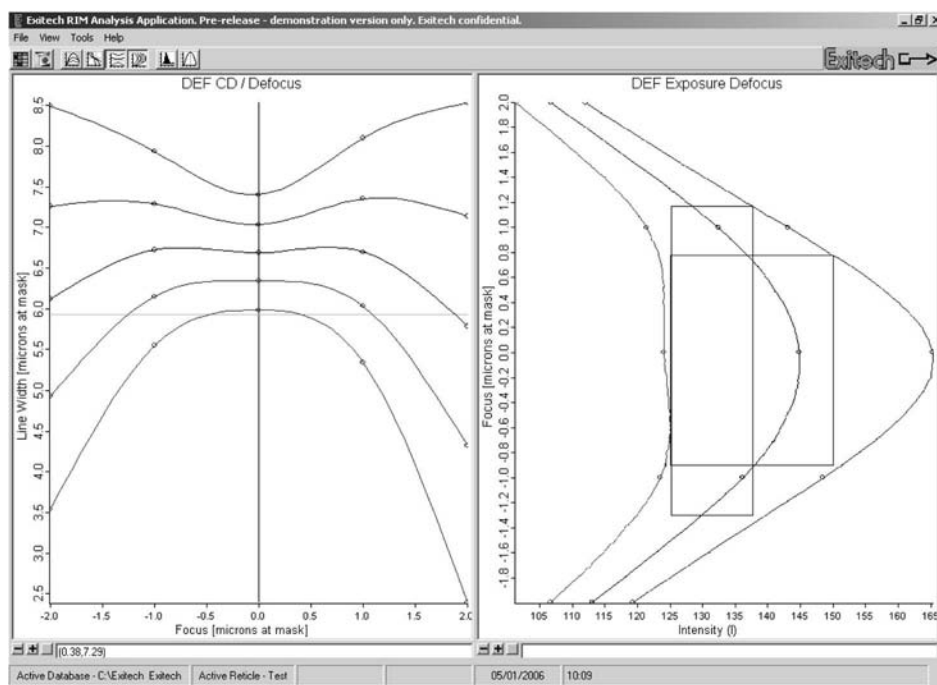


Figure 9.45 Bossung and process window plots.

the actual lithography process of interest. A dose tolerance related to the exposure control latitude of the exposure tool is selected, and the software calculates the corresponding focus-exposure process windows for which satisfactory printing is expected. These are shown for two different settings as the two rectangles in Fig. 9.45. The process windows will, of course, be different for defect-free and defect-containing sites. The software allows a comparison and assessment to be made of whether there is a sufficient process window for the reticle to be used despite the presence of a defect. If not, the defect will likely need to be repaired and inspected again afterwards.

For ease of use, the RIM-13 GUI is highly configurable and flexible. For example, Fig. 9.46 shows all the panels displayed together in a single screen shot.

9.5 Summary and Future Outlook

The MS-13 and RIM-13 are the first commercial EUVL tools capable of high-resolution imaging at EUV wavelengths specifically designed for use by the semiconductor industry for next-generation lithography (NGL) applications. Two MS-13 Microstepper tools have been installed at customer sites and routinely produce sub-50-nm resolution imaging in photoresists. The RIM-13 tool is a reticle imaging actinic microscope capable of capturing aerial images from EUV reticles with illumination and imaging characteristics that emulate full-field production scanner tools. This tool fulfills essential industry requirements for actinic inspection

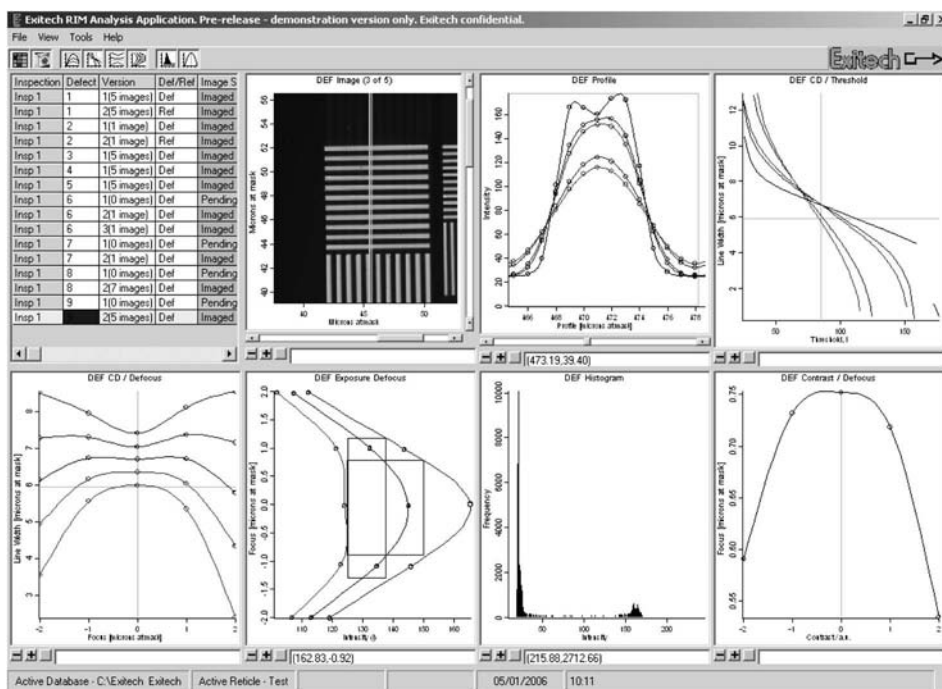


Figure 9.46 Single screen shot of multiple image analysis panels.

and printability studies of amplitude and phase defects on blank and patterned EUV reticles. Both tools are highly automated and conform to the SEMI standards for wafer and mask handling by transferring reticles from standard SMIF boxes and returning them after inspection. Looking further into the future as lithography moves through successive nodes beyond 32 nm, roadmaps for the development of higher-resolution versions of the MS-13 and RIM-13 tools are currently under consideration.

Given the long lead times, high risks, and costs to develop tools in a challenging new technology such as EUVL, projects like the MS-13 and RIM-13 are invaluable for providing early learning and building infrastructure. They allow tool providers and users alike to continue developments that will enable production-worthy tools and processes to be ready when the semiconductor industry eventually adopts EUVL for high-volume manufacturing (HVM)—currently predicted on the ITRS roadmap to be between 2011 and 2013. Because the return on the investment (ROI) required to develop such tools is unlikely to be accrued before HVM adoption, shorter-term interim R&D tool markets must be developed to enable wider EUVL participation and to enable ROI for tool and process providers.

Acknowledgments

The development of the EUV tools described in this chapter would not have been possible without the many outstanding contributions made by Exitech mechanical, electrical, and software engineers M. Booth, O. Brisco, A. Brunton, J. Cashmore, P. Elbourn, G. Elliner, J. Greuters, P. Grünewald, R. Gutierrez, M. Harman, J. Hirsch, S. Hough, L. Kling, N. McEntee, S. Mundair, D. Rees, P. Richards, V. Truffert, I. Wallhead, and M. Whitfield. Essential to the success of these projects was the great skill and enthusiasm provided by many subsuppliers and collaborators, including AIXUV, BOC Edwards, Brookes Automation, Carl Zeiss SMT, CVT Polaron, Electrogrip, SSG Tinsley, Hyperion Developments (formerly Paragon Optics), IRD, IDE, Leica Microsystems, Physik Instruments, Rockwell-Anorad, Schneeberger, Xtreme Technologies, LLNL, LBNL, Sandia National Laboratories, and the University of Wisconsin. We also gratefully acknowledge the many helpful contributions to these projects made by Intel and SEMATECH technical staff. Finally, the work benefited greatly from a license agreement with the EUV LLC that covered access to and use of their intellectual property. A great thank you is extended to all those individuals and organizations that helped Exitech bring these challenging EUV projects to fruition.

References

1. A. Brunton, J. Cashmore, P. Elbourn, et al., "High-resolution EUV Microstepper tool for resist testing and technology evaluation," *Proc. SPIE* **5374**, 869–880 (2004).
2. M. Booth, O. Briso, A. Brunton, et al., "High-resolution EUV imaging tools for resist testing and aerial image monitoring," *Proc. SPIE* **5751**, 78–89 (2005).
3. A. R. Stivers, P.-Y. Yan, G. Zhang, et al., "EUV mask pilot line at Intel Corporation," *Proc. SPIE* **5567**, 13–22 (2004).
4. L. C. Hale, R. M. Hudyma, J. S. Taylor, R. L. Thigpen, and C. A. Chung, "High NA camera for an EUVL Microstepper," paper presented at 15th Annual American Society for Precision Engineering, Scottsdale, Arizona, October 2000.
5. R. M. Hudyma, "An overview of optical systems for 30 nm resolution lithography at EUV wavelengths," *Proc. SPIE* **4832**, 137–148 (2002).
6. E. Sohmen, "Optical system for EUV Microstepper," 3rd International EUVL Symposium, Miyazaki, Japan, Paper To01 (Nov. 2004).
7. O. Oestreich, R. Klein, F. Scholze, et al., "Multilayer reflectance during exposure to EUV radiation," *Proc. SPIE* **4146**, 64–71 (2000).
8. J. M. Roberts, T. Bacuita, R. L. Bristol, et al., "One small step: the world's first integrated EUVL process line," *Proc. SPIE* **5751**, 64–77 (2005).
9. H. B. Cao, W. Yueh, J. M. Roberts, et al., "EUV resist patterning performance from the Intel microexposure tool (MET)," *Proc. SPIE* **5753**, 459–466 (2005).

10. M. Chandhok, S. H. Lee, E. M. Panning, J. Roberts, and H. B. Cao, "Characterization of flare on Intel's EUV MET tool," *Proc. SPIE* **5751**, 293–300 (2005).
11. P. Naulleau, K. A. Goldberg, E. Anderson, et al., "Status of EUV micro-exposure capabilities at the ALS using the 0.3-NA MET optic," *Proc. SPIE* **5374**, 881–891 (2004).
12. P. Naulleau, K. A. Goldberg, E. Anderson, et al., "EUV microexposures at the ALS using the 0.3-NA MET projection optics," *Proc. SPIE* **5751**, 56–63 (2005).
13. M. Booth, A. Brunton, J. Cashmore, et al., "RIM-13: A high-resolution imaging tool for aerial image monitoring of EUV reticles," *Proc SPIE* **5992**, 762–773 (2005).
14. M. Booth, A. Brunton, J. Cashmore, et al., "RIM-13: A high-resolution imaging tool for aerial image monitoring of patterned and blank EUV reticles," *Proc. SPIE* **6151**, B1–12 (2006).
15. R. Lebert, C. Wies, B. Jaegle, et al., "Status of EUV-lamp development and demonstration of applications," *Proc. SPIE* **5374**, 943–953 (2004).
16. R. Hudyma, "High numerical aperture ring field projection system for extreme ultraviolet lithography," U.S. Patent 6,033,079 (2000).
17. M. Kroon and R. Stuik, "Luminescent materials for EUV detection purposes," *Proc. SPIE* **4343**, 665–675 (2001).
18. B. La Fontaine, et al., Submicron, soft x-ray fluorescence imaging," *Appl. Phys. Lett.* **66**, 282–284 (1995).
19. Semiconductor Equipment and Materials International (SEMI), <http://www.semi.org>.
20. R. Atkinson, "A simple theory of the Johnson-Rahbek effect," *J. Phys. D Appl. Phys.* **2**, 325–332 (1969).



Malcolm Gower has published more than 150 papers covering the scientific and industrial applications of photons, lasers, and optics. He has written widely on laser applications, authoring chapters in *Laser Processing in Manufacturing* (Chapman and Hall), *Nanotechnology in Medicine and the Biosciences* (Gordon and Breach), the *Handbook of Laser Technology & Applications* (Taylor & Francis), and *Optical Phase Conjugation* (Springer-Verlag). He has held research and teaching positions at the NASA-Ames Research Center; the University of California, Berkeley; the University of Oxford; and the Rutherford Appleton Laboratory. He was co-founder, chairman, and technical director of Exitech, a leading manufacturer of photon-based micro- and nanofabrication tools. In 2006, he founded Nanophoton Technologies, a company specializing in applying photonics to nanotechnology. He is a Fellow of the Institute of Physics (IoP) and the Institution of Engineering and Technology (IET). In recognition for Services to Industrial Laser Development, he was appointed a member of the Order of the British Empire (MBE) in 1993 by Queen Elizabeth II.

Chapter 10

Fundamentals of EUVL Scanners

Kazuya Ota

Contents

10.1	Introduction	494
10.2	Illumination Optics	494
10.2.1	Illumination optics design	494
10.2.2	Source requirements	496
10.2.2.1	Source size	496
10.2.2.2	Repetition frequency	497
10.2.3	Thermal loading of illuminator	497
10.3	Projection Optics	498
10.3.1	Numerical aperture	498
10.3.2	Magnification and field size	501
10.4	Stages	502
10.4.1	Reticle and wafer stages	502
10.4.2	Reticle chuck	503
10.4.3	Wafer chuck	505
10.5	Sensors	506
10.5.1	Reticle focus sensor	506
10.5.2	Wafer focus sensor	506
10.5.3	Wafer alignment sensor	507
10.5.4	Aerial image sensor	507
10.5.5	Dose sensor	507
10.6	Handling Systems	508
10.6.1	Reticle handling system	508
10.6.2	Wafer handling system	508
10.7	Vacuum and Environment System	508
10.8	Budgets	509
10.8.1	Overlay budget	509
10.8.2	Focus budget	509
10.8.3	Wafer throughput budget	510
10.9	Summary	511
	Acknowledgments	511
	References	512

10.1 Introduction

Other than their use of different wavelengths, EUV and DUV scanners are similar instruments. Since there are no substantial transparent materials for EUV light, the illumination and projection optics must be catoptric and the light path must be in a vacuum. Much more effort and a greater cost are needed to switch the wavelength from 193 to 13.5 nm than to switch it from 248 to 193 nm.

In a DUV scanner, light with a 193-nm wavelength emitted from an argon-fluorine (ArF) excimer laser is directed to a reticle by illumination optics that consist of many optical elements. Images on a reticle are projected onto a wafer by projection optics of 1/4 magnification. A reticle and a wafer are each mounted on the scanning stage, and they are run synchronously at a speed that corresponds to the magnification of the projection optics. Fiducial marks on the stages are used for various calibrations. A wafer alignment sensor detects the position of the wafer alignment mark on a wafer. The distance between the wafer surface and the projection optics is measured with a wafer focus sensor.

An EUV scanner uses light with a 13.5-nm wavelength from a laser-produced plasma (LPP) source or a discharged-produced plasma (DPP) source. The illumination and projection optics consist of reflective optical elements; EUV reticles are a reflective type as well. The reflective elements are coated with molybdenum-silicon (Mo/Si) multilayers (MLs), and the reflectivity is in the range of 60 to 70%. Because the reflectivity of Mo/Si-coated elements can be easily degraded by carbon contamination or oxidation, the partial pressure of hydrocarbon and water inside EUV scanners must be controlled to a very low level. However, the body, stage, wafer alignment sensor, and wafer focus sensor can be designed with optical lithography technology.

10.2 Illumination Optics

The performance required of illumination optics is uniformity of the field intensity and coherency, and transmissibility from the source to a reticle. The system should use as few mirrors as possible because the reflectivity of Mo/Si MLs is at best only 70%. Other than this fundamental performance requirement, the illumination optics of the current DUV scanner has additional functions, but some of these functions must be downgraded on EUV scanners because of the limitation on the number of mirrors.

10.2.1 Illumination optics design

The DUV scanner design, which makes use of fly's-eye lenses, is the most reasonable for optical scanners. As an example, a multifaceted mirror system¹ for EUV scanners is introduced below. This system has two reflectors composed of multifaceted mirrors; one reflector has arc-shape elements and the other has rectangular elements (see Fig. 10.1).

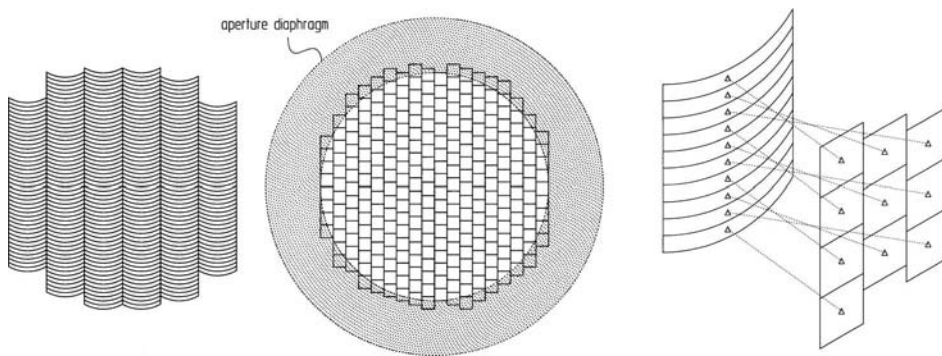


Figure 10.1 Two reflectors composed of multifaceted mirrors. (Reprinted from Ref. 1 and Ref. 17.)

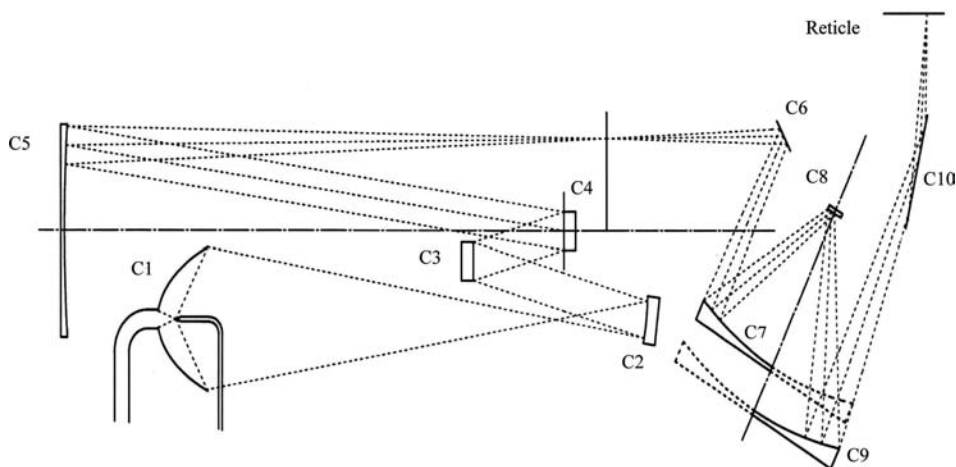


Figure 10.2 EUV illumination optics. (Reprinted from Ref. 17.)

Figure 10.2 shows the entire EUV illumination optics. It consists of an ellipsoidal collector C1, collimator C2, arc-shaped multifaceted reflector C3, rectangular multifaceted reflector C4, condenser C5, folding mirror C6, image relay mirrors C7, C8, and C9, and grazing mirror C10. Mirrors C1 through C9 are coated with Mo/Si MLs. C10 is coated with an appropriate material such as ruthenium (Ru) or platinum (Pt).

A pinhole and/or a Si, beryllium (Be), or zirconium (Zr) membrane window are located between C1 and C2 to eliminate debris and out-of-band light. C1 is generally considered to be part of the source unit, and the focusing point after C1 is called the intermediate focus (IF). C3 and C4 have their elements arranged side by side in a dense configuration. These two reflectors make the field intensity and illumination coherency uniform. C4 is conjugate to the aperture stop in the projection optics. Various illumination conditions, such as a high coherence factor,

a low coherence factor, and annular and off-axis illumination, can be adapted by adjusting stops on C4.

An intermediate image plane between C5 and C6 is the reticle conjugate, which contains a static slit opening that determines the dynamic field uniformity and a scanning slit that makes it possible to select the exposure area, such as a test elements group (TEG) pattern. This illumination design has nearly full specifications for wafer scanners, but it probably has too many mirrors to achieve high wafer throughput. Some optimization and compromise are necessary among the wafer throughput, uniformity, and additional functions.

10.2.2 Source requirements

As mentioned in Sec. 10.1, the current potential EUV source technologies are LPP and DPP sources. Their structural differences are considerable, and the EUV emission from a DPP source is more difficult to collect. An LPP has a large space for arranging illumination optics around the emission point except for the obscuring solid target, and more than 2π sr of emitted light is collectable. In contrast, a DPP source has large electrodes that tend to interfere with the light reflected by the first mirrors. To compensate for this disadvantage, DPP sources tend to employ a concentric grazing mirror unit as a collector to focus light at IF.

10.2.2.1 Source size

Light from the LPP source is emitted into a large solid angle. The ellipsoidal collector C1 is able to collect more than 2π sr (up to 3π sr) of light. Theoretically, the collectable étendue is limited by the field size, the numerical aperture (NA) of the projection optics, and the coherence factor. Figure 10.3 shows the relationship

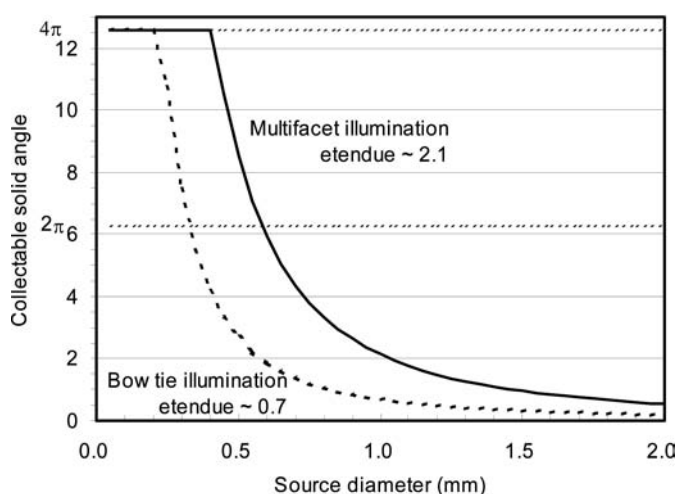


Figure 10.3 Relationship between collectable solid angle and source size. Multifaceted illumination and “bow tie” illumination² are compared. (Reprinted from Ref. 17.)

between collectable solid angle and source size, where the ring field size on a wafer is 1×22 mm, the NA is 0.25, and the coherence factor is 0.7. The relationship between source size and collectable solid angle is a trade-off. If the emission angle is large, the source size should be small, or the greater part of the power is lost through the illumination optics.

The stability of the emission point is also important. Pulse-to-pulse position instability substantially enlarges the source size. A light source with diameter d and stability $\pm a$ is equivalent to a perfectly stable source with diameter $d + 2a$. Therefore, fluctuation of the emission point should be suppressed so it is as small as possible.

10.2.2.2 Repetition frequency

The repetition frequency of the source is an important parameter. Each point on a wafer requires many pulses to achieve critical dimension (CD) uniformity. The average number of pulses irradiated onto each point N_{pulse} is given by

$$N_{\text{pulse}} = F_{\text{pulse}} \times W_{\text{slit}} / V_{\text{scan}},$$

where F_{pulse} is the pulse frequency, W_{slit} is the field size along the scanning axis, and V_{scan} is the scanning speed. Scanning speed is controlled such that the number of pulses is an integer. However, some points receive $N_{\text{pulse}} + 1$ and other points receive $N_{\text{pulse}} - 1$ pulses because of scanning synchronization imperfection. This phenomenon causes CD nonuniformity. Although current DUV scanners have graded areas at both slit ends to mitigate this phenomenon, a minimum average number of pulses of 50 is required for CD control. Assuming that N_{pulse} is 50, W_{slit} is 1 mm, and V_{scan} is 200 mm/s, the required repetition frequency is 10 kHz. If V_{scan} is 100 mm/s, then a 5-kHz repetition frequency is sufficient.

The pulse-to-pulse intensity stability of the source must meet the specifications within the designated number of pulses. Assuming that the pulse-to-pulse intensity fluctuates with Gaussian distribution σ_{pulse} , this fluctuation is averaged into $\sigma_{\text{pulse}} / \sqrt{N_{\text{pulse}}}$. If the pulse-to-pulse intensity instability is 7% rms and the average number of pulses is 50, CD uniformity is 1% rms.

10.2.3 Thermal loading of illuminator

Among the mirrors in the EUV scanner, the ellipsoidal collector C1 receives and absorbs the maximum power. The absorbed radiant energy is converted into thermal energy, which raises the temperature of the C1 mirror. Temperature control of the back surface of this mirror is necessary so that interdiffusion of MLs does not occur at high temperatures. The critical temperature limit is about 200°C.³

Assuming that the laser power is 10 kW, nearly 70% of the laser power is converted to the radiant energy in 2π sr, the collectable solid angle is π , the collectable EUV power is 50 W, and the distance between the source and mirror is

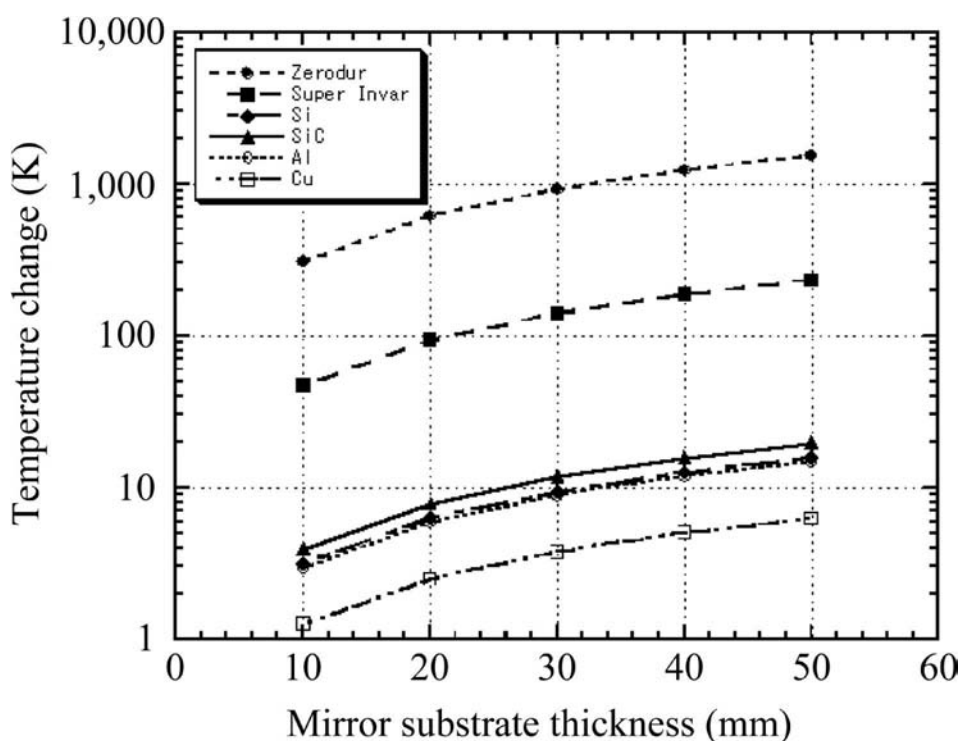


Figure 10.4 Temperature change of the mirror surface. (Reprinted from Ref. 17.)

150 mm, the irradiated power on the mirror substrate per unit area is 4.9 W/cm^2 . Temperature change of the mirror surface is shown in Fig. 10.4, where the horizontal axis shows the thickness of the mirror substrate, and the back surface is temperature-controlled. The thickness limit of the C1 mirror substrate is less than 10 mm for low-expansion glass, 40 mT for super invar, and more than 100 nm for SiC, Si, aluminum (Al), and copper (Cu). If super invar, SiC, Al, or Cu is used for the C1 mirror substrate, a surface-smoothing technique, such as electro-less nickel plating⁴ or polyimide coating,⁵ is required to obtain higher reflectivity.

10.3 Projection Optics

10.3.1 Numerical aperture

The uncertainty of a new patterning technology makes it difficult to decide the NA of high volume manufacturing (HVM) lithography tools. The Engineering Test Stand (ETS), the world's first full-field EUV scanner, was designed to have a 0.1 NA to study 100- to 70-nm patterns, and the k_1 factor was 0.74 to 0.52. ASML and Nikon individually planned to develop their own EUV alpha scanners, but they selected the same 0.25 NA. For 45-nm and 32-nm resolution, a 0.25 NA was used with k_1 factors of 0.83 and 0.59, respectively. The depth of focus (DOF)

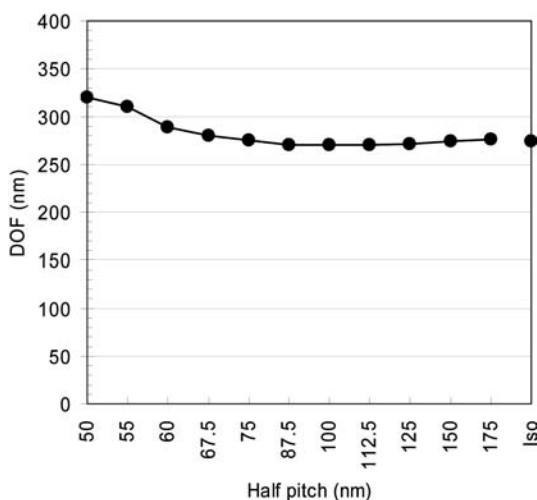


Figure 10.5 DOF with a 50-nm pattern (NA = 0.25). (Reprinted from Ref. 17.)

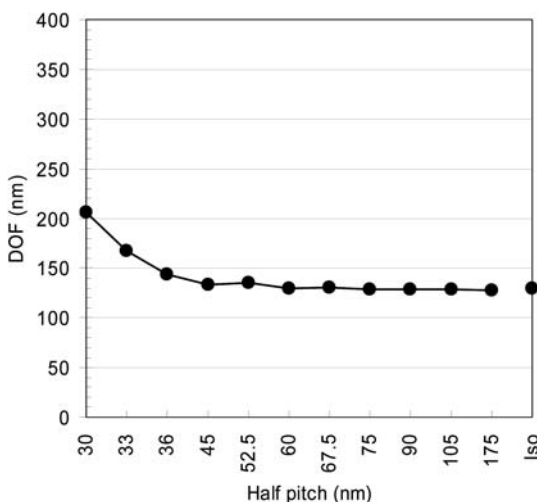


Figure 10.6 DOF with a 25-nm pattern (NA = 0.25). (Reprinted from Ref. 17.)

was simulated under the conditions of a 0.25 NA, a coherence factor of 0.8, and a target line width of 50 nm; the result is shown in Fig. 10.5. The horizontal axis shows the half-pitch of a dense pattern, and the vertical axis shows the DOF with a CD variation of $\pm 7\%$. For this simulation, binary patterns were used; the pattern width error was $\pm 2\%$ and the dose error was $\pm 2.5\%$. A 320-nm DOF was obtained with 50-nm lines and spaces. Figure 10.6 shows the DOF of 25-nm lines, assuming logical patterns. The designed pattern width was 30 nm on the wafer, which was reduced to 25 nm by an over dosage exposure. A 130-nm DOF was obtained with an isolated line.

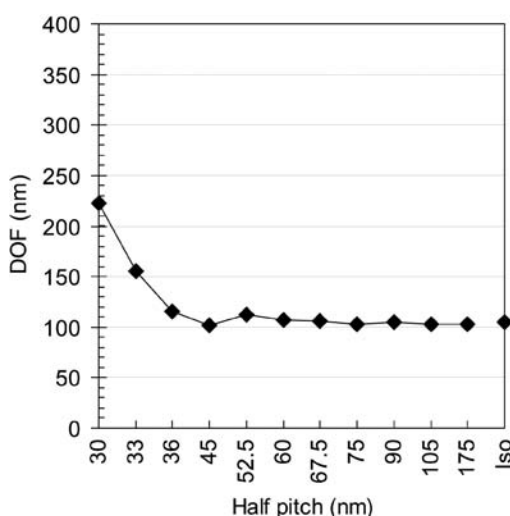


Figure 10.7 DOF with a 25-nm pattern ($NA = 0.25$, obscuration 25%).

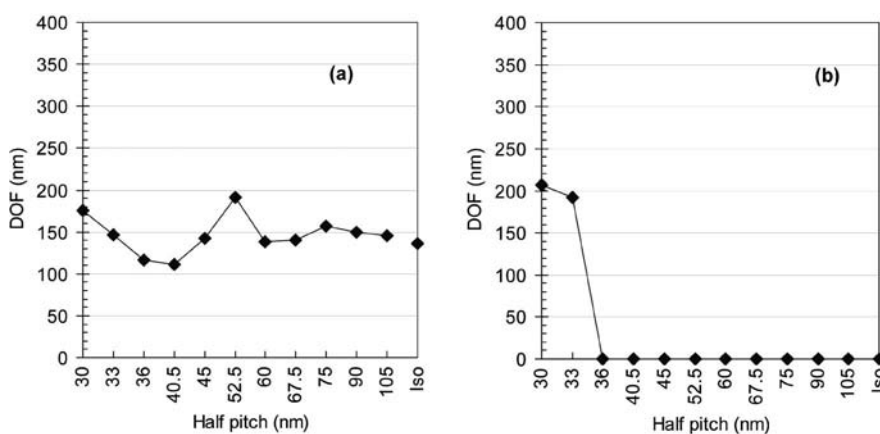


Figure 10.8 DOF with a 25-nm pattern with $NA = 0.25$ for (a) no obscuration, and (b) 25% central obscuration.

To increase the NA to more than 0.25, some eight-mirror systems have been proposed.^{6,7} It may be that a projection optical system having a central obscuration is a strong candidate for a higher numerical aperture system, because that kind of optics can relatively realize a higher numerical aperture and fewer aberrations. To employ an optical system having a central obscuration, it is important to evaluate its influence on DOF. Figure 10.7 shows the DOF for 25-nm lines with a 0.25 NA and a 25% central obscuration, where 25% is the ratio of the radius at the pupil plane. There is no significant difference between Figs. 10.6 and 10.7. As a result, circuit pattern design rule restrictions are unnecessary in the explored parameter space.

However, if a phase shift mask (PSM) is used, a different result is obtained. Figure 10.8 shows the DOF with a 15-nm line pattern; Fig. 10.8(a) shows results

with no obscuration optics, and Fig. 10.8(b) shows results with 25% obscuration optics. In this simulation, the designed pattern width was 30 nm on the wafer, which was reduced to 15 nm by an over-dosage exposure. The phase shift pattern consists of a 30-nm (4 $\times$) chromium (Cr) line and 90-nm (4 $\times$) shifter lines on both sides of the Cr line.

10.3.2 Magnification and field size

The field size of current DUV scanners is 26 mm $\times$ 33 mm; the reticle is a square with six-inch sides and the magnification of the projection lens is 1/4. A large area is required for high wafer throughput. On the other hand, 1/5 magnification is expected with reticle pattern drawing, where the field size is 22 $\times$ 26 mm. The demerit of 1/5 magnification is a lower wafer throughput than with 1/4 magnification, because the number of fields in a wafer is 1.7 times larger and stepping times are consequently larger.

The merit of 1/5 magnification is a higher overlay accuracy. The incident angle of reticle illumination light must be tilted slightly so that incident light and reflected light do not overlap each other, because no half-prism for EUV light is available. The NA must be considered when deciding on the incident angle. The lower limit of the incident angle equals the arcsin of the NA on the reticle side, which corresponds to the product of the NA on the wafer side and the magnification of the projection optics. The field width in the scanning direction also must be included. This relationship is shown in Fig. 10.9.

Additional space is needed for the arrangement of the folding mirror. Assuming a field width of 1 mm on the wafer, a distance between the reticle and the folding mirror of 400 mm (plus an extra 10 mm of space) the incident angle is 130 mrad with 1/4 magnification and 111 mrad with 1/5 magnification. The image

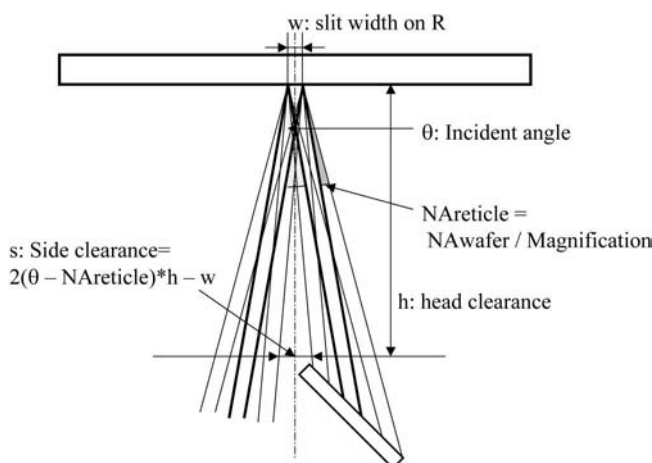


Figure 10.9 Relationship between incident angle and NA. (Reprinted from Ref. 17.)

placement shift on the wafer upon defocusing of the reticle Δ is given by

$$\Delta = \theta \delta_z m,$$

where θ is the incident angle, δ_z is the defocus of the reticle, and m is the magnification. Assuming that the overlay budget for this shift is 3 nm, a 92-nm defocusing of the reticle is allowed with 1/4 magnification and 135 nm with 1/5 magnification; that is, tolerance for reticle z control with 1/5 magnification is about 1.5 times looser than with 1/4 magnification. This margin can be shared among reticle flatness, reticle chuck flatness, and reticle focus control. Moreover, it has been shown that a nonnormal incident angle produces intensity asymmetry between +first-order diffraction light and –first-order diffraction light, wafer telecentricity breaks, and image placement shifts.^{8,9} Clearly, a small incident angle is more advantageous.

The 1/4 and 1/5 magnifications of the projection optics have their advantages and disadvantages. The 1/4 magnification has the advantage of good wafer throughput while the 1/5 magnification has the advantage of overlay. Of course, the 1/5 magnification reticle has the advantage of small CD variation from pattern drawing. In integrated circuit (IC) mass production, a large field size (26 × 33 mm) is used only in the initial product development phase; a 22 × 26 mm field is sufficient for subsequent production. Improving the overlay and CD uniformity has a corresponding benefit to scanner productivity that partly offsets the reduced wafer throughput.

10.4 Stages

We can apply the same stage technologies used for DUV scanners to EUV scanners, i.e., linear motor actuators and an air levitated/guide system. The air pads support the weight of the stage with little friction, and linear motor actuators drive the stage with high acceleration and speed. When we use this concept for EUV scanners, we have to modify the system to be vacuum compatible—for example, to place air pads outside the vacuum chamber or to adopt air pads with air inlets surrounding the outlets.

10.4.1 Reticle and wafer stages

There are several systems for wafer exposure tools. A contact aligner and a proximity aligner have no projection optics and the projection magnification is 1/1. Stages used for the tools do not have to move during wafer exposure. A mirror projection aligner has projection optics with 1/1 magnification. Since the projection area of the mirror projection aligner is arc-shaped and the mask is rectangular, the mask stage and the wafer stage run synchronously at the same speed. A wafer stepper has projection optics with 1/5, 1/4, 1/10, or 1/2.5 magnification. Since the projection area of the wafer stepper is much smaller than the wafer, e.g., 26 × 33 mm², the

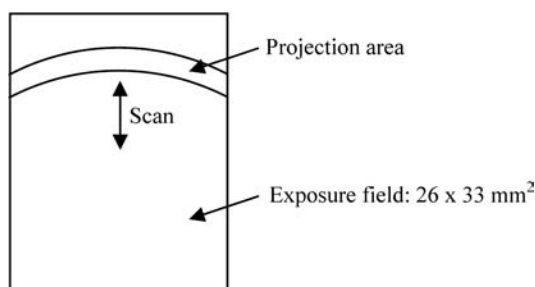


Figure 10.10 Exposure field and projection area of an EUV scanner.

wafer stage must step to the next field one after another and repeat the exposure as many times as the field number, i.e., step and repeat. The wafer stage of a wafer stepper must have high positioning accuracy for overlay and great acceleration for high wafer throughput. A reticle stage of the wafer stepper does not necessarily move during wafer exposure.

A wafer scanner is similar to a wafer stepper except it has a flat rectangular projection area, e.g., $26 \times 8 \text{ mm}^2$. The radius of a circle in which a $26 \times 33 \text{ mm}^2$ rectangle is inscribed is 42.0 mm, but the radius of a circle in which a $26 \times 8 \text{ mm}^2$ rectangle is inscribed is only 27.2 mm, so a wafer scanner can have smaller optics than what is needed for a wafer stepper. A wafer scanner provides a $26 \times 33 \text{ mm}^2$ exposure field to scan the wafer stage and the reticle stage synchronously, and the wafer stage steps to each field one after another like a wafer stepper. Both stages must have high synchronization accuracy for overlay and great acceleration for higher wafer throughput.

Regarding the EUV exposure tool, since it is impossible to obtain a large-enough projection area for the stepper, we must adopt a scanning system. The projection optics of the EUV scanner has an arc-shaped projection area like that shown in Fig. 10.10. The scanning speed of the reticle stage is four times faster than the speed of the wafer stage if the projection optics has $1/4$ magnification. Higher acceleration and greater speed are effective in achieving high wafer throughput, but ultimately the source power limits the throughput of the scanner. Accordingly, we do not need such a high acceleration speed for an EUV scanner as those for DUV scanners.

10.4.2 Reticle chuck

Electrostatic chucks are used for the reticle chuck and the wafer chuck of EUV scanners, because vacuum chucks, which DUV scanners commonly use, do not operate in vacuum. The reticle chuck must hold a reticle during exposure so the reticle does not slip due to acceleration of the reticle stage. We can calculate the required chucking force F_{CHUCK} for a reticle chuck by

$$\mu(F_{\text{CHUCK}}/k - mg) > ma,$$

where m is the mass of the reticle, a is the stage acceleration, μ is the friction coefficient of the chuck, g is the gravitational acceleration, and k is the safety factor. If $m = 0.3$ kg, $a = 39.2$ m/s², and $\mu = 0.2$, F_{CHUCK}/k has to be more than 47 N. Assuming the chucking area is 0.02 m², the minimum required chucking pressure is 3 kPa. The SEMI standard P40 provides specifications for EUV reticle chucks, and it specifies a chucking pressure of 15 kPa, so the safety factor is 5.

There are two overlay error mechanisms due to the chuck nonflatness, out-of-plane distortion (OPD) induced error and in-plane distortion (IPD) induced error. EUV scanners must employ hemi-telecentric optics because of the use of reflective reticles. The positional shift of an image on a wafer Δx is expressed as

$$\Delta x_{\text{OPD}} = \alpha \cdot \Delta z / m,$$

where α is the incident angle of illumination to the reticle, Δz is the reticle defocus, and m is the magnification of the projection optics. If α is 105 mrad, Δz is 48 nm, and m is 4, Δx_{OPD} is 1.3 nm. This is the OPD induced overlay error. To reduce the OPD induced error, SEMI P40 provides the flatness requirement of <48 nm over a 150-mm length in both axes.

The thickness of a reticle is 6.35 mm. If a chuck has a local slope, the reticle on the chuck bends during chucking and a pattern on the reticle shifts according to the angle of the local slope as follows:

$$\Delta x_{\text{IPD}} = t \cdot \theta / m,$$

where t is the thickness of the reticle (6.35 mm), and θ is the local slope of the chuck. If θ is 1 μ rad, Δx_{IPD} is 1.6 nm. This is the IPD induced overlay error. To reduce the IPD induced error, SEMI P40 provides several flatness requirements in several spatial wavelengths.

Thermal load is also an issue for the reticle chuck. An EUV reticle is coated with a Mo/Si ML and its reflectivity is less than 70%. An absorber layer covers the ML by some coverage ratio, so more than half of the input light energy is converted to heat. If the heat is not removed efficiently, the temperature of the reticle rises and thermal expansion of the reticle will affect the overlay. We calculated thermal change of reticle and chuck with a simple 1D model shown in Fig. 10.11.

A reticle is positionally fixed by a chuck mounted on a base plate. We fixed the temperature of the base plate then calculated the saturation temperature at the reticle front surface, the reticle back surface, the chuck front surface, and the chuck back surface (see Table 10.1).

In this calculation, we assumed the reticle thickness T_1 was 6.35 mm, the chuck thickness T_2 was 30 mm, the EUV power of 1 W was converted to heat, the coefficient of thermal conductivity of the reticle was 1.46 W/mK, and the coefficient of thermal conductivity of the chuck was 3.64 W/mK. The heat-transfer coefficient between the reticle and chuck was 30 W/m² K with no temperature control and 450 W/m² K when the temperature was controlled. The heat-transfer coefficient between the chuck and base was 20 W/m² K with no temperature control and

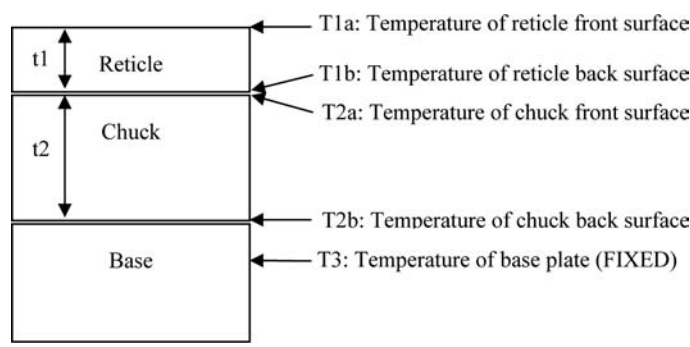


Figure 10.11 1D model for reticle thermal analysis.

Table 10.1 Saturation temperature of reticle and reticle chuck.

Temperature control condition	(1) No temperature control	(2) Chuck backside ^a	(3) Chuck backside and reticle backside ^b
Reticle front surface (K)	4.26	2.14	0.76
Reticle back surface (K)	4.07	1.95	0.56
Chuck front surface (K)	2.59	0.47	0.47
Chuck back surface (K)	2.22	0.10	0.10

^a Apply some active heat conducting means between the chuck and the base plate.
^b Apply some active heat conducting means between the reticle and the chuck in addition (2).

450 W/m² K when the temperature was controlled. The temperature differences between the surfaces of the reticle and the chuck were determined mostly by the coefficient of thermal conductivity of each material. The temperature difference between the reticle back surface and the chuck front surface, and the temperature difference between the chuck back surface and the base plate, were determined by the heat-transfer coefficients, respectively. Tolerance of reticle expansion depends on the overlay budget and there being no clear tolerance boundary, but 3 nm/132 mm (= 23 ppb) is probably within the tolerance range. Assuming the coefficient of thermal expansion to be 10 ppb/K, temperature control of at least the chuck is necessary.

10.4.3 Wafer chuck

The flatness of a wafer chuck within an exposure field must be better than the image DOF, and a flatness of 50 nm or less is required. However, the flatness requirement for the entire wafer chuck is more flexible than that for the reticle chuck, because a scanner has a wafer focus system and can control the height of the wafer field by field.

Thermal load is also an issue of the wafer chuck. A wafer absorbs almost all EUV light energy, which is converted to heat. Since a wafer has a very small heat capacity, the temperature of the wafer rises easily and wafer thermal expansion

produces overlay errors. If the thermal conductance between a wafer and a chuck is low, e.g., $30 \text{ W/m}^2 \text{ K}$, the temperature of the wafer rises by 0.03 to 0.04 K. Assuming the coefficient of thermal expansion of a Si wafer to be 2.6 ppm/K, the wafer will expand by 20 to 30 nm/300 mm. However, if the chuck restrains the wafer expansion and the chuck expansion is lower than the tolerance, this situation is acceptable; however, we must control the slip between the wafer and chuck.

If we introduce helium (He) between a wafer and a chuck, the thermal conductance between them will increase, e.g., $450 \text{ W/m}^2 \text{ K}$. In this case, heat generated at the wafer during exposure is transmitted to the chuck, and the temperature of the wafer rises only by 0.005 K. In this case, thermal current in a chuck is much higher than the previous case, so it is desirable that the thermal conductivity of the chuck be higher.

10.5 Sensors

10.5.1 Reticle focus sensor

The reticle height during exposure must be controlled because the z -directional reticle shift affects overlay. The required precision of the reticle height control is about 10 to 20 nm—much tighter than that required of a DUV scanner and comparable to the required precision of wafer height control. Therefore, a reticle focus sensor is needed. A reticle focus sensor must detect only monotonous structure, i.e., an absorber layer on a ML, while a wafer focus sensor must detect several layer structures. However, the thickness of the absorber layer is about 100 nm, which is several times thicker than the required precision. The absorber area ratio varies from place to place in an exposure field (Fig. 10.12), and a reticle focus sensor needs to detect the surface of the absorber layer regardless of the absorber area ratio.

10.5.2 Wafer focus sensor

Wafer focus is not a characteristic EUV issue. Instead, it is considered to be an extension of a DUV issue. An oblique-incidence optical sensor using visible light may be used as a wafer focus sensor. Since the wafer stage of the EUV scanner is located in a vacuum, the lack of air fluctuation degrades sensor repeatability. Sensing points are arranged along the ring field. Forward- and backward-

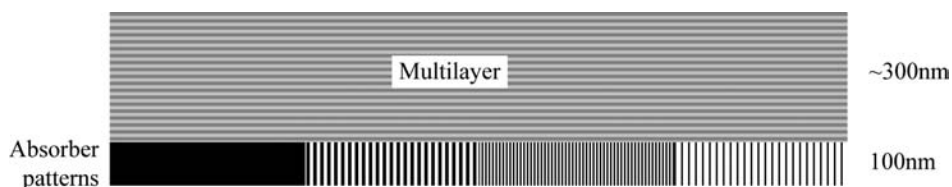


Figure 10.12 Absorber area ratio varies from place to place in an exposure field.

sensing points are required to control the focus during stage scanning. In addition, a focus sensor that uses exposure light is needed to calibrate the visible sensor. An aerial image sensor, described in Sec. 10.5.4, can be used as this calibration sensor.

10.5.3 Wafer alignment sensor

The off-axis sensor is a good candidate for a wafer alignment sensor in EUV scanners as well as for DUV scanners. The field image alignment (FIA) sensor of the Nikon Step and Repeat System (NSR)¹⁰ detects microscopic images using visible broadband light and is negligibly affected by the asymmetric chemical-mechanical polishing (CMP) processed pattern. The desired unification of circuit patterns and alignment marks is impossible because visible light is insufficient for resolving 50-nm lines. Scanning probe microscopes such as the atomic force microscope (AFM) have very high resolution, but the lifetime of probes restricts the productivity of scanners. Still, it is possible to use a scanning probe microscope to calibrate between circuit patterns and alignment marks.

The direct alignment of wafer marks with reticle marks, which was once the mainstream method by using proximity aligners and a mirror projection aligner, does not work on wafer steppers or scanners because the projection optics have large chromatic aberrations. The compensation elements enable direct alignment, but other limitations, such as a usable bandwidth or usable diffraction orders, narrows the process tolerance of the wafer. These restrictions are the primary reasons why the direct alignment method is not used on wafer steppers or scanners, despite its overlay advantage. There is some possibility of adopting direct alignment on EUV scanners because EUV scanner projection optics have very small chromatic aberrations between EUV and visible light.

10.5.4 Aerial image sensor

An aerial image sensor can be used for various calibrations, including a stability check of projection optics aberrations, focus sensor calibration, and alignment baseline measurement. A plate on a wafer stage has some patterns like a knife edge or some slits, and a detector that detects the light that transmits the patterns or the light scattered by the patterns. This technique does not depend on the EUV wavelength, but because the light intensity is very low compared with that of a DUV scanner, it is challenging to develop an aerial image sensor for an EUV scanner, especially for an alpha tool because of its low light intensity.

10.5.5 Dose sensor

To control the exposure dosage, the EUV light intensity at the wafer plane must be measured. The EUV light power per unit area (mW/cm^2) and the resist sensitivity

(mJ/cm²) are necessary to calculate the required exposure time. The intensity measurement is done before the wafer exposure, because it is impossible to measure the intensity on the wafer during exposure. In-situ power monitoring is done with a sensor(s) in the illumination optics. This protocol is the same as that of a DUV scanner. One concern is that the sensitivity of EUV may be altered by contamination over time and will need to be recalibrated.

10.6 Handling Systems

10.6.1 Reticle handling system

Reticle handling is one of the critical issues of EUVL because no pellicle is yet available for production use. It is challenging to keep a reticle clean during handling in an exposure tool. There are risks of particle generation in direct contact by end-effectors and venting/pumping inside a loadlock. To avoid direct contact and to protect patterns from particles, a platelike membrane may be used. The end-effectors contact the platelike membrane, which is removed after the reticle is chucked on a reticle stage. The backside of the reticle must be kept clean, because particles between a mask and a chuck cause IPD-like and OPD-like nonflatness of a mask or a chuck. To protect the backside, the dual pod concept has been proposed for contamination control.¹¹ It is also necessary to protect a reticle on a chuck, and several ideas have been proposed, such as using thermophoretic force,^{12,13} electrophoretic force, or drag force of the airflow.

10.6.2 Wafer handling system

For device mass production, an EUV scanner is expected to have a high wafer throughput of 100 wafers per hour (WPH). To achieve the high throughput, wafers must be brought into a vacuum and quickly carried out into the air. However, quick pumping down and venting generates particles, so it is very difficult to manage high wafer throughput with only one loadlock. Besides, adiabatic expansion by quick pumping down cools the reticle in the loadlock and degrades the overlay.

10.7 Vacuum and Environment System

From the light transmittance point of view, a high-vacuum environment is not required for an EUV scanner. But ML reflectivity is easily reduced by carbon contamination and oxidation, so mirror contamination control is the most important issue for the vacuum environment system of an EUV scanner. For example, if reflectivity of each mirror is reduced from 68 to 67%, light throughput from the source to the wafer decreases by 14% (assuming six mirrors for projection optics, three normal incident mirrors for illumination optics, and one reticle). A vacuum system is usually baked to reduce the water outgassing, but a scanner cannot be baked because

it has many precise components easily affected by heat. A capping layer on the ML is probably required to prevent oxidation.¹⁴ To reduce carbon contamination, molecular oxygen can be introduced.¹⁵

10.8 Budgets

10.8.1 Overlay budget

An example of an overlay budget is shown in Table 10.2.

Error budgets for each factor are around 2 nm, and variations in the sub-nm range are not always significant without improvement of the registration measurement accuracy. Reducing the number of error factors is also important. The registration of circuit patterns is essential, but wafers and reticles are aligned using alignment marks and registration is evaluated using a registration mark such as the box-in-box mark. If these marks and patterns could be combined into one pattern, overlay accuracy would be effectively improved.

10.8.2 Focus budget

An example of a focus budget is shown in Table 10.3.

Table 10.2 Example of an overlay budget of an EUV scanner.

	Error factor	Tolerance (nm)
Mean (X)	Reticle drawing (Reticle alignment mark, wafer alignment mark and registration mark)	±2
	Accuracy of alignment sensor	±1.5
	Distortion stability	±1.5
	Dynamic distortion	±2.5
	Baseline stability	±1.5
	Reticle <i>z</i> control (reticle chuck flatness and reticle focus control)	±1.5
	Reticle flatness: ±50 nm	±1.3
	Subtotal	±4.6
Intrawafer variation (σ)	Wafer thermal deformation	±2
	Wafer stage grid accuracy	±1.5
	Wafer stage positioning accuracy	±3
	Enhanced global alignment	±2
	Wafer process distortion	±1.5
	Subtotal	±4.6
Intrafield variation (σ)	Reticle drawing (IC pattern)	±2
	Reticle thermal expansion	±1.5
	Projection optics distortion stability	±1.5
	Projection optics dynamic distortion	±2.5
	Reticle <i>z</i> control	±1.5
	Reticle flatness	±1.5
	Magnification error	±1
	Wafer process distortion	±1.5
	Subtotal	±4.7
	Total ($X + \sigma$)	±11.2

Table 10.3 Example of a focus budget of an EUV scanner.

	Error factor	Tolerance (nm)
Focus offset	Total focal deviation of projection optics	15
	Absolute focus calibration accuracy	10
	Total offset	25
Focus variation (σ)	Wafer focus sensor repeatability and stage control	15
	Wafer chuck flatness	10
	Stability of projection optics	10
	Reticle focus sensor repeatability and stage control	3
	Reticle and chuck flatness	3
	Total variation	21
Total focus error	Tool total focus error (offset + variation)	46
DOF	DOF	100
	Usable DOF (DOF – total focus error)	54

The image plane of projection optics is not necessarily flat due to the aberrations; this non-flatness is called total focal deviation. Focus sensors measure the wafer and reticle height, but the sensors must be calibrated with another absolute sensor such as an aerial image sensor. These errors are offset errors. The repeatability of focus sensor measurements, stage height control, projection optics stability, and flatness of chucks are focal variation factors.

10.8.3 Wafer throughput budget

A typical wafer throughput model¹⁶ is shown in Table 10.4. The energy required for exposing a wafer is obtained with field-wafer parameters. Assuming a field size of 25×25 mm and 89 fields in a wafer, 78.7% of the wafer area is exposed. As a 25-mm field height is formed by masking a 26-mm field with an aperture, 3.8% ($= 1/26$) of the light power is blocked. Assuming the resist sensitivity to be 5.0 mJ/cm^2 , 2.9 J of energy is needed to expose all fields in a wafer.

The power at the wafer is determined from the source power, illuminator conditions, reticle conditions, and projection optics box conditions. The total transmission of the illuminator and the projection optics box, respectively, are assumed to be 8.4% and 8.1%. The overall component degradation factor includes the collector reflectance degradation, ML mirror reflectance degradation, spectral purity transmission degradation, and so on. It is expected that 115 W of light power is attenuated to 0.321 W from the IF to the wafer as a result.

The exposure time per wafer can be calculated by dividing the total exposure energy at the wafer by the exposure power at the wafer. The stage overhead time includes the scanning stage acceleration and deceleration time, the wafer alignment time, the wafer exchanging time, and so on. The required scanning length for a reticle stage is longer than the 25-mm field size because it includes a 2-mm slit width and about a 3-mm arc height. Time for running this 5-mm extra length may

Table 10.4 Typical wafer throughput model.

Throughput	wfr/hr	100
Time per item		
total time wfr	sec	36.0
stage overhead	sec	27.0
exposure time	sec	9.0
Field-wafer parameters		
wafer diameter	mm	300
% wfr exposed	%	78.7
penalty for not using full field height	%	96.2
resist sensitivity	mJ/cm ²	5.0
Intermediate derivatives at wafer		
total energy/wfr	J	2.9
power at wfr	watt	0.321
PO-box		
reflectivity, mirror	%	67.5
no. near normal mirrors		6
bandwidth mismatch loss	%	5.0
polarization loss	%	5.0
gas absorption PO	%	5.0
total transmission PO	%	8.1
Reticle		
reflectivity reticle	%	65.0
power at reticle	watt	6.1
Illuminator		
total transmission Ill	%	8.4
General		
overall component degradation	%	37.0
Power captured clean inband photons	watt	115.2

be counted as a part of the exposure time, but in this model it is included in the stage overhead.

10.9 Summary

This chapter has described EUV scanner subsystems, which include illumination optics, projection optics, a wafer alignment sensor, a wafer focus of the EUV scanners, etc. The overlay budget, the focus budget, and a wafer throughput model were also described. The greater part of DUV scanner technology can be applied to EUV. In the near future, the increased source power and high-sensitivity resists are expected, although some optimization and compromises are needed among wafer throughput, dose uniformity, and additional functions of the illumination optics.

Acknowledgments

The authors would like to thank Naomasa Shiraishi for his work on DOF calculation.

References

1. H. Komatsuda, "Novel illumination system for EUVL," *Proc. SPIE* **3997**, 765–776 (2000).
2. W. C. Sweatt, "High-efficiency condenser design for illuminating a ring field," in *OSA Proc. Soft X-Ray Projection Lithography*, A. M. Hawryluk and R. H. Stulen, Eds., Vol. 18, pp. 70–72 (1993).
3. D. Stearns, et al., "Thermally induced structural modification of Mo-Si multilayers," *J. Appl. Phys.* **67**, 2415–2427 (1990).
4. K. Murakami, et al., "Reflecting mirror and the manufacturing method," Japanese Patent Application No. 10-339799 (Dec. 1998).
5. R. Soufli, et al., "Smoothing of diamond-turned substrates for extreme-ultraviolet illuminators," *Opt. Eng.* **43**, 3089–3095 (2004).
6. D. R. Shafer, "Projection lithography system and method using all-reflective optical elements," US Patent Number 5,686,728 (Nov. 1997)
7. Y. Omura, "Projection optical system, and projection exposure apparatus having the projection optical system, projection method thereof, exposure method thereof and fabricating method for fabricating a device using the projection exposure apparatus," US Patent Application No. US 2002/0176063.
8. K. Otaki, et al., "Asymmetric properties of the aerial image in extreme ultraviolet lithography," in *Dig. Microproc. Nanotech. 2000*, pp. 46–47, Tokyo (2000).
9. K. Otaki, "Asymmetric properties of the aerial image in extreme ultraviolet lithography," *Jpn. J. Appl. Phys.* **39**, 6819–6826 (2000).
10. K. Ota, et al., "New alignment sensors for wafer stepper," *Proc. SPIE* **1463**, 304–313 (1991).
11. K. Ota, "A new concept of EUV reticle particle protection in handling and new carrier standard proposal," EUV Mask Technology and Standards Workshop, Miyazaki, Japan (Nov. 2004).
12. S. J. Choi, et al., "Massively parallel simulations of Brownian dynamics particle transport in low pressure parallel-plate reactors," *J. Vac. Sci Tech. A* Vol. 14, 660(1996).
13. D. Rader, et al., "Verification studies of thermophoretic protection for EUV masks," *Proc. SPIE* **4688**, 182–193 (2002).
14. S. Bajt, et al., "Improved reflectance and stability of Mo-Si multilayers," *Opt. Eng.* **41**, 1797–1804 (2002).
15. M. Malinowski, et al., "Use of molecular oxygen to reduce EUV-induced carbon contamination of optics," *Proc. SPIE* **4343**, 347–356 (2001).
16. K. Ota, et al., "EUV source requirements for EUV lithography," EUV Sources for Lithography (SPIE Press Book), 27–43 (2006).
17. K. Ota, K. Murakami, H. Kondo, T. Oshino, K. Sugisaki and H. Komatsuda, "Feasibility Study of EUV Scanners," *Proc. SPIE* **4343**, 60–69 (2001).



Kazuya Ota is a Staff Scientist in the EUVL Development Department at Nikon, responsible for determining the EUV exposure tool specifications and components. He graduated in physics from Nagoya University and began his career in 1983 as a design engineer of a wafer alignment system for wafer steppers. He carried out the aspherical surface metrology using interferometry at ASET EUVL Laboratory from 1998 to 2001. He started researching EUV reticle handling technology at Selete in 2006.

Chapter 11

EUVL System Patterning Performance

Patrick Naulleau, John E. Bjorkholm, and Manish Chandhok

Contents

11.1	Introduction: The Benefits of EUV Imaging	516
11.2	Imaging with the 0.1-NA ETS Optic	517
11.2.1	Static imaging characterization of the 0.1-NA ETS optic	518
11.2.2	Low- k_1 printing with modified illumination	522
11.2.3	Determining the impact of limited resist resolution	524
11.2.4	Early demonstration of chromeless phase-shift-mask printing in the EUV range	527
11.2.5	Buried programmed defect printability study	528
11.3	Imaging with the 0.3-NA MET Optic	530
11.3.1	Predicted performance	530
11.3.2	Demonstrating resist-limited performance	536
11.4	System Contributors to Line Edge Roughness	539
11.4.1	LER transfer from the mask to the wafer	539
11.4.2	Mask roughness effects on LER	543
11.4.3	Mask roughness effects on printed contact size variations	548
11.5	Flare in EUVL Systems	551
11.5.1	Sources of flare and estimating flare from surface roughness	551
11.5.1.1	Introduction	551
11.5.1.2	Sources of flare	552
11.5.1.3	Light scattering and surface roughness	553
11.5.1.4	Power spectral densities	554
11.5.1.5	Point-spread functions	555
11.5.1.6	Calculation of flare	557
11.5.1.7	Measured and projected flare in EUVL systems	558
11.5.2	Flare characterization of the Intel MET	559
11.5.2.1	Introduction	559
11.5.2.2	Kirk test	559
11.5.2.3	Flare measurements versus feature size	560
11.5.2.4	Modeling flare on the MET	561
11.5.2.5	Orientation dependence of flare	563
11.5.2.6	Across-field flare measurements	563
11.5.2.7	Measurements of the MTF as a function of pitch	565

11.5.3 Impact of flare on patterning performance and flare variation compensation	565
11.5.3.1 Introduction	565
11.5.3.2 Impact of flare on process window	566
11.5.3.3 Impact of flare on LWR	567
11.5.3.4 Flare mitigation	568
11.5.3.4.1 Dummification	568
11.5.3.4.2 Negative tone	569
11.5.3.4.3 Flare dependent within die CD variation	570
11.5.3.4.4 CD sensitivity to flare	570
11.5.3.4.5 Flare versus proximity effects	572
11.5.3.4.6 Flare variation compensation	573
11.5.3.4.7 FVC methodology	574
11.6 Summary	576
Acknowledgments	577
References	577

11.1 Introduction: The Benefits of EUV Imaging

The great promise of EUV lithography (EUVL) comes from its tremendous reduction in wavelength, small numerical apertures (NAs), and large operational k_1 factors. The latter two parameters lead to the very important conclusion of long extendibility of the technology.

Being simply an extension of conventional optical projection lithography, the standard lithographic resolution equation holds. Namely, the resolution R can be expressed as

$$R = \frac{k_1 \lambda}{\text{NA}}, \quad (11.1)$$

where λ is the imaging wavelength, NA is the numerical aperture, and k_1 is the Rayleigh constant. The Rayleigh constant is affected by several variables, including illumination conditions and mask architecture. Assuming a conservative k_1 factor of 0.5, which can be achieved readily with conventional illumination and a binary amplitude mask, the half-pitch resolution of a 0.3-NA EUV (13.5-nm wavelength) system would be 22.5 nm. Using resolution enhancement techniques such as off-axis illumination and/or phase-shift masks, the ultimate resolution k_1 factor can be decreased to 0.25, corresponding to a 0.3-NA resolution limit of 11.25 nm.

Even further extendibility can be obtained by pushing the NA to 0.5. Practical 0.5-NA optical designs have recently been demonstrated.¹ At this NA, the resolution limits become 13.5 and 6.75 nm for the $k_1 = 0.5$ and $k_1 = 0.25$ cases, respectively. It is illustrative to view the simulated aerial images to understand the significance of the larger k_1 factor compared to that we have grown accustomed to with 248- and 193-nm lithography. Figure 11.1 shows calculated aerial images for a 0.3-NA EUVL system with conventional disk illumination and partial coherence

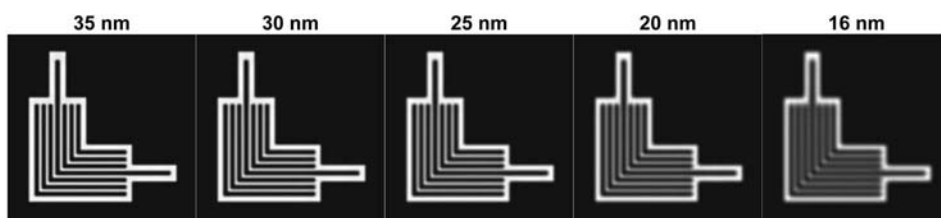


Figure 11.1 Aerial image modeling results for 0.3-NA EUV printing under disk illumination with a partial coherence of 0.7.

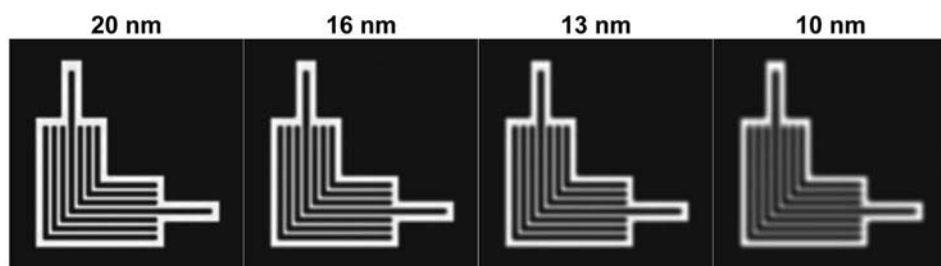


Figure 11.2 Aerial image modeling results for 0.5-NA EUV printing under disk illumination with a partial coherence of 0.7.

of 0.7. Strong image modulation is clearly observed even at the 20-nm half-pitch level. Figure 11.2 shows similar results for a 0.5-NA system. Strong image modulation using conventional illumination and a binary amplitude mask is achieved down to 13 nm. As noted above, even better imaging performance can be achieved when we consider the use of techniques such as modified illumination and/or phase-shift masks.

Another significant benefit of the lower NA of EUVL systems is the relatively large focus latitude it affords. The depth of focus (DOF) can be expressed in terms of the wavelength and the NA as

$$\text{DOF} = \frac{k_2 \lambda}{\text{NA}^2}, \quad (11.2)$$

where k_2 is a constant representative of the lithographic process conditions. A typical value for k_2 for a conventional process is 0.5. For a 0.3-NA system operating at its diffraction limit (~ 22 -nm half-pitch resolution), the DOF would be 75 nm. Using an optimized process, the DOF could be increased to 150 nm.

11.2 Imaging with the 0.1-NA ETS Optic

We begin our imaging discussion with the 0.1-NA full-field Engineering Test Stand (ETS) system² developed by the Virtual National Laboratory (VNL) and the EUV Limited Liability Corporation (EUV LLC; see Chapter 2). For a review of even earlier EUV printing results, refer to Chapter 1.

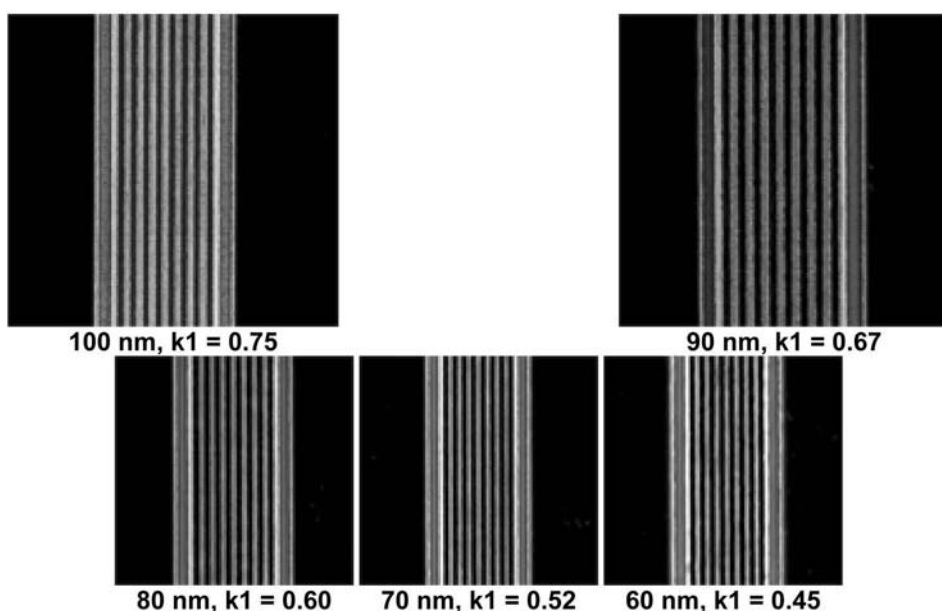


Figure 11.3 Series of dense-line images ranging from 100-nm CD down to 60-nm CD. All images were recorded with conventional disk illumination and a partial coherence of 0.8.

11.2.1 Static imaging characterization of the 0.1-NA ETS optic

Although the ETS was a full-field step-and-scan system, the performance characterization results presented here are limited to microfield static exposures obtained from the Subfield Exposure Station (SES) at Lawrence Berkeley National Laboratory (LBNL).^{3–6} We chose to describe the static system because it was unencumbered by various system issues such as scanning stages and a stand-alone source and therefore is more representative of the ultimate imaging capabilities of a 0.1-NA EUV system. Detailed descriptions of the performance of the full ETS can be found in the literature.^{7–10}

The SES had a static microfield size of approximately 100 μm at the wafer, while the ETS optic itself had a well-corrected field size of 24×6 mm. Although the instantaneous static field size was limited to 100 μm , the full 24-mm arc-shaped field of view could be covered one subfield at a time by moving the entire system (with the exception of the illuminator components) under the beam. The SES used the same reflection masks architecture used in the ETS. In addition, the SES supported variable partial coherence (σ) settings ranging from approximately 0 to 1 and enabled the generation of arbitrary pupil fills such as dipole and the ETS six-channel fill.²

We begin by considering the experimental resolution limit of the 0.1-NA ETS optic. Figure 11.3 shows a series of equal line-space images ranging from a half-pitch of 100 nm down to 60 nm. The features were printed using a dark-field mask where each nine-bar pattern is positioned in a local bright field slightly larger

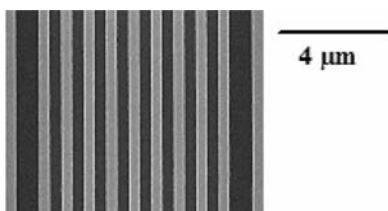


Figure 11.4 Scanning electron microscope image of the 100 nm coded features on the mask. Light areas correspond to absorber areas (lines) and dark areas correspond to reflective multilayer areas (clear areas or spaces).

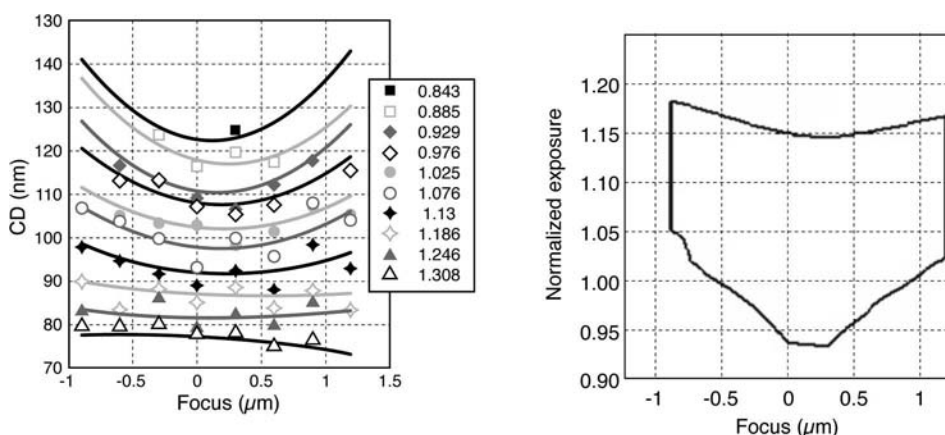


Figure 11.5 Results of a $\pm 10\%$ CD-change process window for 100-nm half-pitch features. The legend values represent the normalized dose.

than the nine-bar pattern itself. Figure 11.4 shows a scanning electron microscope (SEM) image of the 100-nm coded features on the mask. The resist images shown in Fig. 11.3 were all recorded in a Shipley EUV 2D resist under conventional disk illumination with a σ of 0.8. Because the ETS optic had a NA of 0.1, these prints correspond to k_1 factors of 0.75 through 0.45.

Although Fig. 11.3 demonstrates resolution down to a 60-nm half-pitch, a practical measure of the achievable resolution must be based on process-window size or DOF at a given exposure latitude (EL). The process-window results presented here correspond to $\pm 10\%$ critical dimension (CD) changes and the DOF is quoted with 10% EL. Figure 11.5 through Fig. 11.8 show Bossung plots and corresponding process-window plots for half-pitches down to 70 nm. The 60-nm case is not shown since no measurable process window was found. The plot in Fig. 11.9 shows a summary of the DOF results through the half-pitch. At 100-nm CD, a DOF of approximately 2 μm is observed, with the DOF dropping approximately linearly to 0.8 μm at a CD of 70 nm.

Repeating the same analysis on focus exposure matrix (FEM) data from isolated features yields the DOF results in Fig. 11.10. The isolated line features demonstrate an increased DOF relative to the nested features and a decreased DOF

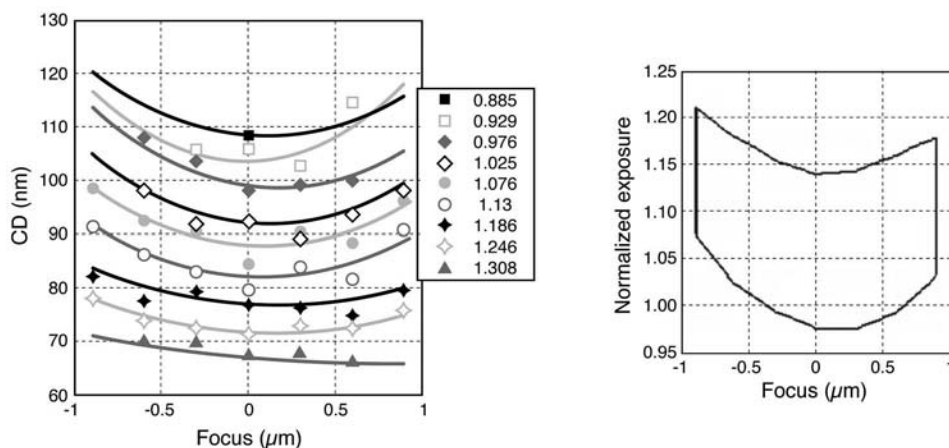


Figure 11.6 Results of a $\pm 10\%$ CD-change process window for 90-nm half-pitch features.

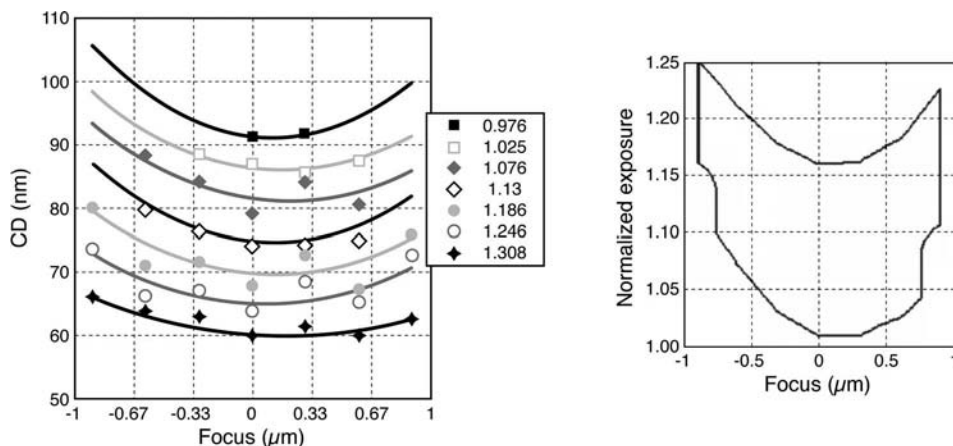


Figure 11.7 Results of a $\pm 10\%$ CD-change process window for 80-nm half-pitch features.

sensitivity to CD. Better than $2\text{-}\mu\text{m}$ DOF is demonstrated down to 70-nm CD. The Bossung plots show both the measured data (symbols) and fitted data (lines) used to actually determine the process window. The fitted data is based on 2D fitting of the CD surface through both dose and focus, which explains the apparent discrepancies between some of the fits and the plotted 1D through-focus data. This method minimizes the impact of our experimental dose uncertainty, which is on the order of 2%.

Finally, we consider the process window on loose-pitch contacts. Figure 11.11 shows the Bossung plots for contacts coded as 100/300-nm CD/pitch and 90/270-nm CD/pitch, respectively. Extracting the DOF yields $1.3\text{ }\mu\text{m}$ for 100-nm CD and $1.0\text{ }\mu\text{m}$ for 90-nm CD. By analyzing the 90-nm coded results in the under-dosed condition, we can extract DOF results at CDs of 80 and 70 nm. However, because these 80-nm and 70-nm results are derived from 90-nm coded features,

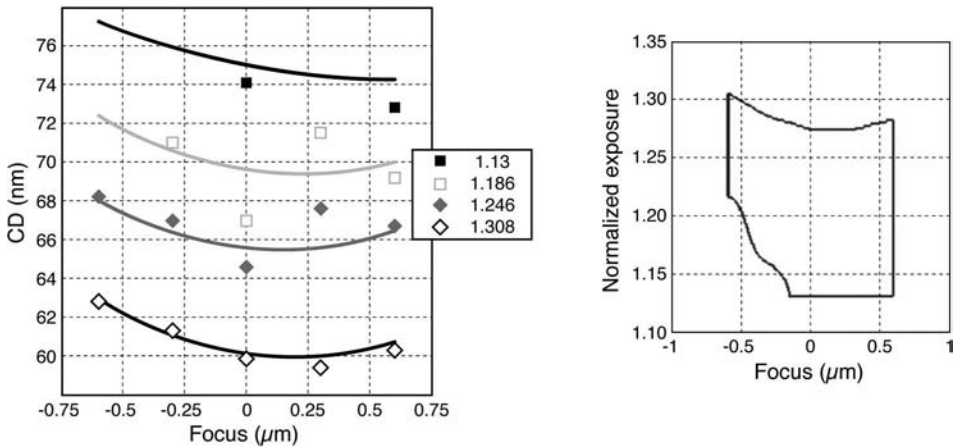


Figure 11.8 Results of a $\pm 10\%$ CD-change process window for 70-nm half-pitch features.

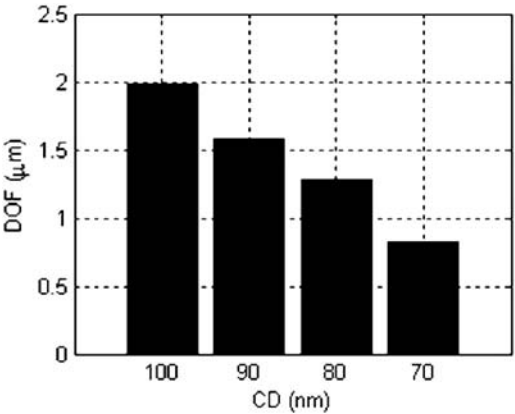


Figure 11.9 DOF as a function of CD based on the process-window results from Fig. 11.5 through Fig. 11.8 and an EL of 10%.

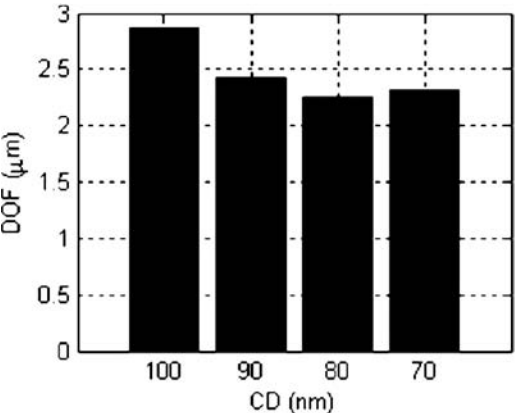


Figure 11.10 DOF as a function of CD for isolated line features using the same criteria used in Fig. 11.9.

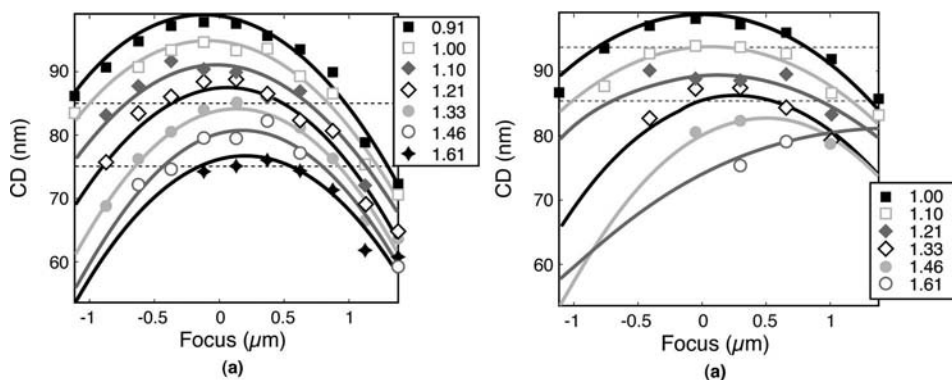


Figure 11.11 Bossung plots for contacts coded as (a) 100/300-nm CD/pitch, and (b) 90/270-nm CD/pitch.

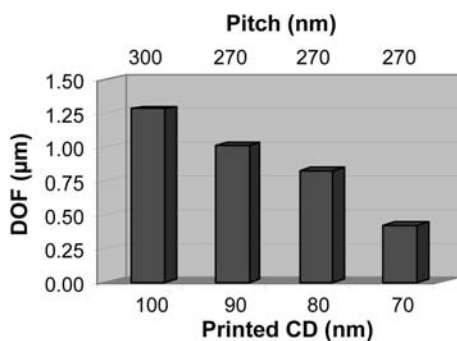


Figure 11.12 Summary of DOF results on loose-pitch contacts. The 100-nm contacts have 300-nm pitch, and the 90- to 70-nm contacts have 270-nm pitch.

the pitch remains 270 nm. Figure 11.12 summarizes the DOF results on the loose-pitch contacts.

11.2.2 Low- k_1 printing with modified illumination

A significant advantage of the programmable coherence illuminator available on the SES was its ability to employ modified illumination for resolution enhancement. Figure 11.13 shows equal line-space image printing down to 50-nm half-pitch with dipole illumination (Fig. 11.15). For comparison, Fig. 11.14 shows 50-nm line-space printing using conventional disk $\sigma = 0.7$ illumination. The resolution enhancement for the vertical features comes at the cost of horizontal resolution, as can be seen in the 70-nm elbows in Fig. 11.16. By going to annular illumination $0.6 < \sigma < 0.8$, we can achieve a compromise of some resolution enhancement while maintaining rotationally invariant performance (Fig. 11.17).

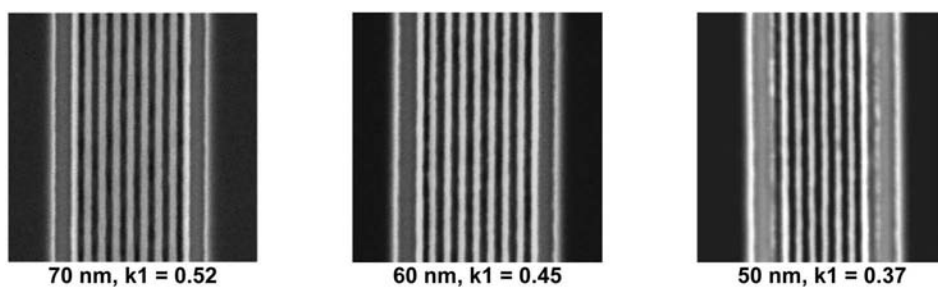


Figure 11.13 Printing results from the 0.1-NA ETS optic using dipole illumination (see Fig. 11.15).

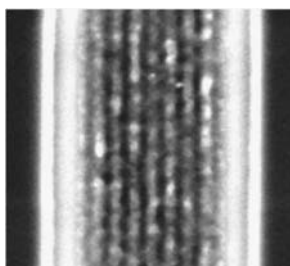


Figure 11.14 Printing results from the 0.1-NA ETS optic using disk illumination.

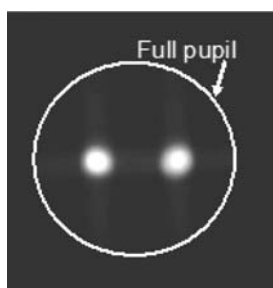


Figure 11.15 Dipole illumination used to obtain the prints in Fig. 11.13.

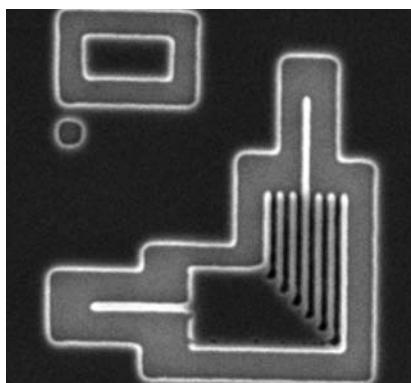


Figure 11.16 A 70-nm elbow pattern printed with the 0.1-NA ETS optic using dipole illumination.

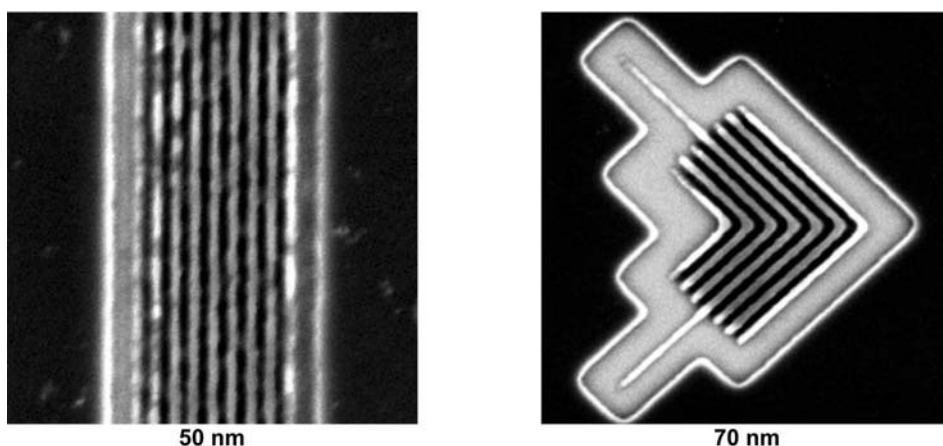


Figure 11.17 Printing results from the 0.1-NA ETS optic using annular $0.6 < \sigma < 0.8$ illumination.

11.2.3 Determining the impact of limited resist resolution

A significant issue for EUV is the resolution of the resist itself. We have now reached a regime where the point-spread function (PSF) of the resist has become comparable to that of the optics we are using. This raises the question of how to measure this PSF and what impact the resist actually has on the printing.

The power of the PSF approach^{11–13} comes from its simplicity. This simplicity greatly improves the extrapolation capabilities of the model compared to finely tuned and complex multiparameter models. The contrast transfer function technique¹⁴ has been employed to determine the PSF of the Rohm and Haas EUV-2D resist¹⁰ used in all the imaging examples above. The work described in Ref. 14 showed the EUV-2D PSF to be 50-nm full-width half maximum (FWHM) assuming Gaussian shape. Here we consider how well the PSF approach matches observed imaging characteristics and how important a role the resist limitations play in the resolution limits observed in the printing results described in Secs. 11.2.1 and 11.2.2.

The imaging metric we consider is the process-window size as a function of partial coherence (σ) and feature size. Figure 11.18 shows the experimentally measured DOF. The DOF is determined based on an acceptable feature size variation of $\pm 10\%$ and a 10% EL. The results are somewhat counter-intuitive in that the partial coherence, which is varied from 0.2 to 0.7, has very little effect on the performance. Figure 11.19 shows a similar plot based on aerial-image modeling and assumes an ideal threshold resist. The aerial-image modeling incorporates the wavefront previously measured using EUV interferometry.⁵⁰ The rms wavefront error in the first 37 Zernikes is 0.69 nm. Moreover, the wavefront used in the modeling incorporates measured frequencies that cover a 1.5- μm radius in the image plane. Note the striking difference between the modeling and experimental results, especially in terms of the impact of partial coherence. This discrepancy indicates that the particulars

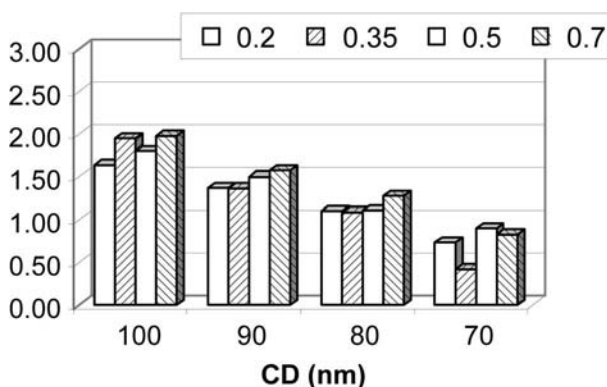


Figure 11.18 Experimentally measured DOF as a function of partial coherence and feature size for a 0.1-NA EUV optic operating at a wavelength of 13.4 nm.

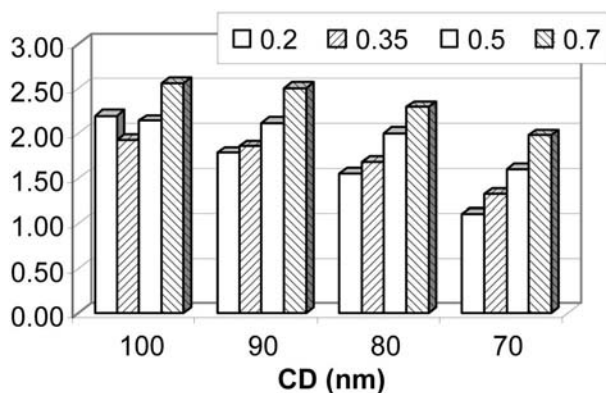


Figure 11.19 Predicted DOF based on aerial-image modeling and assuming an ideal threshold resist.

of the resist, ignored by the simple threshold model, play a significant role in the observed imaging performance.

Figure 11.20 shows the DOF results based on the PSF modeling. The PSF-based modeling serves as a good predictor of the experimental results through both feature size and partial coherence ranges. The average magnitude of the DOF prediction error compared to the experimental results over the 16 measured process-windows is 0.22 μm , with the largest error being 0.30 μm .

It is evident that the resist PSF method is an accurate predictor of observed imaging characteristics, and that resist limitations play a significant role in the performance limits described in this section. Note that the resist limitation predictions found for EUV-2D based 0.1-NA printing were definitively verified through 0.3-NA printing, as described below.

Figure 11.21 shows printing results from a 0.3-NA optic both in an EUV-2D resist and a resolution-improved MET-1K resist by Rohm and Hass. These results

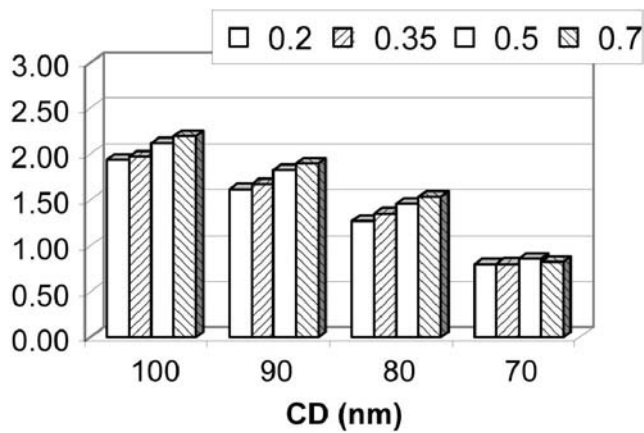


Figure 11.20 Predicted DOF based on aerial-image modeling combined with the PSF-based resist model.

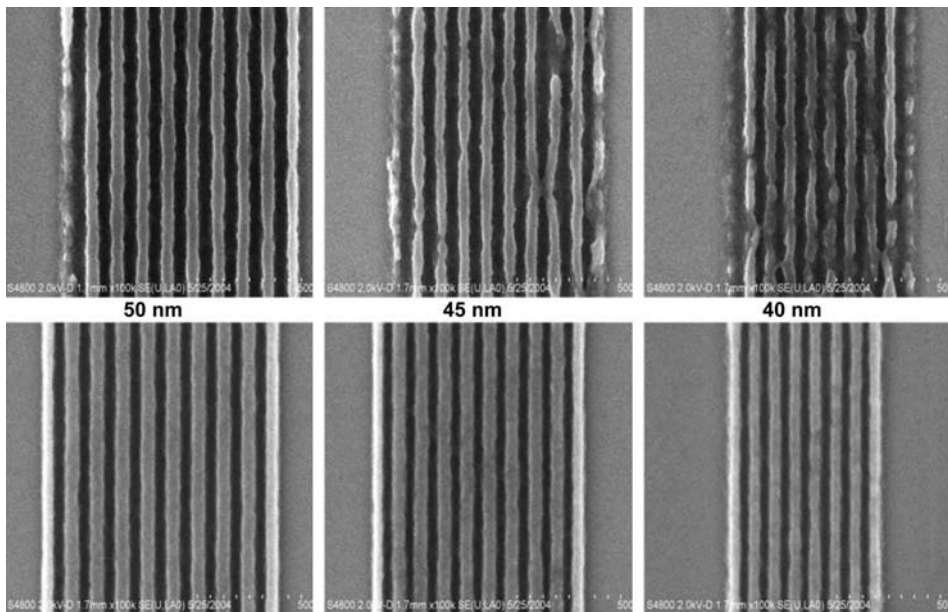


Figure 11.21 Comparison of 0.3-NA printing between the EUV-2D resist (top row) and the MET-1K resist (bottom row).

demonstrate that the PSF approach is able to find the limits of resists even when the resist resolution is better than the optic resolution, as was the case when testing the EUV-2D resist with the 0.1-NA ETS optic. For a more detailed discussion of PSF-based modeling and a direct comparison to conventional resist modeling, see Ref. 15.

11.2.4 Early demonstration of chromeless phase-shift-mask printing in the EUV range

A significant benefit of EUVL is that it is simply an extension of optical lithography, which means that the toolbox of resolution enhancement techniques developed for optical lithography can also be applied to EUVL. One such example is modified illumination, as discussed above. Another example is phase-shift mask technology. Phase-shift masks have played a crucial role in the extension of optical lithography and could also be used in the future to push EUVL to its ultimate limits. Another benefit of phase-shift masks is their utility in print-based aberration measurement techniques.^{15–17}

Perhaps the simplest method to generate a phase-shift mask in the EUV range is to fabricate a relief pattern into the substrate and then overcoat with a multi-layer (ML). This method is nearly identical to the method used to generate high-efficiency phase gratings in the EUV.^{18–23} The relief substrate technique was used for an early demonstration of phase-shift mask printing with the 0.1-NA ETS optic. Figure 11.22 shows through-focus printing of subresolution phase lines on the mask. The printed feature size is on the order of 70 to 80 nm, near the resolution limit of the optic. Note the very stable through-focus performance of the printing over the full 1.6- μm range. Another demonstration of phase-shift printing is shown in Fig. 11.23, where a large phase object is placed adjacent to an absorber feature (the mask layout is shown in Fig. 11.24). As expected from phase-shift printing, only the outline of the large phase structure is printed.

The crucial problem with this method is the fact that the ML-coating process significantly limits the resolution of the phase features one can obtain on the mask.

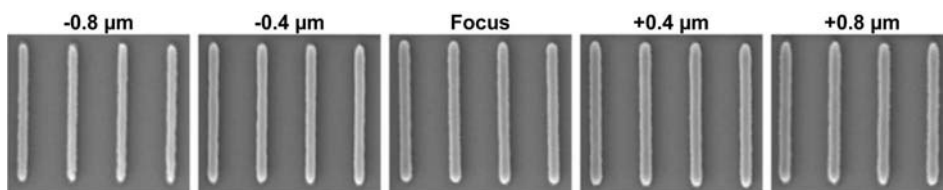


Figure 11.22 Through-focus printing of subresolution phase lines on the mask at 0.1 NA.

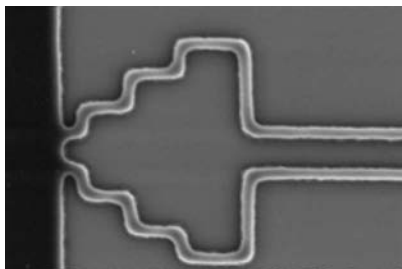


Figure 11.23 Printing of the large phase-shift structure in Fig. 11.24.

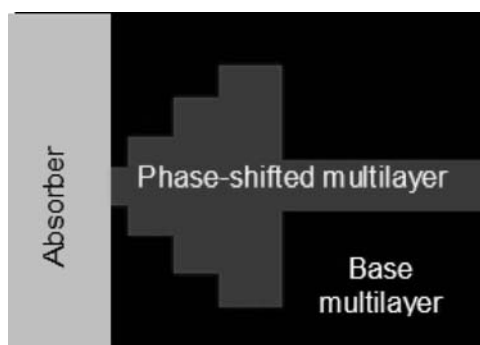


Figure 11.24 Mask layout corresponding to the print in Fig. 11.23.

Since this early work was done, a more sophisticated implementation of phase-shift masks (including attenuated phase-shift masks) based on ML etching has been developed and was recently demonstrated in a 0.3-NA exposure tool.²⁵

11.2.5 Buried programmed defect printability study

One of the largest challenges facing EUVL is the mask defect issue. Of particular concern are the defects buried under or within the ML. These defects render themselves as phase defects (much the same way as we described the fabrication of a phase-shift mask above), so even extremely small defects can remain printable. A promising method to mitigate these problems is through the use of highly smoothing ML deposition techniques.²⁵

To test the effectiveness of this smoothing process, a programmed substrate defect mask fabrication method has been developed.²⁶ The relevant defect sizes on the substrate are on the order of $50 \times 50 \times 50$ nm. Defect patterning was performed using electron-beam lithography to pattern a spin-on-glass resist (hydrogen silsesquioxane or HSQ).²⁷ The resist relief features that remain after processing, which take the form of highly robust silicon dioxide (SiO_2), serve as the programmed defects.

For comparison purposes, two identical programmed substrates were fabricated, one coated with a conventional ion-beam-deposited ML, and the second using the smoothing-enhanced process. After coating, both masks were patterned with an absorber line-space pattern in controlled proximity to the defects using the same electron-beam lithography tool employed to fabricate the defects.²⁹

Figure 11.25 shows an atomic force microscopy (AFM) image from one of the masks immediately following fabrication of the defect layer. The image shows a set of four 50-nm-wide, 50-nm-tall defects. The large 2- μm -wide feature, also patterned in HSQ, was added as a locating aid feature for pre-and post-coating metrology.

Figure 11.26 shows in-focus nominal dose images of defects in proximity to 100 nm as coded lines. The defects are nominally centered in the line-space pattern. The labels associated with each column correspond to the lateral defect dimension,

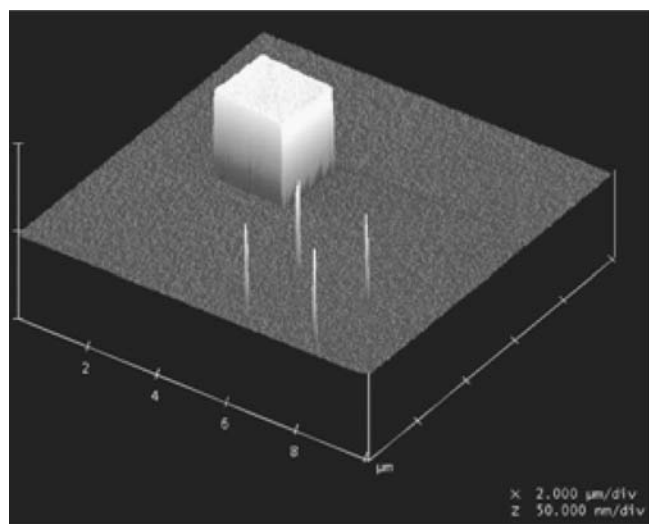


Figure 11.25 AFM image from one of the masks immediately following fabrication of the defect layer. The Z-scale is exaggerated for visualization.

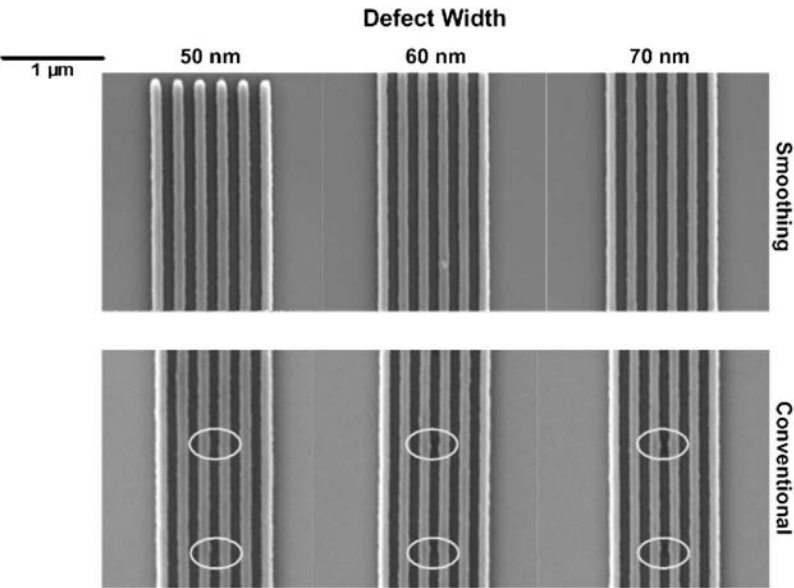


Figure 11.26 Results of defect-printability exposure studies. SEM images are printed in 100-nm lines and spaces with embedded proximity defects of widths ranging from 50 to 70 nm. Results show (top image) smoothing-optimized, and (bottom image) conventional ion-beam deposited MLs. These images were recorded at best focus and close to nominal dose. Where visible, the defect effects on the proximity line widths are circled.

with all defects being 50 nm tall. The top row shows the smoothing-enhanced case, and the bottom row shows the conventional ML case. Smoothing renders 70-nm defects unprintable at best focus, whereas without smoothing, even 50-nm defects are

printable at focus. Where visible, the defect effects on the proximity line widths are circled. Full process-window analysis has shown that the actual printability cutoff, given the present smoothing technology, is approximately 60 nm.²⁷ This is more restrictive than one might predict from Fig. 11.26 because printability increases with defocus.

11.3 Imaging with the 0.3-NA MET Optic

Next, we turn our attention to printing with the 0.3-NA microfield exposure tool (MET) optic. Because initial production tools are expected to have NAs of 0.25 or larger for use at the 32-nm or smaller node, developmental systems at this NA or higher are required today. To meet the need for early development tools, microfield exposure systems have been developed that trade field size and speed for greatly reduced complexity. Similar microfield tools have been crucial to sub-0.2-NA EUV development in the past,^{5,29,30} and as of the writing of this chapter, they serve as the only source for high-NA EUV printing.^{31–34}

11.3.1 Predicted performance

To effectively use the MET tool for resist and mask evaluation, the user must have an accurate knowledge of its aerial-image performance limits. Such knowledge enables the user to decouple optic effects from the resist and mask architecture effects being studied. In this section, we present aerial-image modeling results for the MET tool optic. The modeling results are based on the Set-2 optics manufactured by Zeiss. The MET optic is a two-mirror, 0.3-NA, centrally obscured optical system. The central obscuration has a radius equal to 30% of the full NA of the optic. The Set-2 optic has a 37-Zernike rms wavefront error excluding piston, tilt, and focus of 0.65 nm ($\lambda/21$).³⁵ This wavefront was measured at Zeiss using optical interferometry. The lithographically measured flare (using the Kirk method³⁶) in a 2- μ m line is 8.5%.

The typical illumination in the MET tools is annular with an inner σ of 0.36 and an outer σ of 0.55. For the case of the tool installed at SEMATECH North in Albany, New York, the illuminator also includes an aperture wheel, which allows the pupil fill to be modified. It includes settings for quadrupole with a pole offset of 0.41 and a pole diameter of 0.1, and for dipole, with a pole offset of 0.42 and a pole diameter of 0.1. These sparse pupil fills come at the cost of significant throughput loss, with only 6% transmission for quadrupole and 3% transmission for dipole. The Berkeley tool, on the other hand, has the significant advantage of using a programmable pupil-fill illuminator.³⁷ This advantage offers unlimited flexibility in pupil-fill definition as well as lossless control to enable the use of sparse pupil fills such as dipole and monopole, which would not be feasible in the SEMATECH North tool due to throughput losses.

We begin by comparing the contrast transfer function (CTF) of the SEMATECH North optic under annular illumination to an aberration-free optic. The input

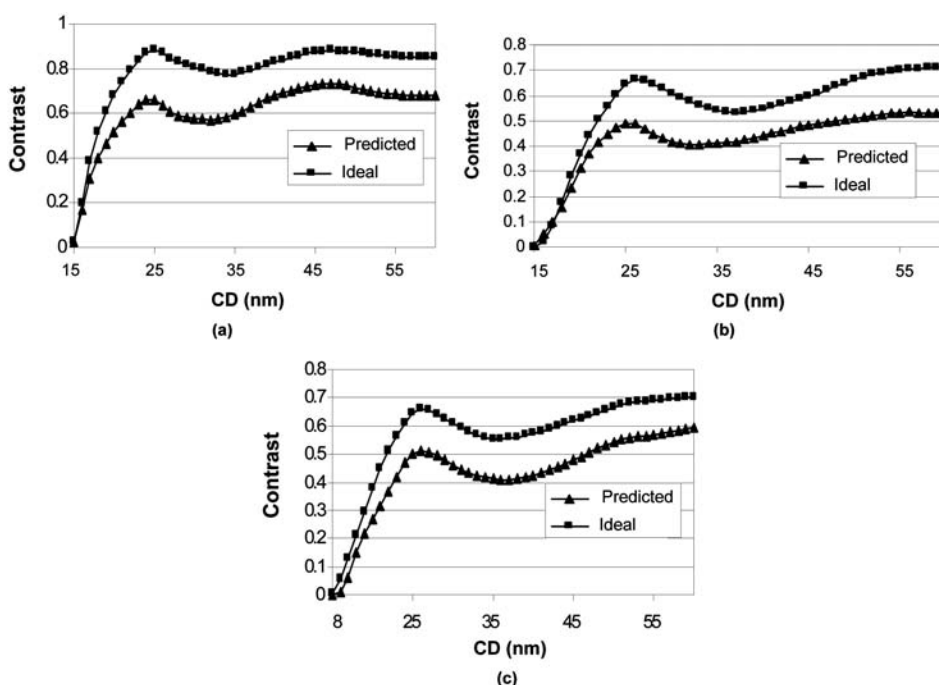


Figure 11.27 CTF computations comparing the SEMATECH North optic under annular illumination to an aberration-free optic. The input pattern is a binary equal line-space pattern and the thin-mask approximation is used. Results are shown at three different focus settings: (a) best focus, (b) 100 nm, and (c) -100 nm.

pattern is assumed to be a binary equal line-space pattern, and the thin-mask approximation is used. Figure 11.27(a) shows the CTF at best focus, and Fig. 11.27(b) and (c) show the CTF at plus and minus 100-nm defocus, respectively. The results show that the primary effect of the optic errors is a constant reduction in contrast, as one would expect from flare. The CTF results show that the roll-off in the optics response occurs at approximately 25 nm for both the ideal and predicted cases. Modeling shows that the characteristic CTF dip at approximately 35 nm is an artifact of the central obscuration and not any aberrations in the optic or the annular illumination.

Next, we consider aerial-image process-window computations. All process windows shown are based on the aerial-image criteria of a $\pm 10\%$ change in CD, an aerial-image contrast of better than 50%, and an image log slope (ILS) of better than 20. The reported DOF is based on a best-fit rectangle to the process window with an EL of 10%.

Figure 11.28 shows annular illumination process-window results for equal line-space vertical features ranging from 20 to 40 nm. At 20 nm, we see excellent iso-focal properties; however, the EL limits the achievable DOF to less than 50 nm. Performance dramatically improves at 25 nm (as one might expect from the CTF plots in Fig. 11.27), where excellent iso-focal properties and a DOF approaching 200 nm are apparent. As feature sizes reach 30 nm and larger, the iso-focal CD

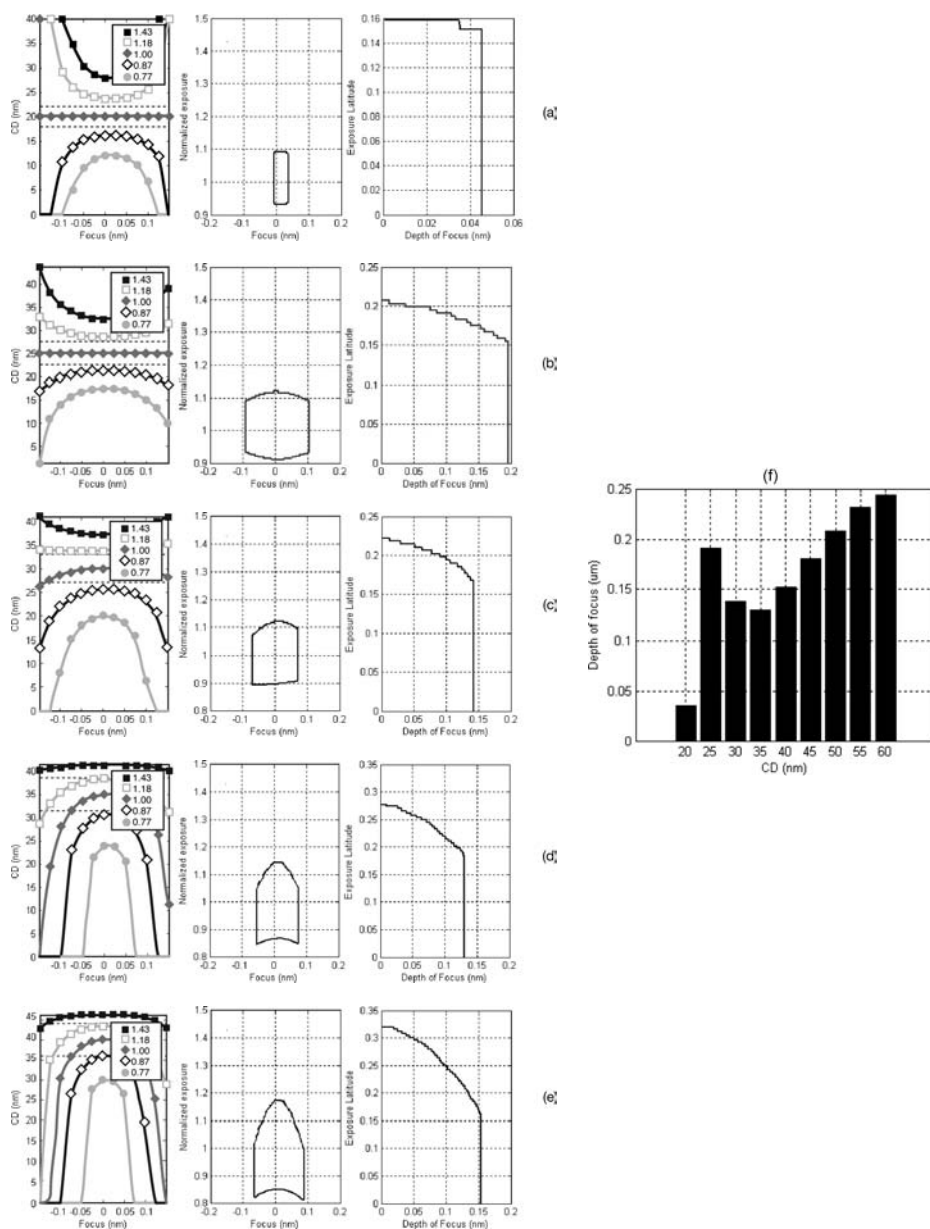


Figure 11.28 Simulated annular illumination process window results for equal-line-space vertical features ranging from (a) 20 to (e) 40 nm. Image (f) shows the computed DOF for feature sizes up to 60 nm. The characteristic dip at 35 nm is an artifact of the central obscuration.

shifts to larger values. This combined with the reduction in contrast, evidenced in Fig. 11.27, causes significant reductions in DOF. Eventually, as the CDs continue to increase, the negative effects of iso-focal shift are offset by the improving

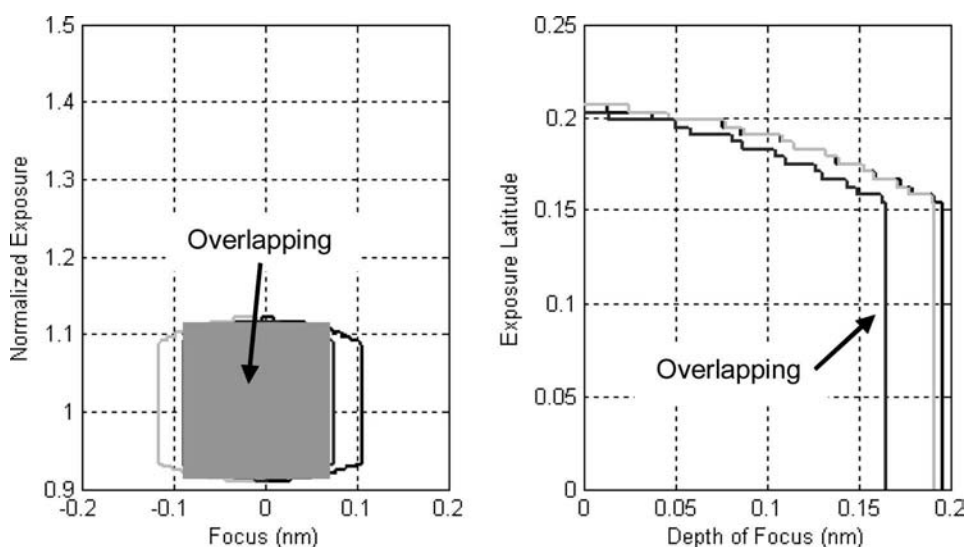


Figure 11.29 Overlapping HV process-window for the representative case of 25-nm nested lines.

EL. Figure 11.28(f) summarizes the computed DOF for feature sizes up to 60 nm. Again, the characteristic dip at 35 nm is evident.

Next, we consider horizontal/vertical (HV) effects that one might expect from astigmatic aberrations. Figure 11.29 shows an overlapping HV process window for the representative case of 25-nm nested lines, including a relative HV focus shift of approximately 25 nm and excellent EL overlap. This offset is found to be nominally constant as a function of feature size. The thin-mask approximation has been used here, so the mask shadowing effects³⁸ are not captured. Such effects would lead to EL offsets between horizontal and vertical features, but can, in principle, be compensated by proper biasing of the mask. Figure 11.30 summarizes the computed HV overlapping DOF as a function of feature size. Figure 11.31 through Fig. 11.33 show the same process-window computations for overlapping HV isolated lines as well as nested and isolated contacts, respectively. In all cases, the illumination is annular.

Next, we consider the effect of the available modified illumination settings on the process window for vertical equal line-space features. The quadrupole illumination in Fig. 11.34 presents a moderate improvement in performance for 20-nm features, which brings the DOF above 100 nm. The most dramatic effect is at 30-nm CD, where the DOF is more than double that of 35 nm or approximately 300 nm. For CDs larger than 35 nm, quadrupole causes a reduction in DOF compared to the annular setting. Figure 11.35 shows the dipole process-window results. This case shows strong improvements at 20- and 25-nm CDs, while no imaging is obtained at 30 and 35 nm. This “dead band” is a result of the interaction of the pole offset and the central obscuration. At CDs larger than 35 nm, we again see a reduction in DOF compared to the annular case.

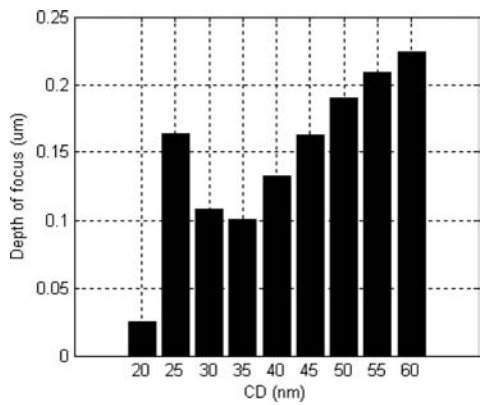


Figure 11.30 Computed HV overlapping DOF as a function of feature size for equal lines and spaces.

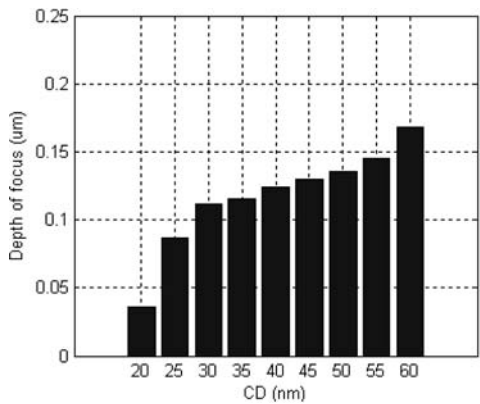


Figure 11.31 Computed HV overlapping DOF as a function of feature size for isolated lines.

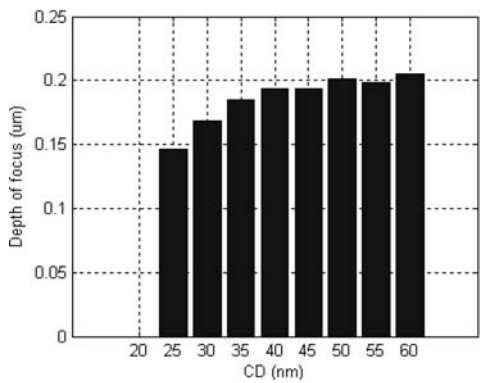


Figure 11.32 Computed DOF as a function of feature size for nested contacts.

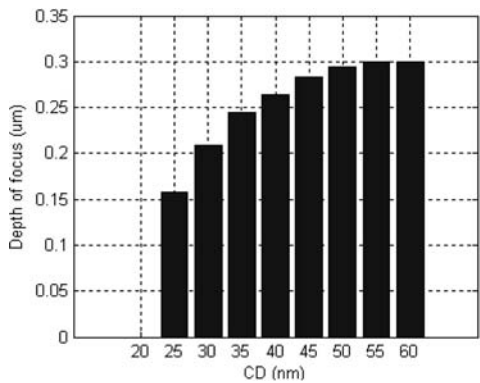


Figure 11.33 Computed DOF as a function of feature size for isolated contacts.

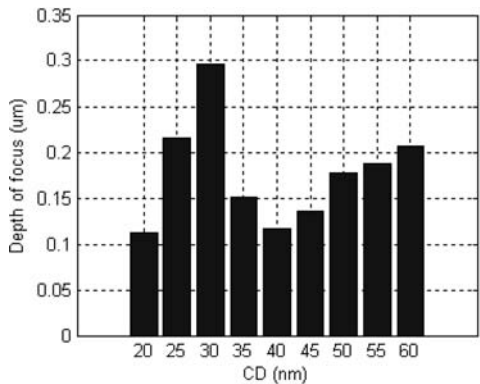


Figure 11.34 Computed DOF as a function of feature size for nested vertical lines with quadrupole illumination.

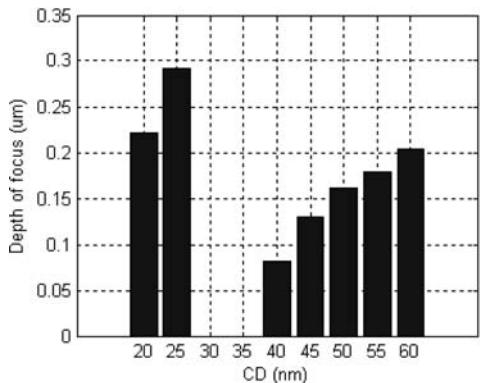


Figure 11.35 Computed DOF as a function of feature size for nested vertical lines with dipole illumination.

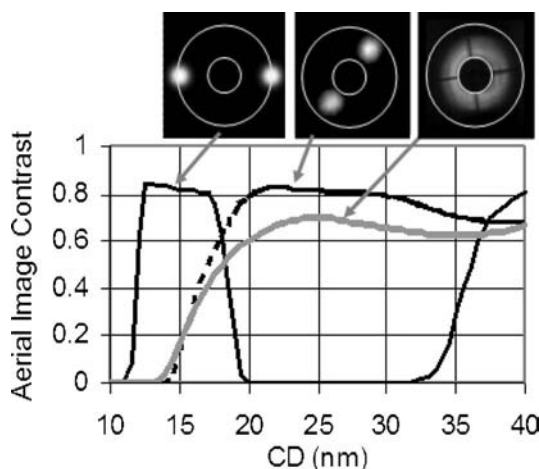


Figure 11.36 Modeling of the aerial-image CTF for three different pupil fills.

The pupil fills discussed above are those compatible with the SEMATECH North MET tool. However, the Berkeley MET tool has significantly greater flexibility. The Berkeley programmable coherence illuminator shown in Fig. 11.36 enables significant improvement in resolution. The modeling results shown in Fig. 11.36 were calculated based on the EUV measured wavefront^{39–41} for the Set-1 optics. Under standard annular illumination ($0.3 < \sigma < 0.7$), the resolution knee occurs at about 23 nm. At 45-deg dipole illumination, the resolution knee is pushed out to approximately 20 nm, and the aerial-image contrast is generally enhanced. Ultimate resolution on vertical lines can be achieved by going to x-dipole illumination with an offset σ of 1, in which case the resolution knee is pushed down to 12.5 nm.

As a result of the interaction between the diffracted orders from the mask and the central obscuration of the MET optic, the x-dipole illumination shows a contrast dead-band in the 20- to 35-nm range. Moreover, the x-dipole case can be shown to suffer from very poor performance on horizontal features. Both of these problems can be overcome by using the 45-deg dipole condition while still achieving a resolution knee of 20 nm—considerably better than any currently available chemically amplified resist.

Note that the resolution enhancement illumination implementation described here is achieved without losses in throughput. Such a lossless implementation is likely not feasible for future high-speed commercial EUV systems. In those systems, the benefits obtained through the use of resolution-enhancing illumination will come at the significant cost of optical throughput.

11.3.2 Demonstrating resist-limited performance

The modeling results above indicate that the MET tools are capable of sub-25-nm resolution. Moreover, in the case of the Berkeley tool, the programmable illuminator enables the resolution to be pushed down below 15 nm. In practice, however,

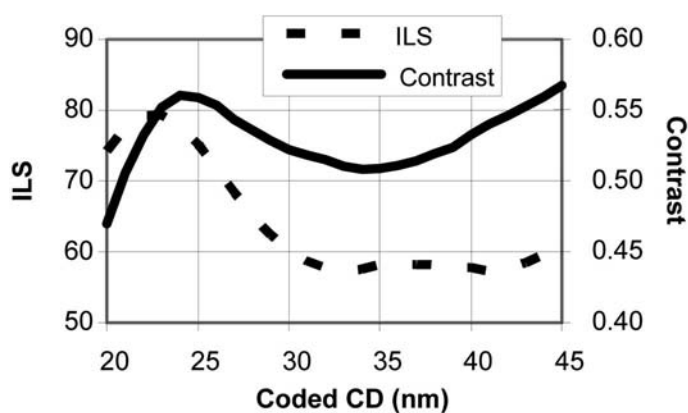


Figure 11.37 Prolith calculated aerial-image ILS and contrast as a function of feature size for equal lines and spaces. The illumination is annular $0.3 < \sigma < 0.7$.

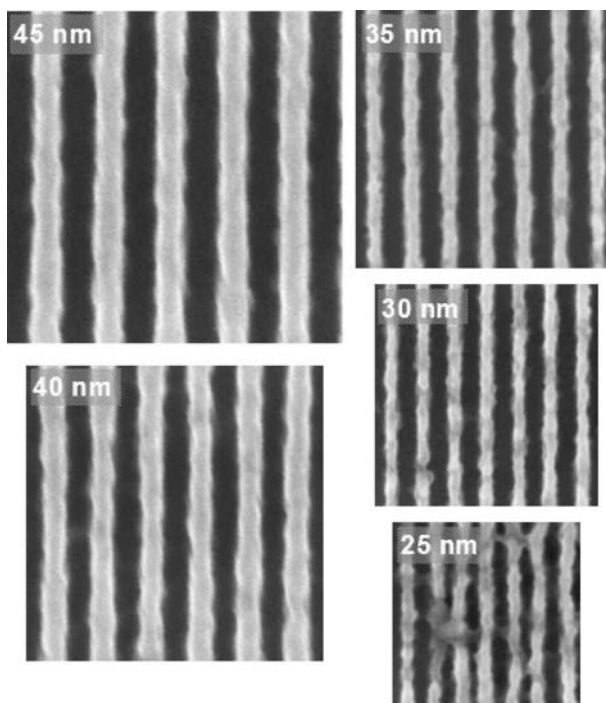


Figure 11.38 Equal line-space images ranging from 45 to 25 nm printed in the experimental KRS resist provided by IBM.

such resolutions have not been achieved since lithographic resolution in the EUV regime is presently resist-limited instead of tool-limited. In this section, we present data supporting this conclusion.

Figure 11.37 shows the Prolith⁴³ calculated aerial-image ILS and contrast as a function of feature size for equal lines and spaces. The Prolith model incorporates

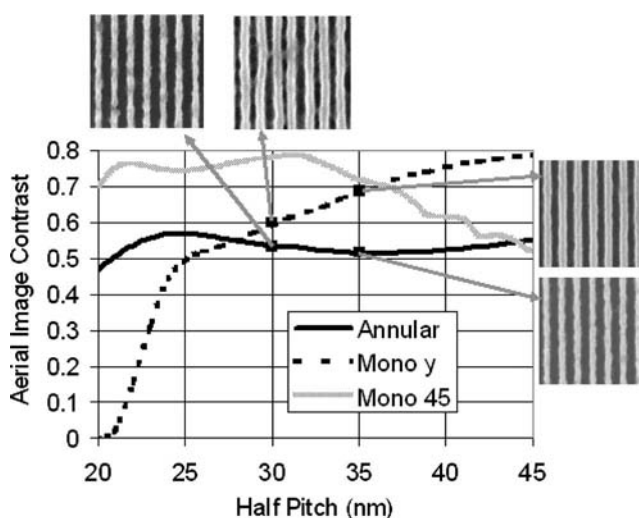


Figure 11.39 Computed aerial-image contrast as a function of CD for three different pupil fills.

the latest wavefront data, combining interferometric measurements obtained during alignment of the optic⁴⁰ and lithographic measurements of the latest state of the low-order astigmatism and spherical error.^{41,42} The illumination is assumed to be annular $0.3 < \sigma < 0.7$. For both the ILS and contrast, the values improve as the feature size shrinks from 35 to 25 nm. Figure 11.38 shows a series of equal line-space images ranging from 45 to 25 nm printed in experimental KRS resist provided by IBM.⁴⁴ Although the KRS resist is not as well characterized at EUV as MET-1K, EUV exposure tests consistently show the KRS resist slightly outperforms MET-1K, making it one of the highest-resolving EUV resists. Contrary to the results in Fig. 11.37, it is evident that imaging performance degrades rapidly for sizes below 35 nm, indicating a resist limit as opposed to an aerial-image limit.

Another way to assess a resist-limited performance state is to probe the printing performance as a function of aerial-image quality. Having a programmable pupil-fill illuminator, the Berkeley system is capable of producing large changes in aerial-image quality at fixed feature sizes (Fig. 11.39). By comparing 35-nm imaging performance, we see that implementing monopole illumination to drive the aerial-image contrast up from approximately 50% to nearly 70% (y-monopole illumination) improves imaging performance. But by performing the same comparison on 30-nm features, we see virtually no improvement in printing performance (pictures not shown) when going from 50% to nearly 80% contrast (45-deg monopole).

Given the resist limitations, it is evident that the optimal illumination choice for resolution enhancement on vertical features among the illumination types studied in Fig. 11.39 is y-monopole because it provides the most contrast gain in the regime where the resist can still respond. Figure 11.40 shows a series of images recorded in the KRS resist under y-monopole illumination, demonstrating

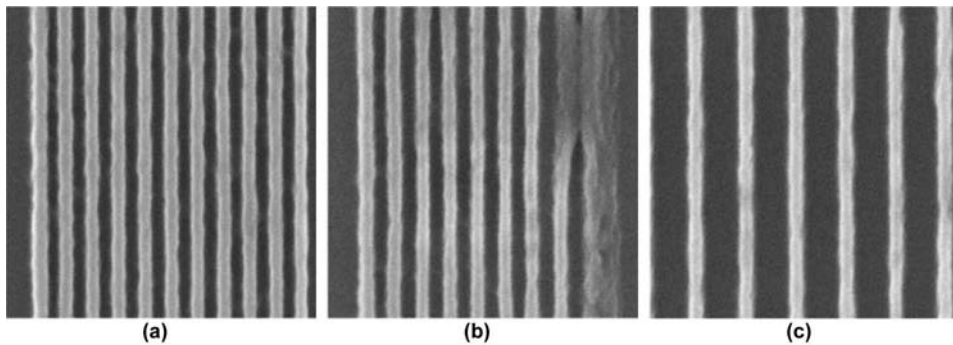


Figure 11.40 Images recorded in the KRS resist under y-monopole illumination: (a) 35-nm lines and spaces, (b) 32.5-nm lines and spaces, and (c) coded 27.5-nm lines with 110-nm pitch. The actual printed size in resist is 28.3 nm.

resolving capabilities down to 32.5 nm for equal lines and spaces and 28 nm for semi-isolated lines.

11.4 System Contributors to Line Edge Roughness

Line edge roughness (LER) remains a significant challenge for EUV. Discussions of LER are usually centered on resist specifications. However, system-level contributors also can be important. In the following three sections, we consider the transfer of LER on the mask to LER on the wafer,⁴⁵ the effect of surface (phase) roughness on the mask with respect to LER at the wafer,⁴⁶ and the related issue of mask surface roughness leading to printed contact-size variation.⁴⁷

11.4.1 LER transfer from the mask to the wafer

It is evident that roughness on the mask will, to some extent, transfer to roughness in the printed feature. In this section, we explicitly study this coupling using computer-simulation methods. For an analytical description of this coupling, see Ref. 45, which presents the concept of the LER transfer function (LTF). This new transfer function differs fundamentally from both the conventional optical transfer function (OTF) and the modulation transfer function (MTF). Moreover, the experimental results in this section demonstrate the impact of current EUV masks on projection-lithography-based LER experiments.

The LTF concept can be readily studied through computer simulation. In addition to providing physical insight into the LTF, this method also facilitates the incorporation of parameters such as aberrations in the optical system and unconventional illumination conditions. One method for computer-based modeling of the LTF involves generating a mask pattern containing a white LER spectrum [Fig. 11.41(a)] and calculating the LER spectrum from the resulting aerial image [Fig. 11.41(b)]. Figure 11.42 shows the resulting input and output LER power spectral densities (PSDs). In this case, the 0.1-NA EUV ETS Set-2 optic^{47–49} is

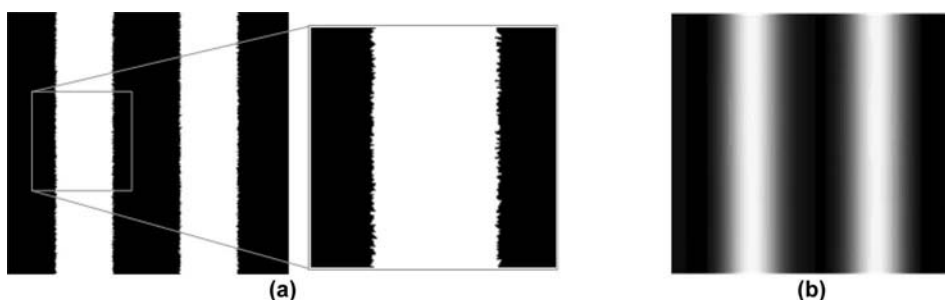


Figure 11.41 (a) LTF simulation input mask with a white LER spectrum and 100-nm features. (b) Computer-calculated aerial image assuming the 0.1-NA ETS Set-2 optic, including the EUV-measured wavefront aberrations and assuming partially coherent illumination ($\sigma = 0.7$).

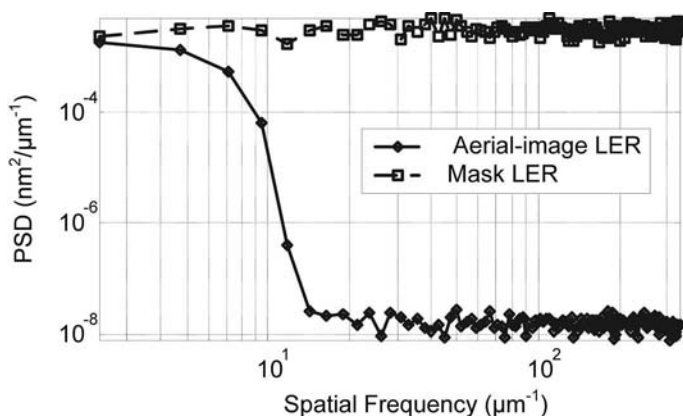


Figure 11.42 LER PSDs for the input mask (upper trace) and output aerial image (lower trace). The PSDs are averages of calculations from four independent realizations of the process described in Fig. 11.41.

modeled. The aerial-image modeling includes the measured wavefront aberrations from the optic⁵⁰ and assumes partially coherent disk illumination with a coherence factor (σ) of 0.7. The mask is modeled as a simple thin binary mask.

The PSDs shown in Fig. 11.42 are actually averages from four separate simulations with four statistically independent white-noise LER masks. This averaging is performed to avoid gaps in the characterization frequencies, which occur when a single white-noise mask is used. The noise floor observed in the PSD is due to the pixilation limits in the various simulation and processing steps. We define the LTF as the square root of the aerial-image PSD divided by the white-noise mask PSD (Fig. 11.43). In the limit of infinite averaging, the white-noise mask PSD will, by definition, be uniform, and the aerial-image PSD will be equal to the white-noise mask PSD at a spatial frequency of 0. Thus, the LTF can be taken simply as the square root of the normalized aerial-image LER PSD in the infinite averaging limit.

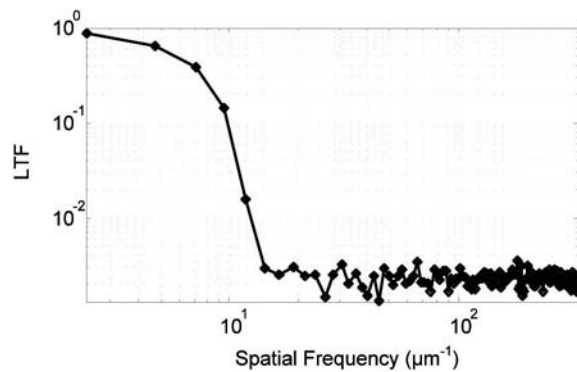


Figure 11.43 LTF derived by taking the square root of the aerial-image LER PSD divided by the white-noise mask PSD from Fig. 11.41.

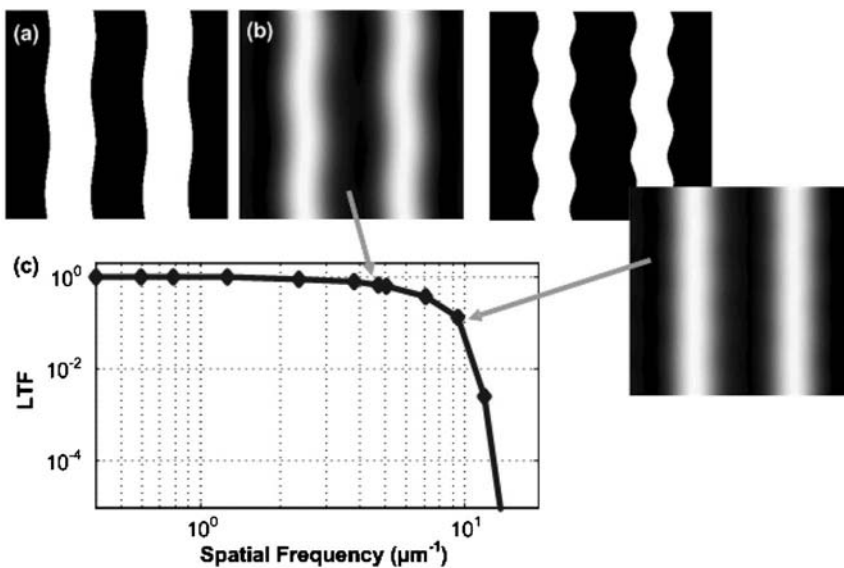


Figure 11.44 (a) Example of a probe mask. (b) Aerial image resulting from the probe mask. (c) LTF generated by calculating the system response to a series of single-frequency LER probes.

Next, we consider the alternate calculation approach of using a series of mask patterns, each with a unique LER frequency, then determining the LER from the resulting aerial images. This provides a discrete sampling of the LTF. Figure 11.44(a) shows an example of a sinusoidal LER mask with an LER period of 210 nm and a feature CD of 100 nm; Fig. 11.44(b) shows the calculated aerial image. This serves as a single-frequency probe of the LTF. By generating a variety of these single-frequency probes, the LTF can be constructed as shown in Fig. 11.44(c). The linearity of this process was verified by considering a single spatial frequency at three different amplitudes covering an order of magnitude. As required for linearity,

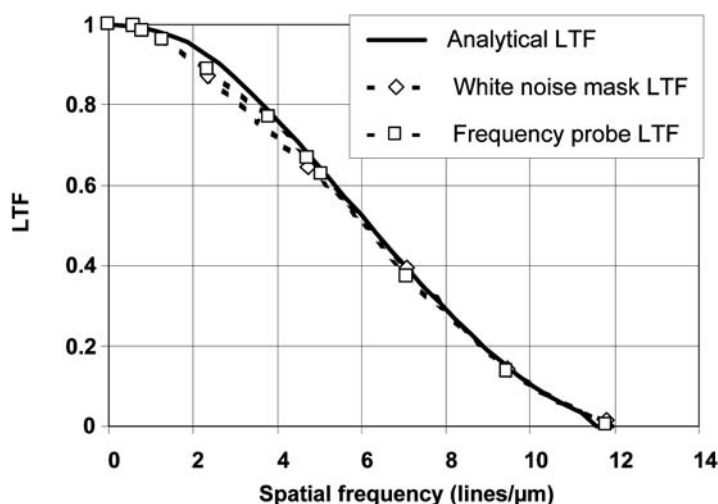


Figure 11.45 Direct comparison of the two LTF modeling methods and the analytical LTF calculation. The analytical LTF is depicted by the solid trace, the white-noise calculated LTF by the diamond symbols, and the single-frequency-probe calculated LTF by the square symbols.

the ratio of the output LER magnitude to input LER magnitude was found to be independent of the input LER magnitude.

Figure 11.45 shows a direct comparison of the two LTF modeling methods presented above as well as the analytical LTF from Ref. 45. The analytical LTF is depicted by the solid trace, the white-noise calculated LTF is depicted by the diamond symbols, and the single-frequency-probe calculated LTF is depicted by the square symbols. The various LTF calculation methods agree extremely well. The small differences between the modeling methods and the analytical method can be attributed to the incorporation of the wavefront error in the modeling methods, which causes the modulation to drop slightly relative to the diffraction-limited case.

Finally, it is also interesting to directly compare the LTF to the MTF. Figure 11.46 shows the MTF (solid trace), the white-noise calculated LTF (diamond symbols), and the single-frequency-probe calculated LTF (square symbols). What is referred to here as the MTF is actually the square wave transfer function under partially coherent illumination, where the illumination conditions are identical to those described above for the LTF modeling. The LTF has a sharper roll-off than that of the MTF. The faster roll-off is due to the 2D nature of the LER and its interaction with the PSF compared to a pure 1D line situation treated by the MTF. The LER coupling is stronger than predicted by the MTF at very low frequencies because the low end of the MTF reduction is dominated by flare [effectively a direct current (DC) background], which does not affect LER coupling. In the case of low-frequency structures affected by flare, the pattern will be faithfully reproduced with a simple DC offset since the LER is quantified, assuming an ideal threshold resist model for which flare has little effect on the LER. This may not be the case

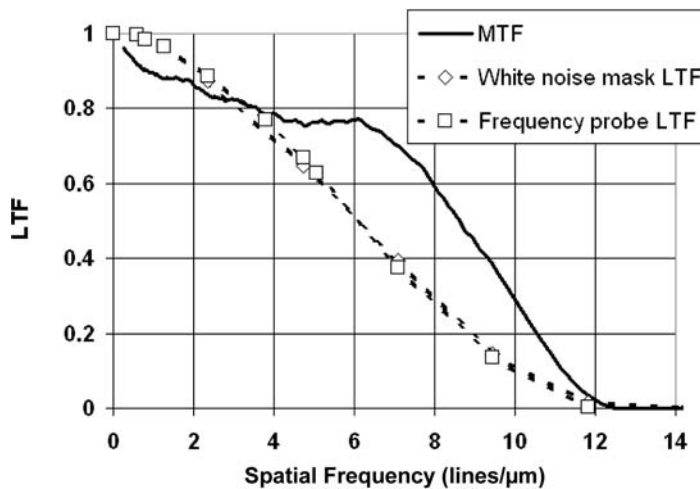


Figure 11.46 Direct comparison of LTF and MTF. What is referred to here as the MTF is actually the square wave transfer function under partially coherent illumination, where the illumination conditions are identical to those described above for the LTF modeling.

for actual resist LER, in which case the reduced line-edge slope could increase the LER, yet this is a fundamentally different effect than the mask-LER coupling issue of concern here.

11.4.2 Mask roughness effects on LER

Another potentially important contributor from the mask is surface roughness coupling to speckle in the aerial image, and consequently LER in the printed pattern.^{51,52} Because EUVL is based on reflective optics and masks, it is particularly vulnerable to this problem because mask roughness is geometrically coupled to phase roughness, scaled by an additional factor of 2 due to the reflection. Using a wavelength of nominally 13.5 nm means that very small levels of roughness on the ML-coated mask can contribute to significant modulation of the phase. Although the lithographic process involves re-imaging the mask to the wafer, the process remains sensitive to phase errors at the mask by virtue of the band-limited imaging process. Moreover, as defocus is introduced into the system, the imaging condition no longer strictly holds, and phase errors at the mask directly couple to intensity variation or speckle. The problem becomes increasingly severe as the illumination coherence is increased,⁵³ which is often done for resolution-enhancing pupil fills.

In principle, the question of mask surface roughness coupling to LER can be addressed analytically using partially coherent image formation theory coupled with the statistical representation of the mask as a random phase object.⁵² However, the problem quickly becomes intractable even under the small phase perturbation approximation. Moreover, an analytic solution becomes even more complex as defocus is considered or the small phase perturbation approximation breaks down.

An alternative analytical approach could use geometric optics while describing the rough mask in terms of slope error. Although this simple approach provides a convenient mechanism for visualizing defocus effects, it completely fails to account for the impact of partial coherence on the process. Given that the mask-roughness-induced LER is fundamentally a speckle issue,⁵³ coherence plays a crucial role. Moreover, the extent to which speckle (small spatial scale intensity variation) couples to LER depends on the aerial-image line-edge slope. Given a fixed speckle contrast, the LER would be worse with smaller line-edge slope. This factor is also ignored by the geometric analysis.

Given the difficulties described above with the analytic approaches, numeric modeling of the partially coherent imaging process remains the most viable method for studying relevant cases of mask-roughness-induced LER. This approach has previously been used to study the in-focus dependence of LER on mask roughness and illumination partial coherence.⁵¹ The numeric modeling approach, however, can be readily extended to study arbitrary imaging conditions, including defocus as well as any other wavefront aberration.

The modeling used here relies on a numeric implementation of partially coherence image formation equations⁵³ coupled with a random phase object description of the mask. Defocus as well as other aberrations can be accounted for by modifying the pupil function of the modeled imaging system. Commercial examples of programs that provide the required partially coherent image modeling capability include Prolith⁴³ and Solid-C.⁵⁴

Of significant concern for analyzing meaningful situations of mask-roughness-induced LER is the roughness description in the model. Masks used in EUVL are reflective and are rendered so through the deposition of a ML coating typically comprised of 40 or more bilayers.⁵⁵ If one starts with knowledge of the uncoated substrate surface, ML growth models can be used to predict the coating properties throughout the stack.^{56,57} From the calculated coating properties, rigorous electromagnetic field modeling could be used to calculate the electric field reflected from the mask.^{58–60} However, such an approach would be extremely time consuming. In most cases relevant to the moderate roughness of interest here, the effect of the rough mask can be readily modeled as a pure phase distribution, where the phase is determined from the geometric path-length differences imparted by assuming the EUV light to be reflected from the top surface of the mask.⁶¹ In practice, this simplification works because the vast majority of the nonconformal ML growth occurs within a small number of layers closest to the substrate. Within the EUV penetration region of a typical 40 or more bilayer ML coating, the layer growth tends to be conformal for the roughness range of interest here. Using this simplified approach, one only needs to measure the topographic profile of the final ML-coated mask.

To consider the importance that mask surface roughness may have on LER, we performed a numeric study using the modeling methods described above in combination with the simplified representation of the mask roughness. The parameters we chose were selected to coincide with EUV print tests performed using a 4 $\times$ -reduction optical system with a NA of 0.1.⁵ The roughness of the mask used in

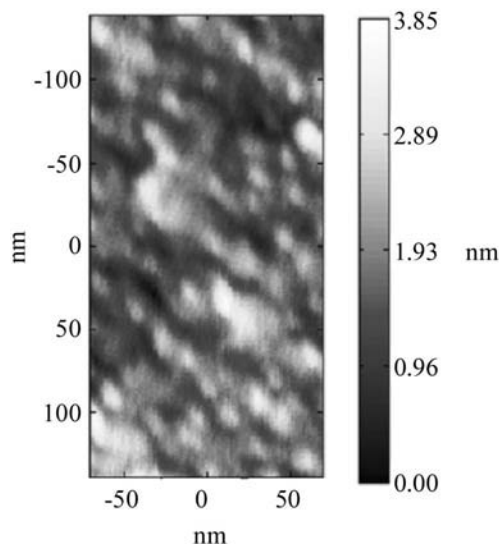


Figure 11.47 Atomic Force Microscope (AFM) image from a clear area on an EUV mask fabricated for printing with a 0.1-NA optic. The rms roughness is 0.54 nm.

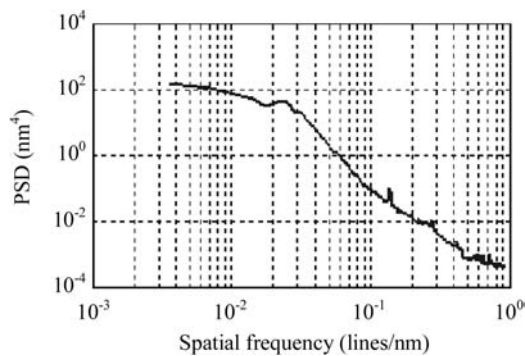


Figure 11.48 Isotropic PSD based on the AFM in Fig. 11.47.

those tests was measured after final patterning using AFM (Fig. 11.47). The measured 0.54-nm rms roughness of that mask was approximately a factor of 2 worse than typical high-quality masks available today. To generate the input mask used in the simulations presented here, the mask surface PSD was calculated (Fig. 11.48) from the AFMs and used to generate a statistical surface of the proper size. Assuming a wavelength of 13.4 nm, the topographic surface was converted to a phase perturbation. This phase distribution was then overlain (multiplied) by an ideal binary amplitude line-space pattern. Figure 11.49 shows the resulting $4\times$ input mask for features designed to print as 100-nm lines and spaces. The completely black areas represent the absorber regions, and the gray-scale regions represent the wrapped phase of the clear regions on the mask. Although the mask rms surface roughness was only 0.54 nm, upon reflection, the induced peak-to-valley phase modulation was greater than 1 wave (2π) based on an illumination wavelength of 13.4 nm.

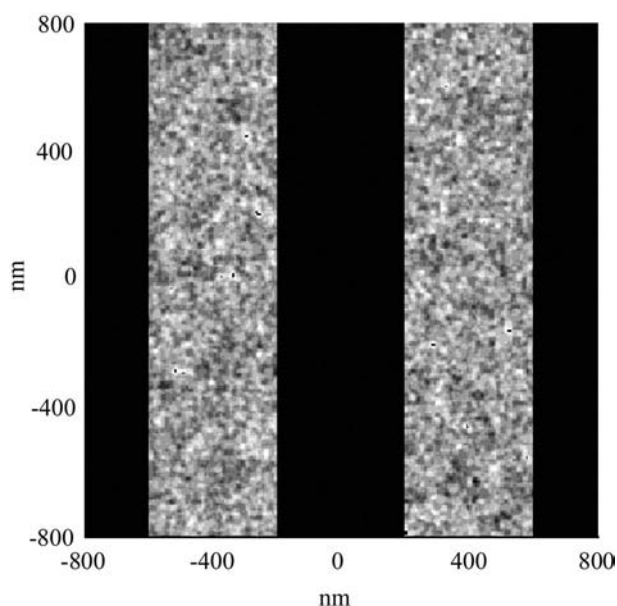


Figure 11.49 Representative input 4× mask for aerial-image simulations. Phase roughness is generated based on the PSD in Fig. 11.48. This particular mask is designed to model 100-nm printed line-space patterns. The solid black regions represent the chrome absorber and the gray-scale regions represent the wrapped phase where black is 0 and white is 2π .

Figure 11.50 shows simulation results for three different printed line widths as a function of focus and the coherence factor σ . An ideal 0.1-NA EUV optical system has been assumed. The small NA utilized by EUV systems allows the aerial-image modeling to be performed under the thin mask and scalar models. An ideal binary resist model is used, and the threshold is set separately for each σ value to provide proper sizing of the 100-nm lines at best focus. The single-sided 3σ LER is then calculated from the resulting binary image as the deviation of the measured line edge from a straight line. Interpolation of the line edge allows the actual threshold position to be determined to subpixel resolution. For the results presented in this section, an image-space pixel spacing of 1.57 nm was used. In practice, this interpolation is crucial because it allows the aerial-image simulations to be performed over a grid size amenable to current memory and processing limitations. In general, the LER gets worse at smaller line-widths, presumably due to the decreased aerial-image line-edge slope. Defocus also plays a crucial role in the mask-roughness-to-LER coupling, with increased coherence enhancing the effect. The increased coherence effect appears to saturate at approximately $\sigma = 0.4$, with LER trends even reversing in some cases. It is interesting to note that at best focus, we see very little dependence of LER on the coherence factor and consistently observe the LER to increase with σ (decreasing coherence).

A more detailed analysis, including a discussion of the importance of statistical variation in the simulation results, can be found in Ref. 62. The statistical analysis results validate the trends shown in Fig. 11.50, including reduced LER with

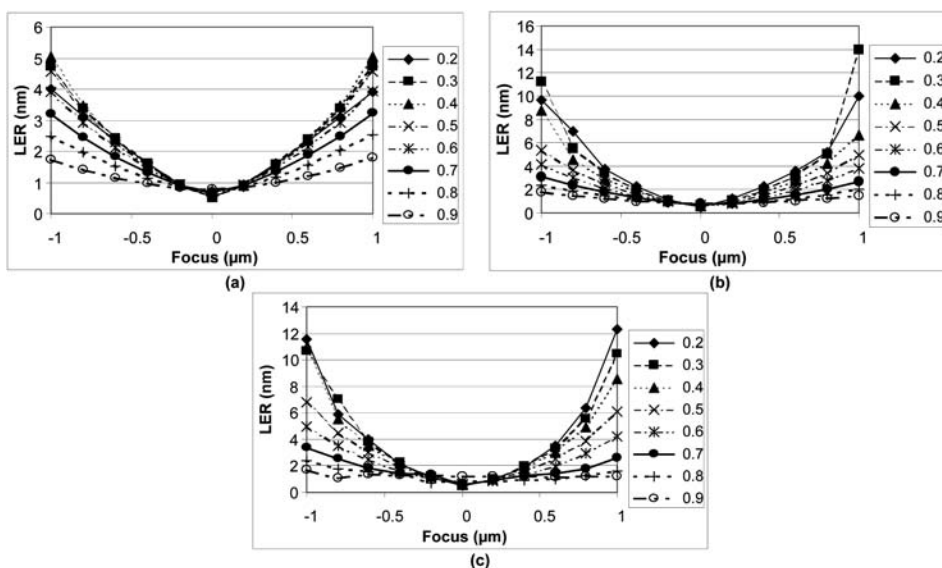


Figure 11.50 Simulation results for three different printed line widths as a function of focus and the coherence factor σ : (a) 100-nm lines and spaces, (b) 90-nm lines and spaces, and (c) 80-nm lines and spaces. An ideal 0.1-NA EUV optical system has been assumed. A binary resist model is used with the threshold set separately for each σ value to provide proper sizing of the 100-nm lines at best focus. The single-sided 3σ LER is then calculated from the resulting binary image.

increasing coherence at best focus. These results also indicate that the coherence effect saturates at approximately $\sigma = 0.4$ and suggest that the trend reversals with coherence shown in Fig. 11.50 are not systematic but rather a manifestation of statistical uncertainty.

Given the strong influence of defocus and the fact that defocus can be thought of simply as an aberration, it is also interesting to consider the effects lens aberrations may produce in the process. A study of this effect can also be found in Ref. 62. For the $\lambda/20$ wavefront error case considered, the results show no significant difference compared to the aberration-free case.

Given the importance of the LER issue for resist development, it is also crucial to consider the expected importance of mask roughness on recent LER studies. Again, this has been considered in detail in Ref. 62. The results indicate that for a 0.1-NA system with a 0.5-nm rms roughness assumed, the mask contribution to LER is negligible provided that focus is adequately controlled.

Next, we consider the impact of NA by studying the mask phase roughness effect on LER for the 0.3-NA MET case. To this end, we generated a new set of simulation masks that correspond to printed line widths ranging from 25 to 50 nm. To generate the roughness on the masks, we used the same PSD as described in Fig. 11.48 while decreasing its magnitude by a factor of 2 to more accurately represent the most recent mask-fabrication capabilities.^{63–65} In all cases, annular illumination with an inner σ of 0.3 is assumed, while the outer σ is allowed to vary

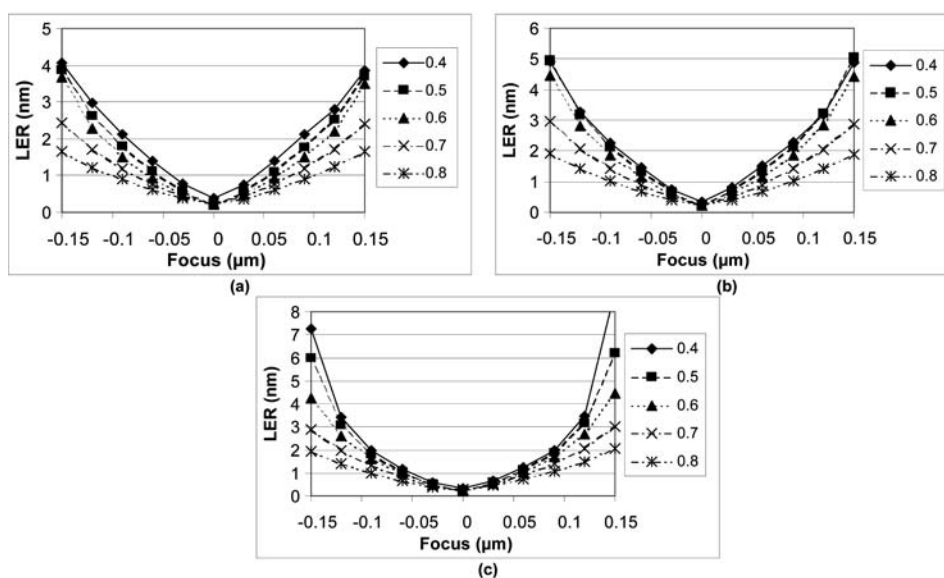


Figure 11.51 LER modeling results for the 0.3-NA MET optic design. Each plot represents a different nested-feature size: (a) 50 nm, (b) 45 nm, and (c) 40 nm. In all cases, the illumination is annular with an inner σ of 0.3, and the individual traces represent different outer σ values.

from 0.4 to 0.8. The simulated focus range is ± 150 nm, with ± 100 nm being the nominal design DOF for 30-nm features. Figure 11.51 shows the modeled LER results through focus for feature sizes from 50 to 40 nm, and Fig. 11.52 from 35 to 25 nm. The major trends are similar to those observed with the 0.1-NA case in that the LER tends to worsen as the coherence is increased, the feature size is reduced, and the defocus is increased. The trend of LER improving with increased coherence at best focus is not evident in this case, which is most likely due to the inner annulus of the illumination being so close to the edge of the central obscuration that it yields significant filtering effects from the pupil. Other anomalies are also observed, such as decreasing LER with decreasing feature size at some coherence settings. An example of this is the LER trend from 40 to 30 nm for an outer σ of 0.5 and smaller. This may be caused by an interaction between the diffracted orders from the object pattern and the central obscuration. Finally, these simulations show that at the edge of focus, the mask-roughness-induced LER accounts for the entire specified resist LER budget for the 45-nm node⁶⁶ unless very low coherence is used. This means that extreme care must be taken when using such a system for LER screening of a resist. Assuming subsequent nodes to have even tighter LER specifications, the problem becomes even more acute.

11.4.3 Mask roughness effects on printed contact size variations

Next, we consider the contact equivalent to LER—contact size variation—and the importance mask phase roughness plays in its determination. As shown above,

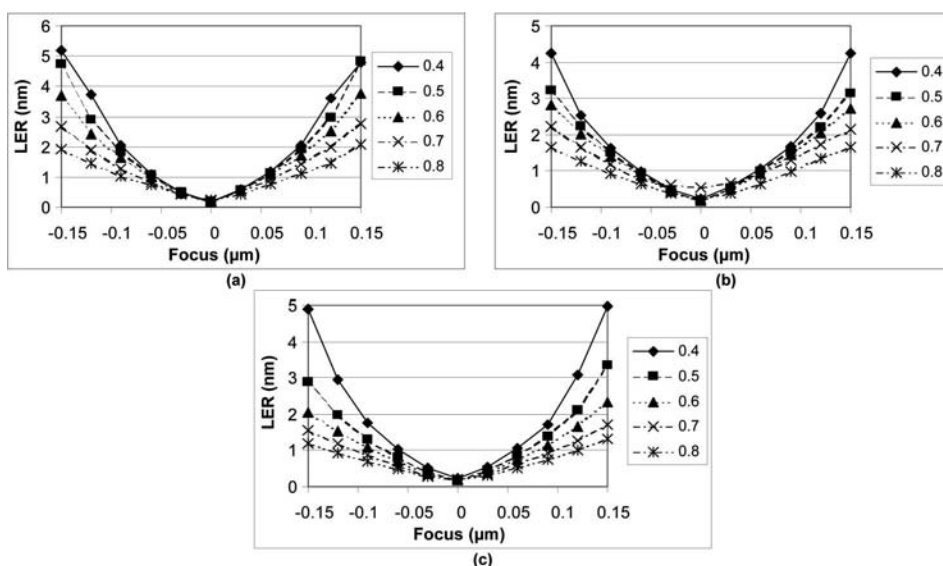


Figure 11.52 LER modeling results for the 0.3-NA MET optic design. Each plot represents a different nested-feature size: (a) 35 nm, (b) 30 nm, and (c) 25 nm. In all cases, the illumination is annular with an inner σ of 0.3, and the individual traces represent different outer σ values.

mask roughness leads to LER through the concept of speckle. When considering the printing of contacts, in the case of most interest where the contact size is close to the diffraction limit, the size of the contact in the image plane will be equivalent to the speckle size. Under these conditions, speckle will cause a global intensity change in the contact aerial image. This intensity change will be random from contact to contact, so a field of contacts would suffer printed size variations.

As discussed above, solving the general problem of partially coherent image formation in the presence of object-plane phase roughness quickly becomes intractable even under the small phase perturbation approximation.⁵² The more specific case of contact printing, however, lends itself well to several simplifications and an analytical solution.⁶⁷ Considering only contact sizes close to the diffraction limit or smaller, and assuming illumination partial coherence of 0.9 and smaller, the image formation problem can be simplified to the coherent imaging case. Coherent imaging analysis holds because under the aforementioned restrictions, the illumination coherence area will be larger than the entire contact. Moreover, because we are dealing with structures that are close to the diffraction limit, the morphology of the imaged structure can be assumed to be approximately equivalent to the optical system PSF, so we need concern ourselves only with the global intensity of the structure.

Because the contacts of interest here are near the diffraction limit, any structure within the contact, phase or otherwise, will not be resolved. Thus, every point within the contact in object space can be assumed to contribute to all points in the imaged contact, and the intensity of the imaged contact can be treated as a coherent summation of all the points in the contact in object space. Assuming mask

roughness, or random phase, this summation will take the form of a random walk whose statistics can be analytically determined. The statistics of this random walk will be equivalent to the statistics of contact-to-contact intensity variations within a field of contacts and thus provides insight into printed contact size variations. Following this methodology, the standard deviation of the normalized intensity can be shown to be

$$\sigma_{\hat{I}} = \frac{2\sqrt{(1/2)[1 + \exp(-2\sigma^2)] - \exp(-\sigma^2)}}{\sqrt{A_c/A_r} \exp(-\sigma^2/2)}, \quad (11.3)$$

where A_c is the area of a single contact on the mask, A_r is the correlation area of the intra-contact mask roughness, and σ^2 is the phase variance of the field reflected from the mask (i.e., directly proportional to the mask roughness). The actual printed contact size variation can be determined by taking into account the slope of the aerial image:

$$\sigma_W = \sigma_{\hat{I}} \frac{dW}{d\hat{I}}, \quad (11.4)$$

where W is the printed contact width. For a more detailed derivation and explanation of the results, see Ref. 67.

Mask yield, and in turn the minimization of mask defects, are crucial issues for EUVL.⁶³ Mask roughness coupling to printed-contact-size variation will have a similar impact on mask yield as that of more conventional defects. For example, using the analysis presented above, one can determine the maximum allowable mask roughness in order to achieve a desired mask yield for a mask containing a given number of contacts. For the analysis below, the following parameters are chosen:

- A lithographic system utilizing a 0.25-NA, 13.5-nm wavelength optic;
- A 4× mask with 120-nm nominally square contacts on the mask (30 nm as printed);
- An intra-contact mask roughness correlation area of approximately 5000 nm² (this corresponds to a coherence diameter of 80 nm, a typical value for a current state-of-the-art EUV mask);
- A desired mask yield of 99%, with each mask containing 10⁹ contacts;
- Contact failure defined as a greater than ±10% width change within a single-sided focal range of 100 nm.

It is important to note that focus can be assumed to affect only the image slope while not impacting the contact-to-contact intensity variation, because under the constraints described above, the effect of the roughness is simply to modulate the overall intensity of each contact and not the morphology of the imaged contact. In the defocused case, the normalization used to determine the normalized aerial image is with respect to the in-focus image, thereby accounting for the reduced

image slope with defocus. Following Ref. 67, the rms mask-roughness limit within the frequency-range limit set by the contact size is 0.15 nm. This compares favorably with current substrate manufacturing capabilities combined with ion-assisted ML deposition techniques,^{64,65} where recent results have yielded rms roughnesses of approximately 0.084 nm within a frequency band covering periods of 120 nm and smaller.

Another potential area of concern for mask roughness is the impact it might have on the printed-contact process-window. Given all the other process window constraints—focus, dose, mask defects, mask CD errors, shot noise, etc.—it would be preferable for the mask roughness term to be essentially negligible. Because the mask-roughness-induced CD error cannot be assumed to be uncorrelated from some significant full-field error sources such as defocus and dose, a safe limit for the mask roughness term might be 5% of the total error budget. Given a 10% 3σ process-window tolerance, the total error budget for 30-nm contacts is 3 nm. Thus, the total acceptable mask-roughness-induced 3σ printed size variation would be 0.15 nm. This corresponds to σ_W less than or equal to 0.05 nm. Using the system parameters described in the previous example, the rms mask-roughness limit within the low-frequency limit set by the contact size becomes 0.045 nm, approximately a factor of 2 better than current fabrication limits. At current fabrication limits (approximately 0.084-nm intra-contact rms roughness for the CD and reduction factor considered here), the mask roughness would account for a total of 0.53-nm 3σ printed contact size variation, which represents a significant fraction of the total error budget. Modeling-based verification of these results can be found in Ref. 67.

11.5 Flare in EUVL Systems

11.5.1 Sources of flare and estimating flare from surface roughness

11.5.1.1 Introduction

The presence of flare in lithographic imaging systems is a problem of ever-increasing importance for the semiconductor industry. Flare is caused by light scattered from the optical components of a lithographic system. Scattering causes the light to be redirected from a bright area of an image into all areas of the image, including those regions intended to be dark. The resulting background illumination, or “flare,” reduces image contrast and the process window for printing. Flare also has a detrimental effect on CD control; localized flare variations, which are inevitable due to pattern density variations, lead to die-to-die and within-die CD variations. Consequently, it is desirable to minimize flare levels in commercial EUVL imaging systems. If the remaining flare levels continue to cause undesirable effects, methods must be developed to compensate for those effects.

EUVL systems are all-reflective, and scattering is caused by the surface roughness of the projection optic (PO) mirrors. As the wavelength of light used for lithography continues to decrease, the relative importance of flare increases. This is because the magnitude of flare is proportional to $1/\lambda^2$, everything else being constant. For EUVL systems, it is especially important that measures be taken to

understand the sources of flare and to learn how to minimize them since the wavelength used, 13.5 nm, is more than an order of magnitude shorter than wavelengths currently used for lithography.

Current methods for polishing EUVL POs yield surfaces that are exceptionally smooth, but which still produce flare levels that would be unacceptable in deep ultraviolet (DUV) or visible lithography. However, EUVL flare is qualitatively different than DUV flare, and this difference makes it much easier to compensate for the undesirable effects of flare in EUVL. This difference is due to the fact that a given surface roughness structure scatters light through an angle proportional to λ . As a result, the EUV flare present in a lithographic feature is determined primarily by the other features in its immediate vicinity. In the DUV wavelength range, the contributions to flare in a feature come from a much larger area. The smaller difference in area makes it feasible to compensate for the undesirable effects of flare in the EUV, whereas it would be much more difficult to do so in the DUV or visible ranges. Compensation methods will be discussed in Sec. 11.5.3.

11.5.1.2 Sources of flare

Figure 11.53 shows a schematic diagram of the four-mirror ETS EUVL POs, where M1 and M3 are convex mirrors and M2 and M4 are concave mirrors. Scattering of light occurs when light is reflected by the mirror surfaces and is caused by surface roughness. The relationship between flare and mirror surface roughness can be used to develop surface specifications for mirrors that yield acceptable flare levels. The required surfaces are ultra-smooth, and it appears that state-of-the-art polishing techniques may be capable of achieving such nearly perfect surfaces in the near future.

The scattering of light by surface roughness is well understood.⁶⁸ However, applying that understanding to an evaluation of imaging system performance is

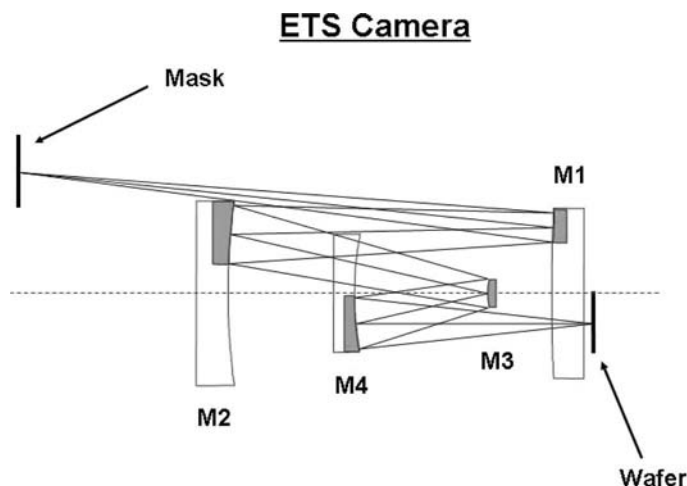


Figure 11.53 Schematic diagram of the ETS (NA = 0.1).

complex.⁶⁹ The situation for EUVL imaging systems is even more complicated, because the surfaces of EUV mirrors are coated with ML thin films in order to achieve high reflectivity. The scattering of light from such ML-coated surfaces presents a number of complications that are not present for scattering from a single surface.

Reference 70 contains an extensive theoretical analysis of light scattering in a ML-coated imaging system and the effects of that scattering on the imaging properties of the POs. A subset of the considerations presented there is applicable to the calculation of flare. The techniques described in this section represent a further simplification that is adequate for EUVL imaging systems. It has been confirmed experimentally that the theory to be described here successfully predicts the flare measured in relatively simple, two-mirror EUVL systems.⁷¹

11.5.1.3 Light scattering and surface roughness

Statistical methods are used to describe surface roughness.^{68–70} The roughness of a surface is described by the 2D PSD of the surface errors (the departures from the ideal smooth surface). We denote that function by $\text{PSD}_2(f)$; it describes the distribution of errors among the different spatial frequencies f . In our work, we explicitly assume that the surface roughness is isotropic so that the power spectrum depends only on the magnitude of f . We denote the isotropic PSD as $\text{PSD}(f)$.

We further restrict our attention to the small roughness limit in which only a small fraction of the light incident onto a surface is scattered. Consider the reflection of a collimated beam of light (having unit intensity, diameter D , and wavelength λ) from a plane surface having a roughness described by $\text{PSD}(f)$. The angular intensity distribution of the scattered light for large angles compared with λ/D , the diffraction angle of the incident beam, is given as

$$I(\theta) = \left(\frac{16\pi^2}{\lambda^4} \right) \times \text{PSD}\left(\frac{\theta}{\lambda}\right), \quad (11.5)$$

where θ/λ is the spatial frequency of that Fourier component of the surface roughness that scatters light of wavelength λ through the angle θ . This fundamental equation is the starting point for calculating flare.

The distribution of light scattered outside of the specularly reflected beam is often referred to as the “wings” of the intensity distribution of the reflected beam. Using Eq. (11.5), it is straightforward to show that the fraction of light scattered between the angles θ_1 and θ_2 is given by $(4\pi/\lambda)^2 [\sigma(f_1, f_2)]^2$, where

$$[\sigma(f_1, f_2)]^2 = \int_{f_1}^{f_2} \text{PSD}(f) 2\pi f df \quad (11.6)$$

is the mean-square surface roughness for spatial frequencies between $f_1 = \theta_1/\lambda$ and $f_2 = \theta_2/\lambda$. The small roughness limit corresponds to $(4\pi\sigma_0/\lambda)^2 \ll 1$, where σ_0 is the mean-square roughness evaluated using $f_1 = 5/D$ and $f_2 = \infty$. Surface

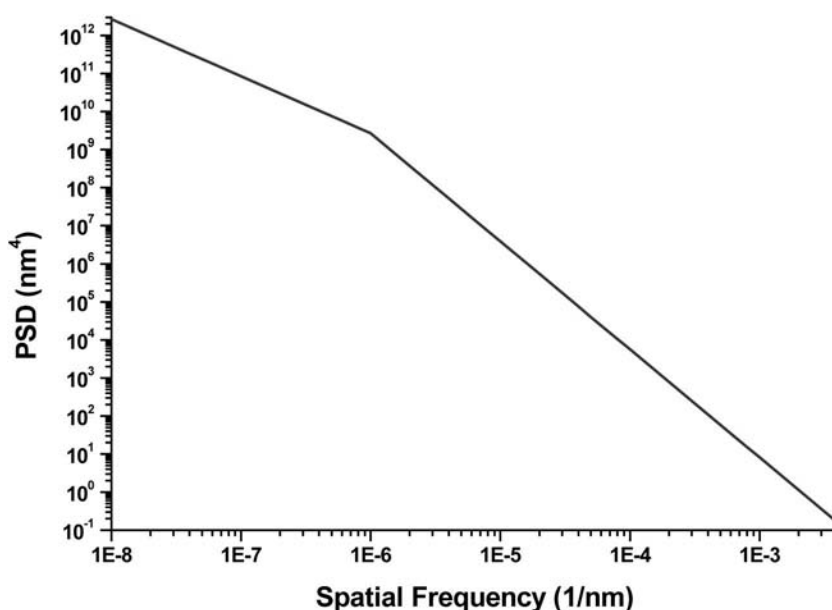


Figure 11.54 Hypothetical PSD for a mirror used for EUVL.

errors having spatial frequencies smaller than $5/D$ are not considered as contributing to scatter since the effects of those errors are usually treated deterministically and are considered “figure errors.” They are typically described by Zernike polynomials and are the cause of imaging aberrations.

11.5.1.4 Power spectral densities

Figure 11.54 shows a hypothetical PSD for an EUVL mirror with a 50-mm diameter. An actual PSD is determined by measuring the departures of the mirror surface from the ideal mirror surface. Three different surface metrology instruments are required to measure the surface errors over the large range of spatial frequencies shown here. The high-spatial-frequency errors, those having spatial frequencies higher than $10^{-3}/\text{nm}$, are measured using an AFM. The mid-spatial-frequency errors, those having spatial frequencies between $10^{-6}/\text{nm}$ and $10^{-3}/\text{nm}$, are measured using an interference microscope. The surface errors having spatial frequencies below $10^{-6}/\text{nm}$ are measured using visible light interferometry. In the fabrication of EUVL optics, separate specifications are set for the allowable rms roughness in the various spatial frequency regions. The PSD shown in Fig. 11.54 has a σ_0 value of about 0.22-nm rms.

Table 11.1 lists the roughness values for the Intel MET mirrors for figure, midspatial frequency roughness (MSFR), and high-spatial frequency roughness (HSFR).

A useful way to determine which frequency ranges contribute most to scattering is to plot the accumulated roughness as a function of spatial frequency. This is shown in Fig. 11.55, where $[\sigma(1/D, f)]^2$ is plotted as a function of the spatial

Table 11.1 Roughness of the Intel MET mirrors as measured at Zeiss for figure, MSFR, and HSFR, where CA-1 is a unit for cycles over the clear aperture.

	Range	M1 (nm rms)	M2 (nm rms)
Figure	CA ⁻¹ –1 mm ⁻¹	0.24	0.20
MSFR	1 mm ⁻¹ –1 μm ⁻¹	0.21	0.18
HSFR	1 μm ⁻¹ –50 μm ⁻¹	0.35	0.28

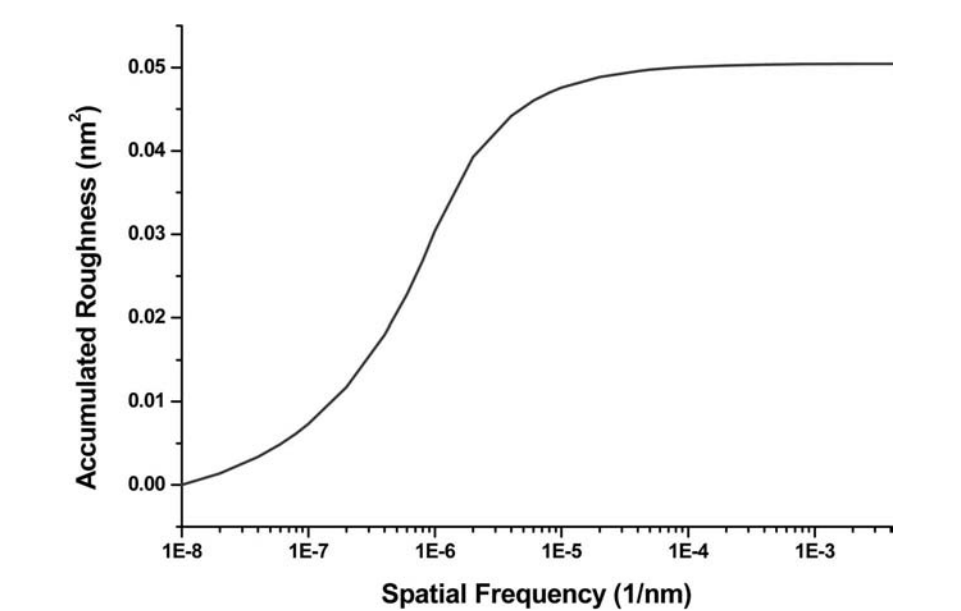


Figure 11.55 Accumulated roughness as a function of upper frequency for the hypothetical PSD plotted in Fig. 11.54.

frequency f . The errors having frequencies less than about $5/D$ are usually treated as deterministic figure errors, and their effects on imaging are calculated using image simulation software such as Prolith. Higher-spatial-frequency errors cause scatter and are usually treated statistically. Figure 11.55 shows that the vast bulk of the scattering occurs for spatial frequencies between $10^{-7}/\text{nm}$ and $10^{-5}/\text{nm}$, corresponding to spatial periods between 10 and 0.1 mm. These frequencies are the primary contributors to flare for submicron features in EUVL systems.

11.5.1.5 Point-spread functions

The ability of a PO to produce a sharp aerial image is characterized by the PSF of the PO. The PSF is simply the intensity distribution (aerial image) produced by the PO of a perfect point source object. In the absence of scattering, the PSF is denoted PSF_0 , and it is determined by diffraction and by the PO aberrations. For an aberration-free PO, PSF_0 is determined solely by diffraction and is given by the well-known Airy function.⁷² If we let $I_0(r)$ be the perfect image of the object (no

diffraction and no aberrations), then the actual image $I(r)$ produced by the PO is given by the convolution of $I_0(r)$ with PSF_0 . That is,

$$I(r) = I_0(r) * \text{PSF}_0(r), \quad (11.7)$$

where the spatial coordinates are in the image plane and the asterisk denotes the convolution operation. This discussion holds only for the case of incoherent illumination of the object. For the more general case of partially coherent imaging, the calculation of the aerial image is more complicated. In all cases, we denote the aerial image formed by the PO in the absence of scattering as $I(r)$.

When scattering is present, an additional component to the PSF is determined by light scattered out of the specular beams. The effects of scattering are treated statistically and are independent of the coherence of the object illumination;⁷⁰ thus, its PSF, which we call PSF_{sc} , is treated somewhat differently. The aerial image in the presence of scattering is determined by the following convolution:

$$I_{\text{sc}}(r) = I(r) * [\delta(r) + \text{PSF}_{\text{sc}}(r)]. \quad (11.8)$$

The function $\text{PSF}_{\text{sc}}(r)$ is closely related to Eq. (11.5). Equation (11.5) can be used to describe the angular distribution of light scattered by the surface roughness of the last mirror, M4. But how does one account for the light scattered by mirrors M1, M2, and M3? Reference 70 carries out a complex theoretical analysis to determine the manner in which the various mirrors contribute to the scatter of the full PO. The interested reader is referred to that work for a full understanding of the issue. For our purposes here, it suffices to say that the distances between the first three mirrors and mirror M4 are irrelevant, and that with proper scaling, the roughness of the first three mirrors can be directly transferred to M4. With this understanding, the PSF due to scattering is given by

$$\text{PSF}_{\text{sc}}(r) = \left(\frac{16\pi^2}{\lambda 4L2} \right) \sum \alpha n^2 \text{PSD}_n \left(\frac{\alpha n r}{\lambda L} \right), \quad (11.9)$$

where $\text{PSD}_n(f)$ is the PSD of the n th mirror, the summation is performed over the mirrors in the PO, and L is the distance from M4 to the image plane (445 mm for the ETS PO). The parameter αn is a scaling parameter determined by the size of the “footprint” of the light beam on the mirrors; specifically, αn is given by the size of the footprint on M4 divided by that on the n th mirror. For the ETS, the various values are $\alpha_1 = 1.77$, $\alpha_2 = 0.884$, $\alpha_3 = 1.76$, and $\alpha_4 = 1$. Equation (11.9) is derived in Ref. 71 and is the key equation presented here.

As an example, we let the hypothetical PSD of Fig. 11.54 describe the surface roughness of all four mirrors of the ETS PO. The resulting $\text{PSF}_{\text{sc}}(r)$ is plotted in Fig. 11.56, where it is also compared with the function (which has been normalized for unit power). It is clear that scattering significantly increases the wings of the PSF, and it is this increase in the wings that causes flare. Note that PSF_{sc} is considerably less than the Airy function for values of r less than about 500 nm.

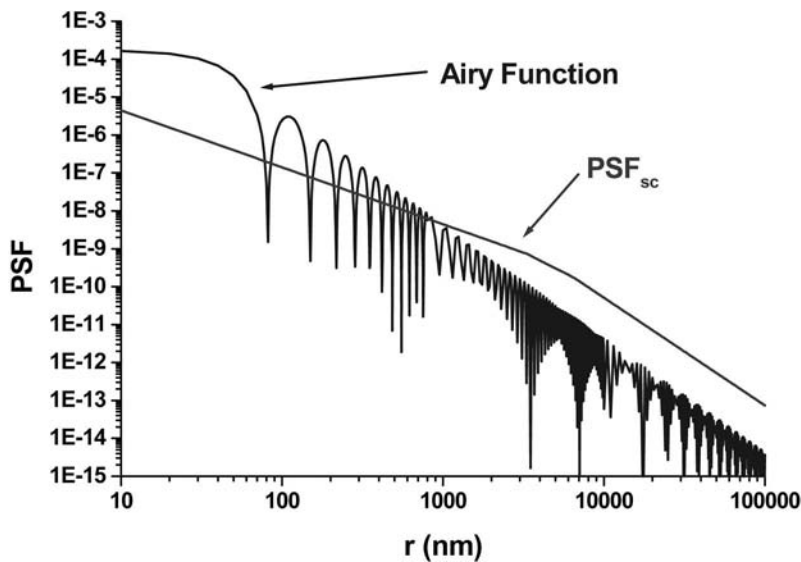


Figure 11.56 Comparison of the Airy function and PSF_{sc} calculated for the ETS PO, assuming that the PSD shown in Fig. 11.54 applies to all four mirrors of the PO. The Airy function is plotted with limited resolution so that its zeroes are not adequately resolved.

This reflects the fact that scattering has little effect on EUVL system resolution. The basic result of scattering is to contribute a background illumination (flare) that reduces image contrast and the process window for printing.

11.5.1.6 Calculation of flare

For a given mask pattern and PO, the image intensity distribution $I_0(r)$ can be calculated using simulation software such as Prolith; this is the image obtained in the absence of scattering. The influence of scattering on the image is then calculated using Eq. (11.8), and the function PSF_{sc} is calculated using Eq. (11.9).

Generally speaking, flare is the additional background illumination added to the mask image by the scattered light. The effect of scattering on the aerial image produced by an EUVL system is shown in Fig. 11.57. The dashed curve shows the aerial image, normalized to a peak intensity of 1, produced by an aberration-free system in which there is no scattering. The solid curve is an example of an aerial image obtained when there is significant scattering in the system. Scattering removes light from the rays in the specular beam that form the aerial image; thus, the amplitude of the gray aerial image is less than that of the dark aerial image. The fraction of light removed from the specular rays is denoted as total integrated scatter (TIS). TIS is the fraction of the light passing through the system that is scattered into all angles; we assume that TIS is constant over the image field. TIS is an estimate of the total amount of scattered light from mirror roughness and is

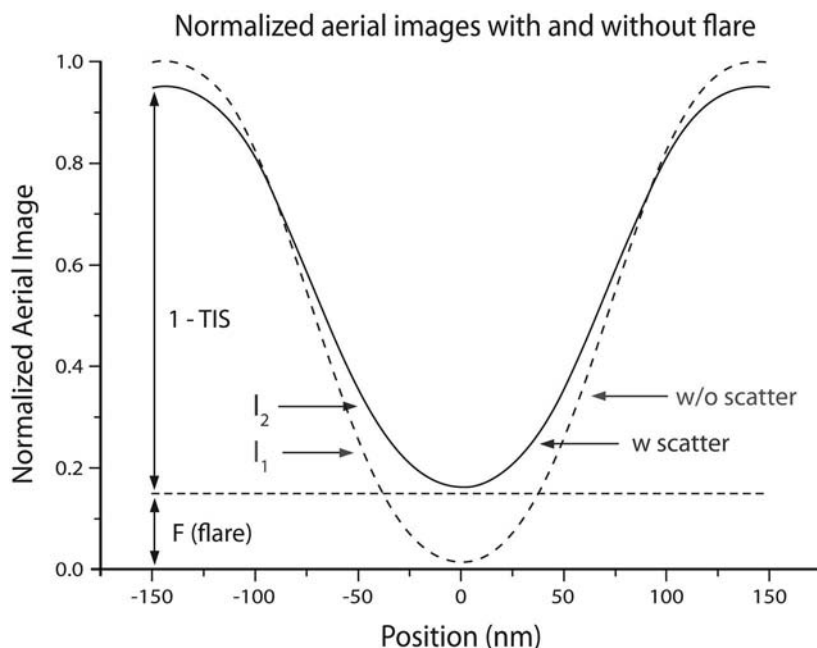


Figure 11.57 Aerial image of an isolated 100-nm dark line in a bright field imaged by a 0.08-NA EUVL system using radiation at 13.5 nm with a partial coherence of 0.7.

calculated using Eq. (11.10):

$$\text{TIS} = \text{No. of mirrors} \times \left(\frac{4\pi}{\lambda} \right)^2 \times (\text{RMS MSFR roughness})^2. \quad (11.10)$$

A portion of the scattered light that is scattered through small angles finds its way to the image plane and causes the background illumination that we refer to as flare. Light scattered through larger angles ends up outside the image field and contributes to a loss in light throughput.

11.5.1.7 Measured and projected flare in EUVL systems

A number of EUVL imaging systems have been fabricated and characterized. Figure 11.58 shows values of flare measured in some two-mirror and four-mirror systems. These results clearly demonstrate that significant improvements in polishing techniques have occurred during the last several years. Also shown are projections of flare levels expected in six-mirror commercial systems that are being developed (Beta 2006 and HVM 2009). Recent MSFR values for two-mirror systems (METs and HiNA 3) are extremely encouraging and give us confidence that the target MSFR of <0.14-nm rms per mirror to get <10% flare could be achieved for these six-mirror, 0.25-NA systems in time for the 32-nm node.

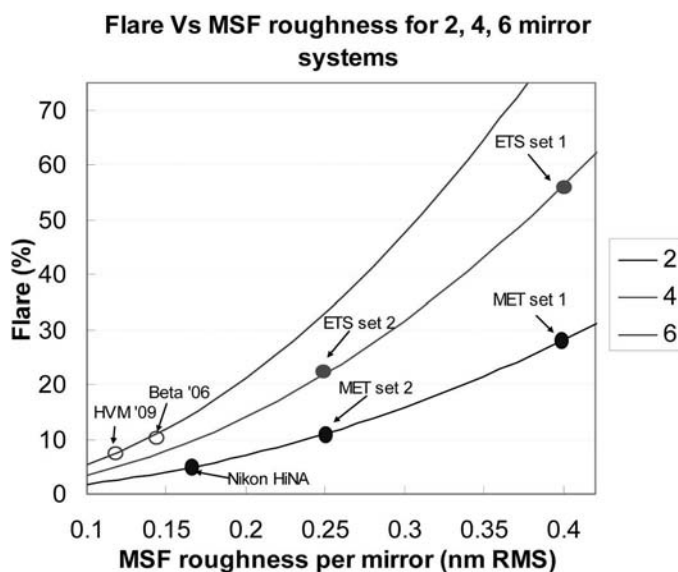


Figure 11.58 Trends of flare vs MSFR for EUVL systems. PSDs for two mirrors polished by the same process for the ETS.

11.5.2 Flare characterization of the Intel MET

11.5.2.1 Introduction

Experiments were performed on the EUV MET at Intel. The MET is a microfield ($600 \times 600 \mu\text{m}$), 0.3-NA, two-mirror lithography exposure tool made by Exitech, Ltd.^{34,76} with resolution down to 30 nm.⁷⁴ The illumination settings used for the flare measurements were annular³⁷: $\sigma_{\text{inner}} = 0.36$, and $\sigma_{\text{outer}} = 0.55$. Twelve-inch Si wafers were used to do the measurements, and all the processing was done using the linked TEL-ACT12 track in Ronler Processing 1 (RP1), a Class 1 clean room fab. The resist thickness measurements were made using a Nanospec, and the feature size measurements were made using a CD-SEM.

11.5.2.2 Kirk test

Flare, which results in unwanted light under nominally dark features, is typically measured using the resist clearing or “Kirk test.”³⁷ The dose to clear (E_0) is divided by the dose to clear a feature, usually a 2- μm line, to obtain the flare. This is a necessary but not sufficient method to characterize flare. As was discussed earlier, the PSF_{sc} is needed to estimate the local flare for a patterned mask. When making this calculation, the following two assumptions are commonly made: flare (and hence the PSF_{sc}) is uniform across the field, and PSF_{sc} is rotationally symmetric. Confidence in these assumptions can only be obtained if they are confirmed by field measurements. Another common assumption is that flare needs to be measured by the 2- μm line. However, the PSF_{sc} for EUVL systems has a strong short-range component, so it would be more accurate to measure flare in EUVL systems using

a 1- μm or even 0.5- μm line.⁷³ It is for these reasons that we consider a suite of measurements to characterize flare rather than the single dimensional measurement typically done using the Kirk test.

The resist-clearing or Kirk test involves measurements of the dose to clear a feature, typically a 2- μm line, to estimate the fraction of the light intensity in the open frame that appears under the 2- μm line. Kirk³⁷ proposed these criteria for the feature size selection: the feature must be much larger than the diffraction limit, and the feature must be much larger than the resist thickness so that it is not impacted by lateral development rate. These additional criteria were suggested by Ref. 73: the feature size must be small enough that it does not suppress flare locally, and the length of the feature must be long enough such that the flare contributed by the Airy disc is negligible. Mack⁷⁴ proposed that the feature size should be selected such that the minimum normalized aerial image intensity due to diffraction (no flare) be less than 0.002 to achieve a 0.2% flare accuracy. Based on these considerations, the flare on the EUV MET was found to be measured by the dose to clear of a 1- μm line.⁴

11.5.2.3 Flare measurements versus feature size

Previously, the EUV-2D resist^{79,80} was used to measure flare on Intel's MET. However, EUV-2D has a dose to clear (E_0) of 8.25 mJ/cm²; at the high doses to measure flare ($\sim 30 \times E_0$), EUV-2D was found to cross-link, which makes precise measurements difficult. Subsequently, a highly sensitive photoresist with a low E_0 of 1.8 mJ/cm² that does not cross-link at high doses was used.

Flare was measured using the resist-clearing technique as a function of feature size from 2.5 to 0.5 μm . In the resist-clearing technique, two types of patterns are exposed over a range of doses, namely, a clear field and a flare test structure (typically a 2- μm line feature). The dose to clear the resist, E_0 , measured for a completely clear field is typically divided by the dose to clear the feature, E_{clear} , to obtain flare. However, for the masks used in these experiments, a nonnegligible amount⁷⁶ of reflectance through the nominally completely dark feature must be subtracted from the measurements. The contribution to flare for the mask used for the measurements was 2.66% (R_{abs}), which was obtained by dividing the reflectivity of the absorber region (1.64% absolute) by the reflectivity of the clear ML region (61.67% absolute).

$$\text{Flare}(\%)|_{\text{feature}} = \left(\frac{E_0}{E_{\text{clear}}|_{\text{feature}}} \right) \times 100 - R_{\text{abs}}. \quad (11.11)$$

Figure 11.59 shows the results for flare measured as a function of feature size at the center of the field for lines oriented in the vertical direction after subtracting the relative absorber reflectivity. The measured flare increases as the feature size decreases. It is 4% for the 1- μm line and increases to 5.2% for the 0.5- μm line.

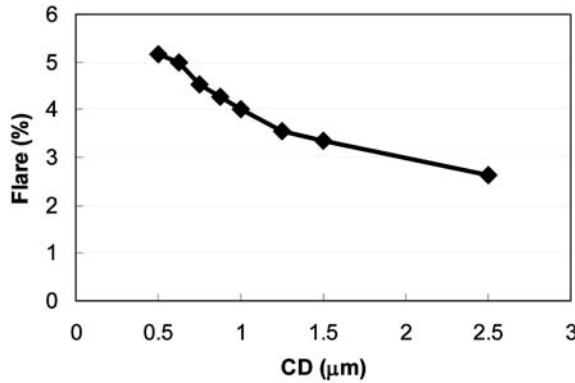


Figure 11.59 Measured flare as a function of feature size on the Intel MET.

11.5.2.4 Modeling flare on the MET

Flare in EUVL arises mostly from scattering off the MSFR of the mirror surfaces. Prior to coating, the PSDs of the mirror substrates within spatial frequencies of 1 mm to 1 μm are measured using an interference microscope. The rms MSFR for mirrors M1 and M2 of the Intel MET are 0.21 and 0.18 nm, respectively.⁷⁶ The TIS is calculated using the formula below:⁸¹

$$\text{TIS} = \text{No. of mirrors} \times \left(\frac{4\pi}{\lambda} \right)^2 \times (\text{RMS MSFR roughness})^2. \quad (11.12)$$

For the Intel MET, and using the roughness from mirror M1, TIS is estimated as 5.6%.

To predict the flare as a function of feature size, it is necessary to first obtain the PSF due to scatter (PSF_{sc}). The PSF_{sc} is the aerial image for a point source object in the presence of scattering. The flare is then computed by convolving the PSF_{sc} with the aerial image of the feature (without flare).

The PSF_{sc} shown in Fig. 11.60(b) is calculated from the PSDs for the Intel MET⁸² using

$$\text{PSF}_{\text{sc}}(r) = \frac{16\pi^2}{\lambda^4 \rho_2^2} \left[\text{PSD}_2 \left(\frac{r}{\lambda \rho_2} \right) + \alpha^2 \text{PSD}_1 \left(\frac{\alpha r}{\lambda \rho_2} \right) \right], \quad (11.13)$$

where $\alpha = M(\rho_2/\rho_1)$, and PSD_1 and PSD_2 are the PSDs for mirrors M1 and M2 [see Fig. 11.60(a)]. For the MET, $\lambda = 13.5$ nm, $\rho_1 =$ distance from the mask to M1 = 449.165 mm, $\rho_2 =$ distance from the wafer to M2 = 300.6 mm, and $M =$ mask reduction ratio = 5, so $\alpha = 3.346$.

Since the features used to measure flare (~ 1 μm) are much larger than the diffraction limit, the first step is to approximate the aerial image by the mask pattern. Hence, the flare of the Intel MET as a function of feature size (Fig. 11.61) is obtained by convolving the PSF_{sc} with the mask pattern $T(x, y)$ for the given feature

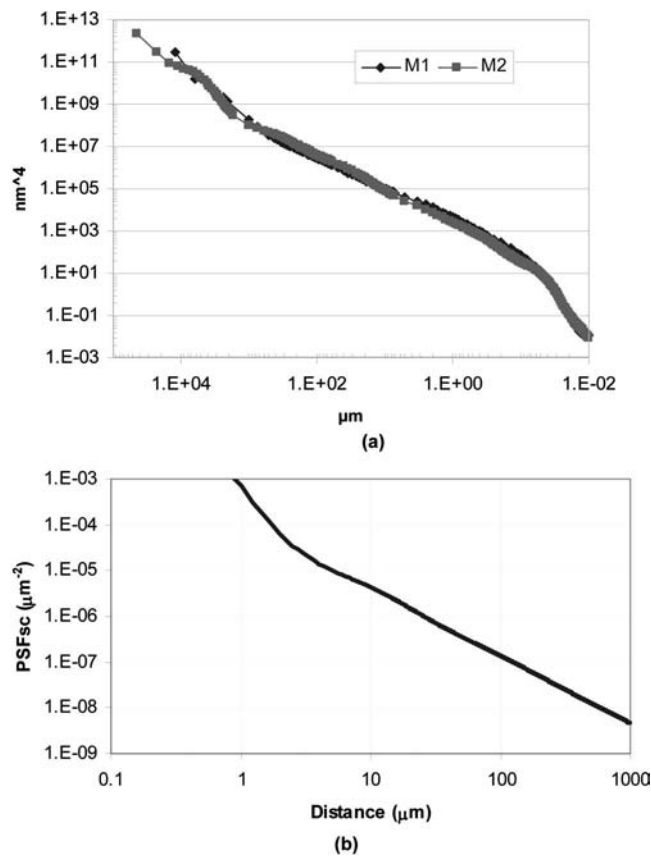


Figure 11.60 (a) PSDs for M1 and M2. (b) PSF due to scatter from PSDs.

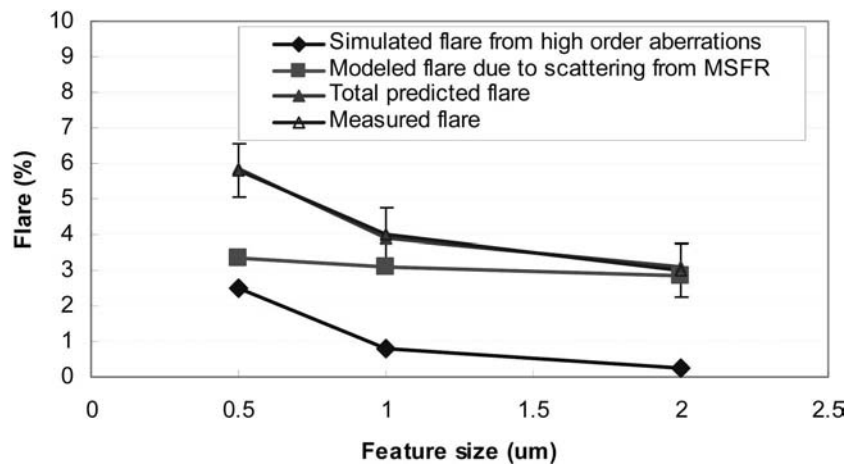


Figure 11.61 Comparison between experimental and predicted flare as a function of feature size.

placed within the $600 \times 600 \mu\text{m}$ field:

$$\text{Flare} \approx \iint_{x=0-600, y=0-600} \text{PSF}_{\text{sc}}(x, y) T(x, y) dx dy. \quad (11.14)$$

The flare for a $1\text{-}\mu\text{m}$ line using the PSF_{sc} is calculated as 3%, which is 1% lower than the measured value. For the $0.5\text{-}\mu\text{m}$ line, the discrepancy between the measurement and model gets worse ($\sim 2.5\%$). Reference 83 showed that higher-order aberrations (above Zernike polynomial³⁷) could also contribute to flare. Simulations of the aerial image with no flare and a perfect mask (perfect absorber) for different line sizes with the raw wavefront error measured using interferometry were run using Iphoto, Intel's proprietary lithography simulator. The simulations used partially coherent, annular (0.36/0.55), nonpolarized illumination. The intensity at the center of the pattern (below the feature) was found to be nearly zero below the $2\text{-}\mu\text{m}$ line, but it increased to 2.3% for the $0.5\text{-}\mu\text{m}$ line. The addition of the intensity below the feature (at the center of the pattern) from the aerial image simulations using the raw wavefront error to the flare calculated using scattering by MSFR results in a better match with the experimental data, as shown in Fig. 11.60.

While modeling the flare as a function of feature size (no flare, perfect mask), it was observed that the aerial image for the $0.5\text{-}\mu\text{m}$ line even without aberrations resulted in a nonnegligible intensity due to diffraction below the feature (at the center of the pattern). Further investigation revealed that this intensity arises from the central obscuration, which is inherent to the MET design.⁷⁷ Increasing the line size to $1 \mu\text{m}$ reduced the minimum normalized intensity below the feature (at the center) to below $1\text{E-}4$. Since the feature size used to measure flare must be independent of diffraction effects, it was determined that the $1\text{-}\mu\text{m}$ line should be used to measure flare on the MET, which would then be 4% as per Fig. 11.59.

11.5.2.5 Orientation dependence of flare

Lee et al. found that in the ETS, the flare in the horizontal (H) direction was greater than the flare in the vertical (V) direction.^{82,83} This result was attributed to the mirror polishing process, which resulted in an asymmetric PSF_{sc} . Flare was measured in the azimuthal direction in 15-deg -angle increments using a spoke pattern with $1\text{-}\mu\text{m}$ lines⁷³ (see Fig. 11.62). The data show that the flare in the horizontal direction is slightly larger (5%) than the flare in the vertical direction (4%).

11.5.2.6 Across-field flare measurements

Typically, flare across the field has been constant in EUVL systems such as the ETS,¹⁴ whereas it is nonuniform across the field for DUV systems.⁸² This is due to the short scattering range of EUV flare compared to DUV flare. A 2D plot of flare across the full field is shown in Fig. 11.63(a), and a 1D plot along the cut-line is shown in Fig. 11.63(b). Figure 11.63(b) shows that flare is a constant at 4.1%

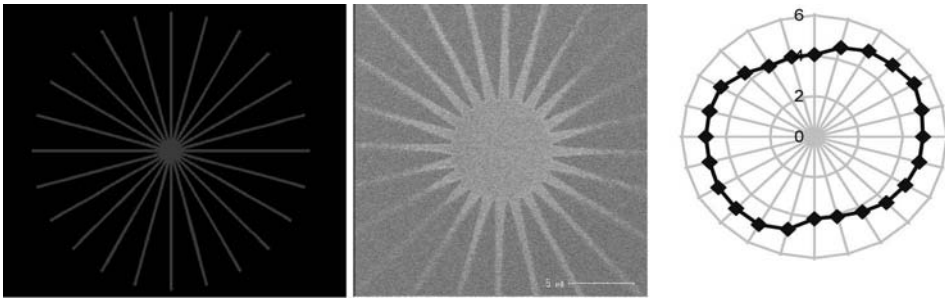


Figure 11.62 Orientation dependence of flare measured on the MET at Intel.

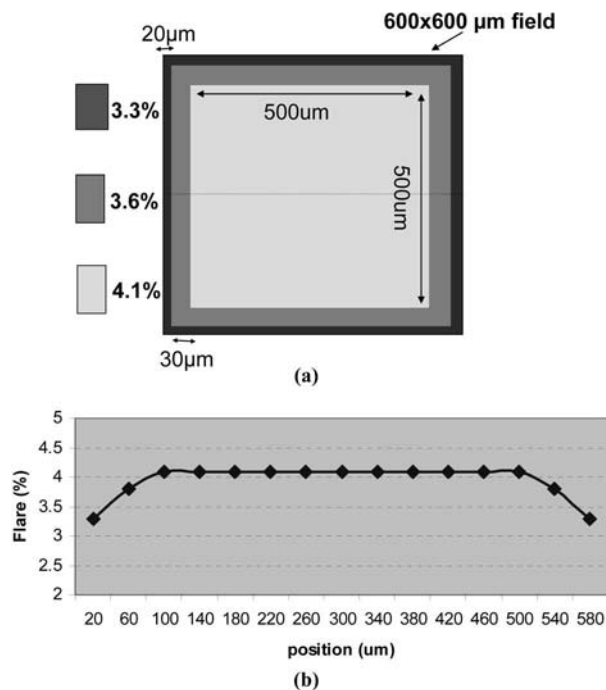


Figure 11.63 Flare measured across the 600-μm field. Flare is a constant at 4.1% across the field except for the very edges of the field.

across the field except for the extreme edges of the field. Flare drops to 3.6% at $\sim 30 \mu\text{m}$ from the edges, and drops even further to 3.3% at $\sim 20 \mu\text{m}$ from the edges. Since the region around the $600 \times 600 \mu\text{m}$ field is dark, the contribution from the region outside the exposed area is negligible, resulting in lower flare at the edge of the field. Thus, the full-field flare measurements verify that EUV flare is constant across the field except for the very edges of the field, and the flare variation across the field is less than 1%.

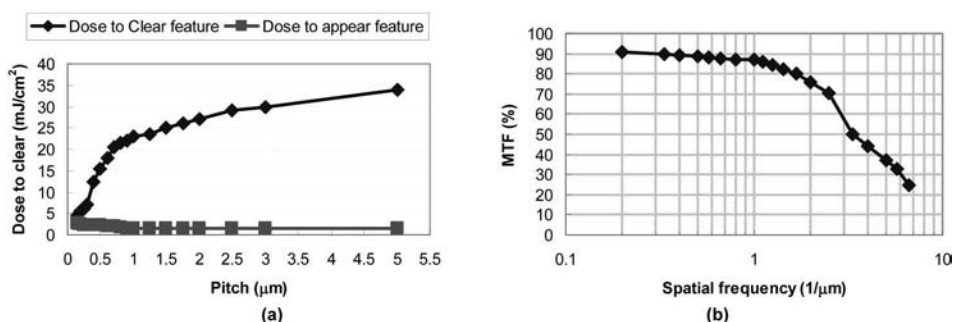


Figure 11.64 (a) Dose to clear and dose to appear vs pitch. (b) MTF vs spatial frequency.

11.5.2.7 Measurements of the MTF as a function of pitch

The MTF, also referred to as contrast, is a fundamental measurement of system performance—exposure tool, mask, and photoresist. MTF measurements have been used to quantify the resolution limits of photoresists.⁷ It has been shown that the inverse Fourier transform of the MTF yields the PSF.⁷³

Gratings of equal line-space features from 50-nm pitch to 5-μm pitch were exposed on the MET at varying doses. The MTF at a particular spatial frequency (k_x , units = 1/pitch) can be obtained by measuring the clearing dose (D_c) and appearing dose (D_a) of the line-space gratings for that particular spatial frequency, and is given by

$$M(k_x) = \frac{[D_c(k_x) - D_a(k_x)]}{D_c(k_x) + D_a(k_x)}. \quad (11.15)$$

When D_c is lower than D_a , no pattern is discernable under the SEM. At the dose to clear, there is sufficient contrast in the SEM image between the region where the feature occurs and the region around it. At this point, the resist in the region around the feature is not completely cleared all the way to the bottom, but the step height is sufficient to determine the edge of the feature under the SEM. D_c and D_a as a function of pitch for the high sensitivity resist are shown in Fig. 11.64(a), and the resulting MTF is shown in Fig. 11.64(b).

11.5.3 Impact of flare on patterning performance and flare variation compensation

11.5.3.1 Introduction

Flare can have a large impact on two main areas: patterning performance, and within-die CD variation. Since increased flare degrades the contrast of the aerial image, the resulting process window will be smaller up to a point where very high flare can result in some features not being printed at all. The degraded aerial image

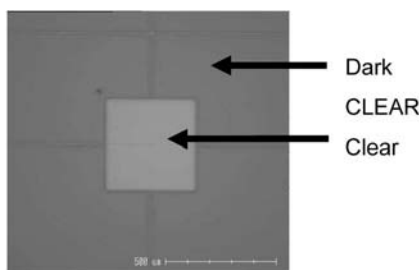


Figure 11.65 Clear areas created in regions of chrome. Increasing the clear-area size increases flare.

can also increase line width roughness (LWR), a parameter that has been shown to impact device performance.⁸⁴

Flare levels can be modulated by the amount of dark regions of a mask. Thus, typical dark-field layers such as the contact layer have low flare, whereas mostly clear layers such as the gate layer (particularly for logic patterns) have high flare. In addition, pattern density variation within the die can result in some areas of the mask getting higher flare and some areas of the mask getting lower flare. This local flare variation will result in within-die CD variations.

We will investigate the impact of flare on patterning performance and examine techniques of mitigating the effects of flare. In addition, within-die flare variation can be compensated to some extent using flare variation compensation (FVC) techniques that are akin to optical proximity correction (OPC) but on a larger length scale. FVC methodologies are now available within commercial OPC software, making this a viable option for reducing flare dependent within-die CD variation.⁸⁵

11.5.3.2 Impact of flare on process window

It is well known that flare results in reduced contrast and has significant impact on the lithography process window.⁸⁶ One way to quantify this is to use a test mask with open areas of varying sizes (windows) cut out within a dark region of the mask (see Fig. 11.65). Larger windows have more open area and hence higher flare. The calculated flare at the center of the window is obtained by convolving the PSF_{sc} [for project optics box (POB) #2 of the ETS—see Fig. 11.73] with the mask pattern and is shown in Table 11.2. The dark regions were made large enough, 1×1 mm in size, to minimize cross contamination of flare between adjacent regions. The CD as a function of dose and focus for 75-nm drawn isolated lines was measured within each of the windows (flare levels). The process windows were extracted for 0, 5, and 15% flare allowing 90 ± 10 -nm CD variations. The trends of DOF and EL as a function of flare are shown in Fig. 11.66. The trend of the degradation of the DOF and EL is nonlinear. Going from no flare to 5% flare resulted in a 30% decrease in DOF (when EL was fixed at 5%), or a 20% decrease in EL (when DOF was fixed at $0.5 \mu\text{m}$).

Table 11.2 Estimated flare levels corresponding to openings (window sizes) in 1 × 1 mm chrome regions on the ETS using the PSF_{sc} for POB2.

Window size (microns)	Flare (%)
1.5	0
3	5
10	10
30	15
400	20

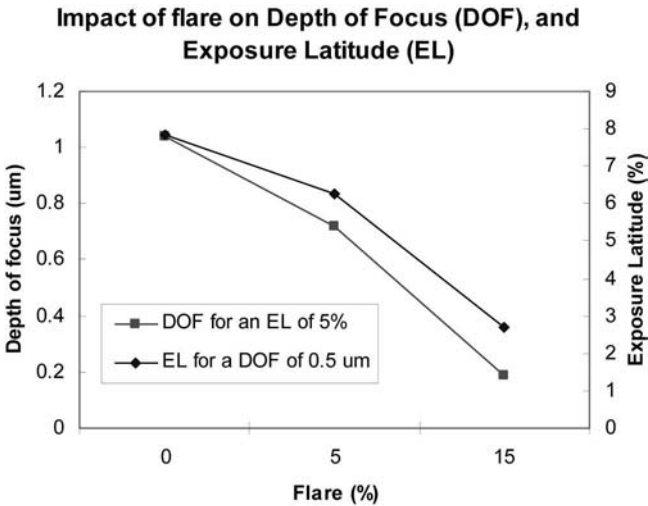


Figure 11.66 Trends of DOF and EL as a function of flare for 75-nm isolated lines.

11.5.3.3 Impact of flare on LWR

In addition to reducing process-window size, flare also affects line roughness. To limit diffraction effects on LWR, the LWR for 2-μm lines was measured as a function of flare. Figure 11.67 shows that as flare increases, the LWR also increases in a nonlinear fashion. LWR does not change when flare is significantly below 15% (~10-nm 3σ), but at 20% flare, a very rough 40-nm LWR is observed. This trend in LWR has been correlated to the decrease in the image log slope (ILS) of the aerial image with increasing flare:^{86–88}

$$ILS = \left(\frac{1}{I_{Thresh}} \right) \times \frac{dI}{dx} \Big|_{I_{Thresh}} . \tag{11.16}$$

The ILS as a function of flare was obtained from simulations. For the EUV-2D resist, a scale factor of 296.5 was used to match the trend of 1/ILS, with LWR showing the correlation between degradation of the aerial image due to flare and LWR. For LWR measurements, it is important to use large feature sizes that are relatively

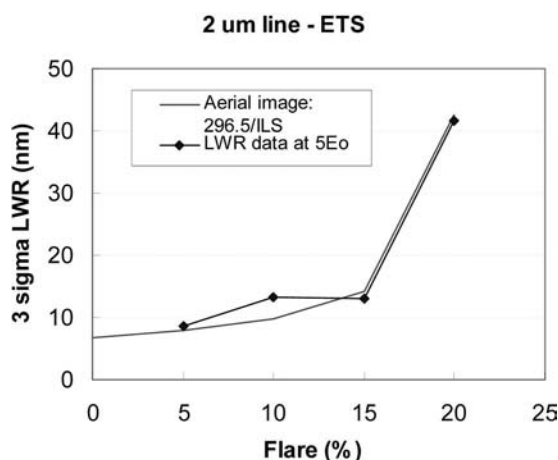


Figure 11.67 Impact of flare on the LWR of a 2- μ m line. The trend matches that of 1/ILS.

free of aerial image effects. Based on the data shown in Fig. 11.67, it was determined that ILS must be >40 1/ μ m for benchmarking the LWR of EUV resists.⁸⁹

11.5.3.4 Flare mitigation

Since increasing flare results in lower exposure latitude, it is desirable to reduce the flare level by increasing the chrome density locally around a feature. There are many ways of doing this, such as the addition of large chrome features called dummification (also referred to as tiling) or small subresolution features. If the chrome density of the entire mask is low, it may be beneficial to reverse the entire tone of the mask and use negative-tone resists. We refer to these methods of flare reduction as flare mitigation.

11.5.3.4.1 Dummification The effectiveness of dummification for flare mitigation was verified by creating an array of dummy features around a test pattern and comparing the result against a control pattern that did not have any dummy features.⁹⁰ The test pattern was a 90-deg elbow pattern consisting of 75-nm lines at a 150-nm pitch that was placed at the center of a 400- μ m window (20% flare) inside a 1 $\times$ 1 mm chrome region. The dummy features consisted of 500-nm squares that were placed either 100 or 250 nm apart within the 400- μ m window (see Fig. 11.68). Since lower flare results in less intensity and hence dose, for the patterns that had dummification, the isolated-line CDs measured were much larger, thus demonstrating that dummification reduces flare. It is estimated that the dummy features that were 250 nm apart resulted in 8% flare, and those that were 100 nm apart resulted in 4% flare. While these results validate the utility of flare mitigation using dummification, design rules and layout constraints limit the application of dummies to real die, particularly for the isolated gates used in microprocessor designs. In order to work around this issue, it is possible to divide the chrome dummy features into

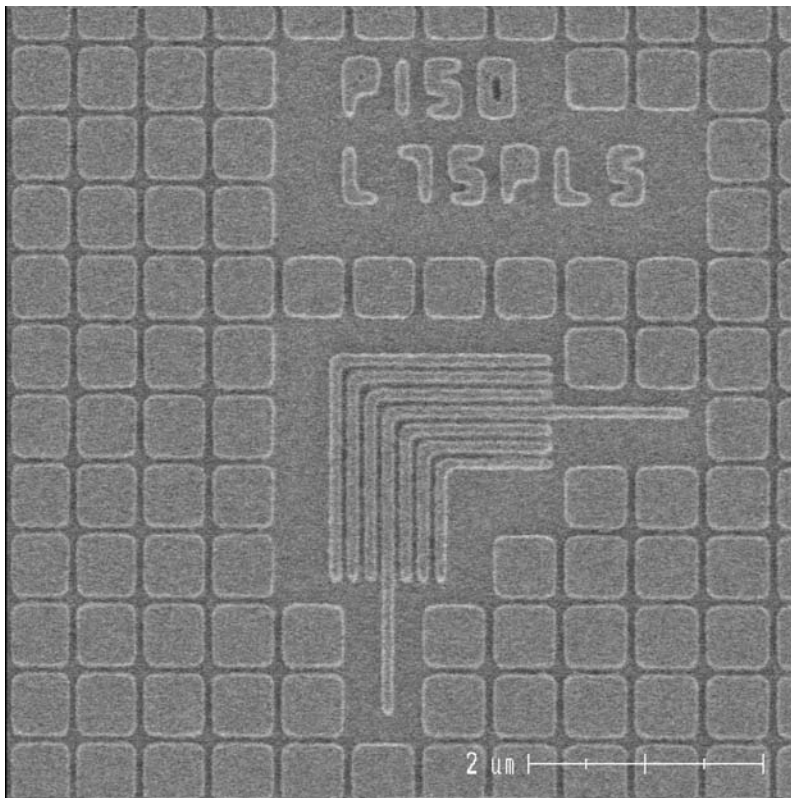


Figure 11.68 Sample dummification of an elbow pattern. The isolated vertical line was measured.

several subresolution assist features (constrained by mask-making capabilities) that could result in similar, albeit less effective, flare mitigation.

11.5.3.4.2 Negative tone For mask patterns that have less than 50% dark area density, such as the gate layer for logic devices, it would be advantageous for flare mitigation to reverse the tone of the mask and then pattern it with a negative-tone resist.⁹⁰ The benefit of this approach is its simplicity, since no additional dummification patterns need to be created on the mask. To demonstrate this approach, two identical patterns, a positive-tone (mostly open field, estimated 17% flare) and a negative-tone version (estimated 2% flare), were printed using positive and negative resists, respectively, on the ETS. The negative-tone resist had very good resolution and smoother line edges (3σ LWR for the negative-tone feature was 7 nm, whereas for the positive tone feature it was 13 nm). The reduced LWR can be attributed to the better aerial image quality due to lower flare. The negative-tone pattern had roughly a $9\times$ lower flare level, and hence the contrast and normalized ILS (NILS) were 87% and 3.2, respectively, whereas the positive-tone pattern had a contrast of 48% and a NILS of 1.57. This result shows the benefits of lower flare on resist patterning.

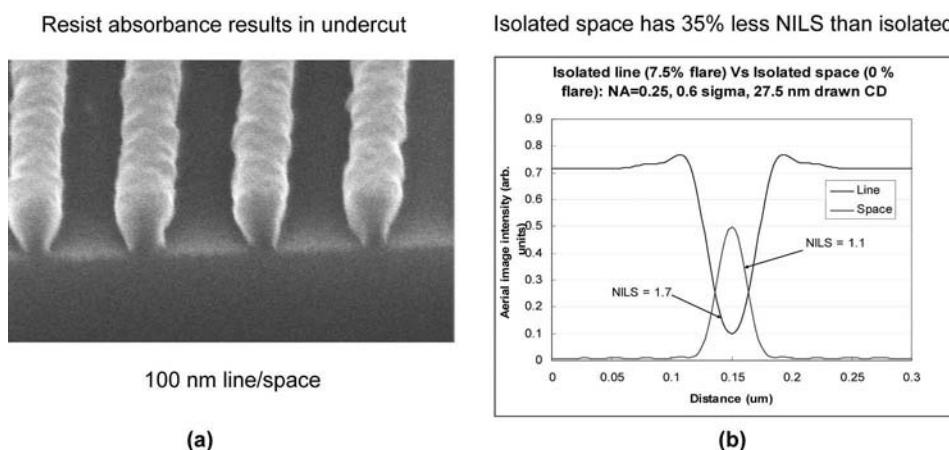


Figure 11.69 Issues with negative-tone patterning. (a) Photoresist absorbance results in undercut. (b) Aerial image of isolated spaces is worse than isolated lines targeted for the 22-nm node.

It has also been observed, however, that negative-tone resists at EUV wavelengths have undercut resist profiles, making them susceptible to topple [see Fig. 11.69(a)]. The undercut occurs due to the fairly large absorption of resists at EUV wavelengths, which results in less light reaching the bottom of the resist.

Another issue with negative-tone resists is that they are required to pattern an isolated space. For the same feature dimensions and exposure conditions, isolated spaces have worse aerial images than isolated lines (even with some flare) at low k_1 factors. In Fig. 11.69(b), simulation results using $NA = 0.25$, $\sigma = 0.6$, and a 27.5-nm drawn CD show that the aerial image metric NILS for an isolated space was 1.1, whereas for an isolated line with 7.5% flare it was 1.7 (35% better). Hence, for negative-tone resists, improvement of the aerial image quality of isolated spaces would be required using resolution enhancement techniques such as off-axis illumination (OAI) and embedded phase shift masks (ePSM).

11.5.3.4.3 Flare dependent within die CD variation Since flare is scattered light that appears even under dark patterns, mask regions that have more dark areas have less flare and vice versa. Hence, the CD for identical features across the die can be different depending on the local flare intensity. This dark-area density-dependent flare variation results in within-die CD variation. For an exposure tool with 10% intrinsic flare, the expected flare range on a gate layer of a typical microprocessor die was estimated to be as much as 6%* (see Fig. 11.70).⁹⁰ Assuming a 1.5-nm/% flare CD sensitivity to flare, the expected within-die CD variation due to flare would be 9 nm. The total CD control budget, of which the allocation to flare variation is just a fraction, is approaching 1 nm. Hence, FVC would be required to meet the tight CD control budget due to flare.

11.5.3.4.4 CD sensitivity to flare A critical parameter that affects CD variation across the die is the CD sensitivity to flare. Aerial image models indicate that

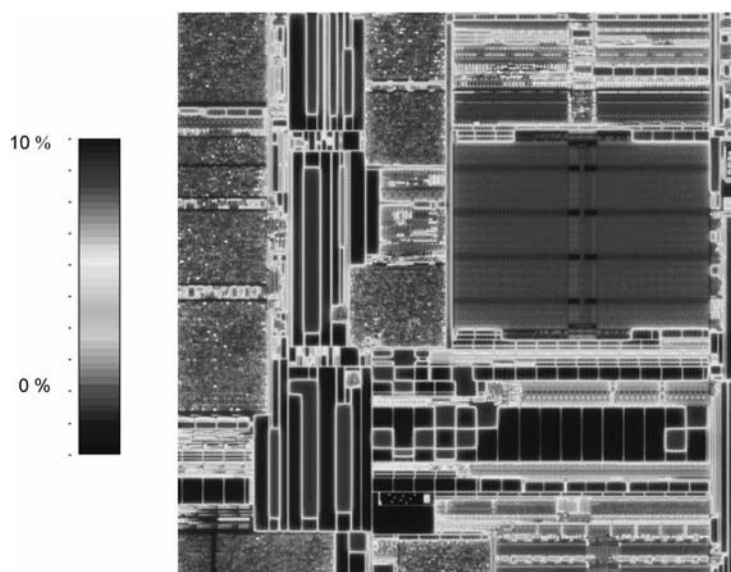


Figure 11.70 Flare variation calculated by the convolution of the gate layer of a typical microprocessor by a scaled version of PSF_{sc} of POB2 for the ETS.

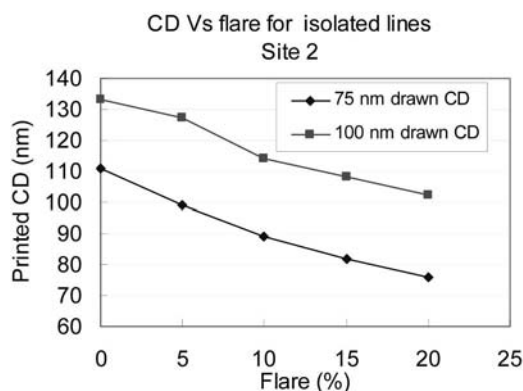


Figure 11.71 CD sensitivity to flare using an EUV-2D resist measured on the ETS.

flare results in a DC offset to the print threshold. However, resist processing could alter the expected response, so it is useful to directly measure the CD sensitivity to flare in resist.⁹⁰ A test pattern can be made such as the one described earlier for open areas (windows) of different sizes cut out within a large dark region. Structures are placed in the center of the windows and measured as a function of window size (flare). The CD decreases as window size (flare) increases in a similar fashion for both the 75- and 100-nm drawn CDs (see Fig. 11.71), and the slope of the curve at 15% flare is 1.5 nm/% flare. As mentioned earlier, the CD sensitivity to flare determines the amount of CD variation induced by density-dependent flare variation.

11.5.3.4.5 Flare versus proximity effects Proximity effects result in CD variation as a function of pitch. Figure 11.72 shows the proximity effect for 75- and 100-nm lines as a function of flare measured using the test pattern described earlier

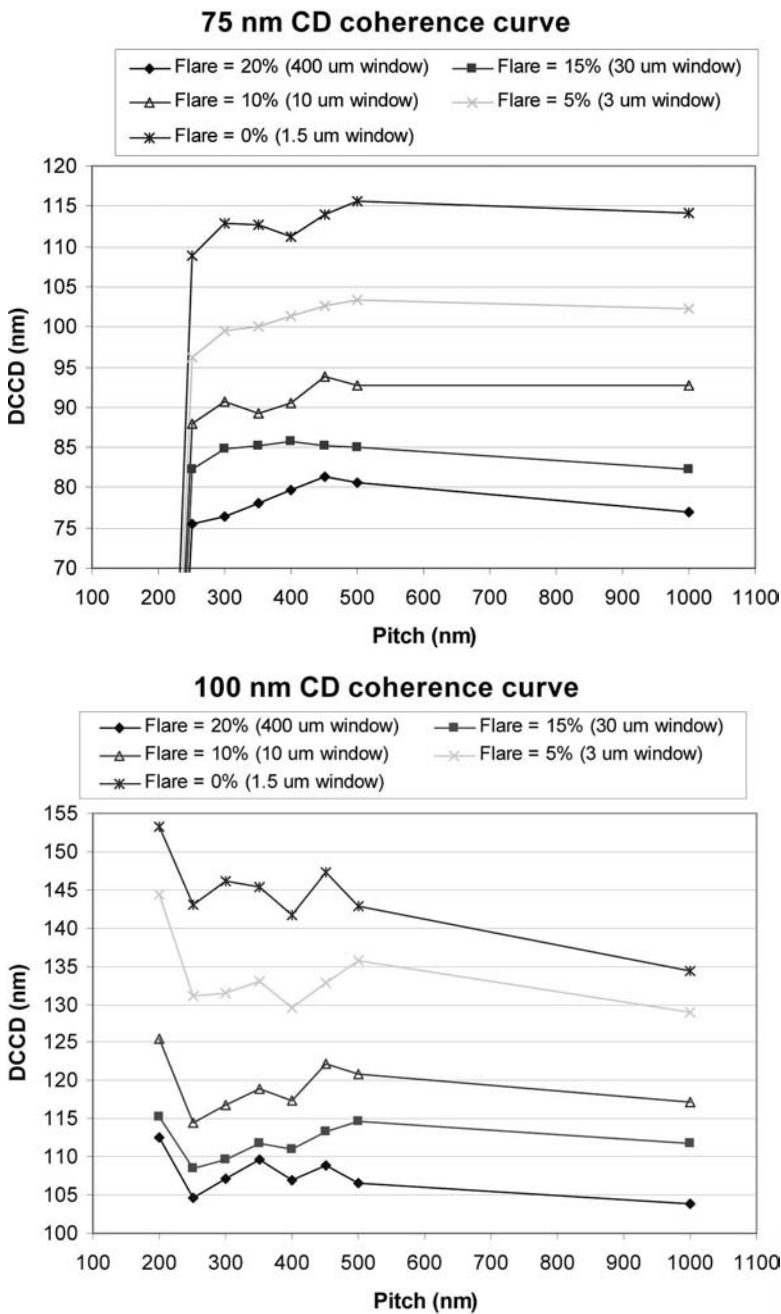


Figure 11.72 Proximity effects as a function of flare.

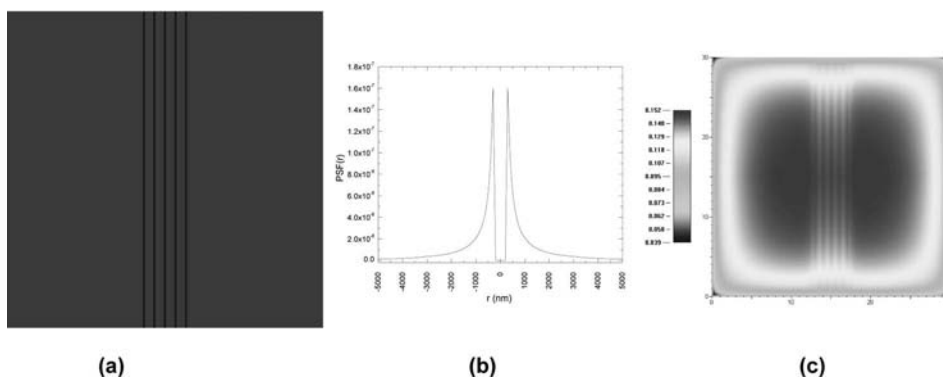


Figure 11.73 Calculated flare variation for a 100-nm line at a 1-μm pitch placed within a $30 \times 30 \mu\text{m}$ window inside a $1 \times 1 \text{ mm}$ chrome region. (a) Pattern. (b) PSF_{sc} for POB2, ETS. (c) Flare variation.

(lines placed within windows of various sizes in a dark region). As expected, increasing the flare results in smaller line CDs, and it appears that the proximity behavior is similar across the flare ranges in the experiment.⁹⁰ This result implies that to first order, optical proximity corrections (OPC) can be done independent of CD compensation due to flare using FVC.

11.5.3.4.6 Flare variation compensation To demonstrate the ability to correct for flare variation, a simple pattern was created consisting of 75-nm lines at a 1-μm pitch placed within a 100-μm window cut inside a $1 \times 1 \text{ mm}$ dark region and exposed on the ETS. The flare variation for this pattern was estimated by convolving the PSF_{sc} for POB2 with the mask pattern.⁸⁶ The parts of the pattern close to the edge of the dark region border have a larger dark-area density and hence have less flare. Since the dark-area density is less at the center of the window than the edge of the pattern, the flare is peaked toward the center of the pattern. The flare variation is similar to that shown in Fig. 11.73, except that for this experiment, the lines were drawn all across the window and not just in the center as in Fig. 11.73.

The CD variation for 75-nm lines is about 13 nm measured at locations 1 to 11 μm from the edge of the window (see Fig. 11.74). Most of the CD variation occurs within the initial 3 μm, and the CD does not appear to vary much beyond 7 μm from the edge, which indicates that the biggest component of the flare variation is from short-range flare.⁹⁰ The modeled CD variation is estimated at about 10 nm and is obtained from the CD sensitivity to flare (1.7 nm/% dose for the resist used in this experiment) and the calculated 6% flare change from 1 to 11 μm of the window's edge.

The algorithm to correct line sizes drawn on the mask to compensate for flare (FVC) is shown below:

$$\text{CD}_{\text{new}} = \text{CD}_{\text{drawn}} + \left. \frac{\partial \text{CD}}{\partial \text{Flare}} \right|_{\text{Flare}_{\text{local}}} \times (\text{Flare}_{\text{nominal}} - \text{Flare}_{\text{local}}) / \text{MEEF}. \quad (11.17)$$

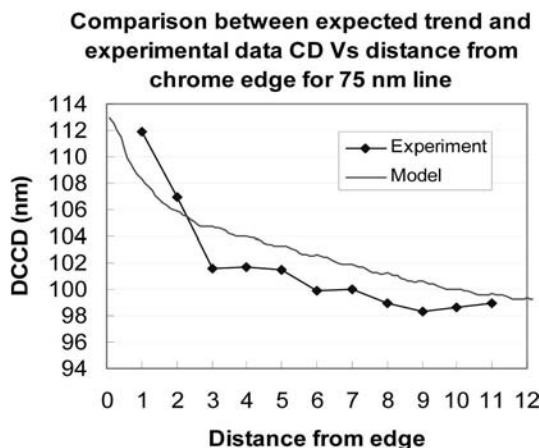


Figure 11.74 Measured and predicted CD variation as a function of distance (in μm) on the test pattern due to flare variation.

A nominal flare level is selected as the “reference,” and drawn CDs at the nominal flare level are unchanged. Local deviations in flare level from the nominal will result in CD changes to the local drawn CD depending on the CD sensitivity to flare and the mask error enhancement factor (MEEF).

11.5.3.4.7 FVC methodology As has been described earlier, an automated FVC tool⁹² is required that can perform the CD correction, either empirically as shown above, or model based where the corrected CD is predicted per an aerial image model. A more likely implementation may be the combination of a model with adjustable parameters fitted empirically to a large experimental data set as in state-of-the-art OPC tools. In any case, knowledge is required of the flare variation and hence the PSF_{sc} or PSF_{F} (PSF due to flare).⁷³ The PSF_{F} must be similar from stepper to stepper (from a given supplier) to avoid the need for a stepper-dependent mask, which would be impractical.

The impact of flare on the aerial image can generally be calculated through the convolution of the aerial image in the absence of flare (I_{σ}) with the PSF_{F} and the Strehl ratio (S) times the delta function (δ) (Ref. 93):

$$I_F(x, y) = I_{\sigma}(x, y) \otimes [S\delta(x, y) + \text{PSF}_{\text{F}}(x, y)]. \quad (11.18)$$

The difficulty in applying Eq. (11.18) to large areas ($1 \times 1 \text{ mm}^2$) stems from the spatial grid requirements imposed by the aerial image. To capture 20-nm feature sizes throughout the exposure field typically demands a grid of 1-nm step increments. As a result, a $1 \times 1 \text{ mm}^2$ area would require 8 TB of computer memory to store the resultant aerial image. Given the huge memory requirements dictated by Eq. (11.18) for the convolution approach, the implementation over large areas cannot be realized by today’s computers in any simple manner. An alternate, although less accurate, approach can be formulated through the widely known and implemented pedestal model for flare.⁹³ Here, the aerial image is calculated through

two separate equations decoupling the PSF from the aerial image. First, the local flare level [$F(x, y)$] is computed by convolving PSF_F with the mask transmission (T_{mask}) over the $1 \times 1 \text{ mm}^2$ area of interest:

$$F(x, y) = T_{\text{mask}}(x, y) \otimes \text{PSF}_F(x, y). \quad (11.19)$$

The local flare value is then introduced as a pedestal or DC offset into the aerial image equation, where the $+F(x, y)$ factor represents the DC offset, and the $[1 - F(x, y)]$ factor represents the rescaling of the aerial image in order to be consistent with energy conservation:

$$I_F(x, y) = I_\sigma(x, y)[1 - F(x, y)] + F(x, y). \quad (11.20)$$

As flare in Eq. (11.19) generally varies spatially on the order of the smallest feature size on the mask ($1\times$), the grid can then be laid out as large as 20 nm, reducing the overall memory storage requirements relative to Eq. (11.18) by a factor of 400. The difficulty of using PSF_F over large areas stems from the exponential-like behavior of the response (Fig. 11.73). One way to substantially reduce the overall memory requirements is to introduce a nonuniform adaptive grid for PSF_F . Near the origin, the range of the function varies quickly, requiring a very fine grid to keep integration errors to tolerable levels. A hundred microns away from the origin, the function varies only slowly, so a relatively coarse grid suffices.

The implementation of flare correction through mask CD resizing can be most readily implemented through the following process flow (see Fig. 11.75). Over

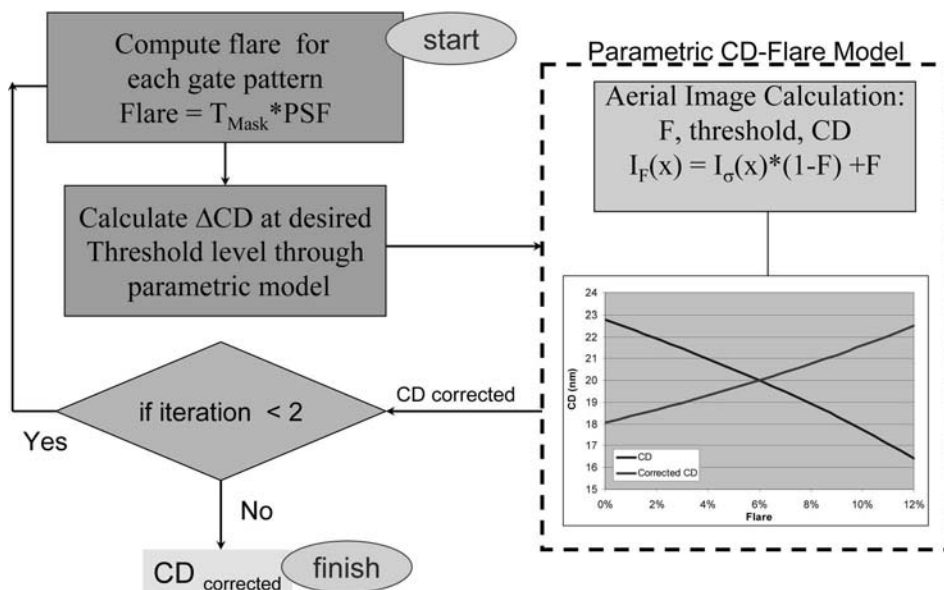


Figure 11.75 Flare Variation Compensation (FVC) methodology.

a given mask area, the flare is first computed through Eq. (11.19). The edge effects also need to be captured for regions by using appropriate patterns on the outside of the mask pattern. The CD sizing to compensate for flare can be done in different ways. One way is to calculate the local aerial image intensity IF using Eq. (11.20), then determine the ΔCD at the threshold intensity and appropriately resize the feature. Another way is to use Eq. (11.18), whereby the difference between the local flare and the flare at a reference location is used to determine the appropriate biasing of the feature, taking into account the experimentally determined CD sensitivity to flare and MEEF. Since CD correction consists of adding and subtracting dark regions to the mask, the actual flare level as a result of CD resizing becomes perturbed. As such, a second iteration may be needed to capture this higher-order effect.

11.6 Summary

Because EUVL is essentially an extension of the projection lithography methods now well known in the industry, the majority of the tools and methods developed in the extension of longer-wavelength lithography can be applied directly to the EUV case. Such tools include, for example, modified illumination and phase-shift masks, ensuring that EUV will be a multigeneration solution. As shown in this chapter, the multigeneration capabilities are further strengthened by the fact that initial deployment of EUV (mostly likely for the 32-nm node) will require a NA of only 0.25. Since feasible designs up to 0.5 NA have been demonstrated, EUV can achieve the 16-nm node with a relatively large k_1 factor (0.6). From that point on, the advanced optical methods mentioned above can be applied to reduce the k_1 factor and further extend the resolution, ultimately down to 6.75 nm.

Despite EUVL's promising potential, resist limits are currently preventing the community from determining the ultimate limits of current optics fabrication methods. Significant questions still remain in terms of the achievable figure quality for EUV optics installed in the field. Achieving true lithographic-quality imaging from EUV optics requires wavefront tolerances in the sub-nm range, which is certainly a daunting task if actinic wavefront metrology is not used. To verify the feasibility of the nonactinic methods currently used to align commercial EUV optics lithographic aberration measurement, methods are required that are capable of high accuracy in the EUV regime. Such capabilities are currently limited by the unavailability of ultra-high-resolution EUV resists. Ultimately, one would like to use a resist with resolution capabilities well surpassing the capabilities of the optics themselves. At this point in time, EUV resists are limited to a resolution of approximately 32 nm. We also note that the wavefront specifications may need to be even tighter than one might expect based on the fact that EUV may be saddled with larger levels of flare than the industry would like.

The statements above lead to the conclusion that we must be careful to not become complacent with respect to the state of EUV optics simply because we cannot presently observe actual optics limitations to compare to predicted limitations.

Acknowledgments

The majority of the work presented here is based on microfield exposure stations implemented at LBNL's Advanced Light Source synchrotron facility. These systems were designed and implemented by the Center for X-Ray Optics (CXRO) led by David Attwood. The mechanical engineering efforts were led by Phil Batson and Senajith Rekawa, whose team included Kevin Bradley, Rene Delano, Drew Kemp, Ron Oort, and Farhad Salmassi. The electrical engineering efforts were led by Paul Denham, whose team included Brian Hoef and David Richardson. The computer engineering effort was led by Ron Tackaberry, whose team included Jeff Gamsby, Bob Gunion, and Hanjing Huang. The authors further acknowledge the invaluable scientific support provided by the CXRO team, including Erik Anderson, Kenneth Goldberg, Eric Gullikson, Deirdre Olynick, and Alex Liddle.

The defect-printability results presented here also relied heavily on ML coating and defect characterization efforts provided by Lawrence Livermore National Laboratory. In particular, we acknowledge Sherry Baker, Paul Mirkarimi, and Eberhard Spiller. Support with resist issues was also provided by Robert Brainard and Thomas Koehler, both formerly of Rohm and Haas. Additional resist support was provided by Carl Larson and Greg Wallraff of IBM's Almaden Research Center.

We would also like to acknowledge Christof Krautschik, Jeanette Roberts, Terence Bacuita, Robert L. Bristol, Heidi Cao, Sang H. Lee, Michael Leeson, Ted Liang, Eric Panning, Bryan J. Rice, Melissa Shell, Wang Yueh, Guojing Zhang, and IMO of Intel Corporation.

Finally, the authors would like to acknowledge their funding sources, without which none of this work would have been possible. In particular the ETS-based work and early MET efforts were funded by the EUV LLC. The later MET efforts were funded by SEMATECH.

References

1. R. Hudyma, 2006 SEMATECH Litho Forum, Vancouver, Canada, May 22–24, 2006. Proceedings available from SEMATECH, Austin, Texas.
2. D. Tichenor, G. Kubiak, W. Replogle, et al., "EUV Engineering Test Stand," *Proc. SPIE* **3997**, 48–69 (2000).
3. P. Naulleau, K. Goldberg, E. Anderson, et al., "Adding static printing capabilities to the EUV phase-shifting point diffraction interferometer," *Proc. SPIE* **4343**, 639–645 (2001).
4. P. Naulleau, K. Goldberg, E. Anderson, et al., "Static microfield printing at the Advanced Light Source with the ETS Set-2 optic," *Proc. SPIE* **4688**, 64–71 (2002).
5. P. Naulleau, K. Goldberg, E. Anderson, et al., "Sub-70 nm EUV lithography at the Advanced Light Source static microfield exposure station using the ETS Set-2 optic," *J. Vac. Sci. & Technol.* **B 20**, 2829–2833 (2002).

6. P. Naulleau, K. Goldberg, E. Anderson, et al., "Static EUV microexposures using the ETS Set-2 optics," *Proc. SPIE* **5037**, 36–46 (2003).
7. S. Lee, D. Tichenor, W. Ballard, et al., "Lithographic evaluation of the EUV Engineering Test Stand," *Proc. SPIE* **4688**, 266–276 (2002).
8. D. O'Connell, S. Lee, D. Tichenor, et al., "Lithographic characterization of improved projection optics in the EUVL Engineering Test Stand," *Proc. SPIE* **5037**, 83–94 (2003).
9. H. Chapman, A. Ray-Chaudhuri, D. Tichenor, et al., "First lithographic results from the EUV Engineering Test Stand," *J. Vac. Sci. & Technol.* **B 19**, 2389–2395 (2001).
10. S. Lee, D. Tichenor, P. Naulleau, and D. O'Connell, "Lithographic aerial image contrast measurement in the EUV Engineering Test Stand," *J. Vac. Sci. & Technol.* **B 20**, 2849–2852 (2002).
11. C. Ahn, H. Kim, and K. Baik, "A novel approximate model for resist process," *Proc. SPIE* **3334**, 752–763 (1998).
12. J. Hong, H. Kim, H. Yune, C. Ahn, Y. Koo, and K. Baik, "Accuracy of diffused aerial image model for full-chip-level optical proximity correction," *Proc. SPIE* **4000**, 1024–1032 (2000).
13. F. Houle, W. Hinsberg, M. Sanchez, and J. Hoffnagle, "Influence of resist components on image blur in a patterned positive-tone chemically amplified photoresist," *J. Vac. Sci. & Technol.* **B 20**, 924–931 (2002).
14. J. A. Hoffnagle, W. D. Hinsberg, M. I. Sanchez, and F. A. Houle, "Method of measuring the spatial resolution of a photoresist," *Opt. Lett.* **27**, 1776–1778 (2002).
15. P. Naulleau, "Verification of point-spread function based modeling of an EUV photoresist," *Appl. Opt.* **43**, 788–792 (2004).
16. P. Dirksen, C. Juffermans, R. Pellens, M. Maenhoudt, and P. Debisschop, "Novel aberration monitor for optical lithography," *Proc. SPIE* **3679**, 77–86 (1999).
17. H. Fukuda, K. Hayano, and S. Shirai, "Determination of high-order lens aberration using phase/amplitude linear algebra," *J. Vac. Sci. & Technol.* **B 17**, 3318–3321 (1999).
18. G. Robins, K. Adam, and A. Neureuther, "Measuring optical image aberrations with pattern and probe based targets," *J. Vac. Sci. & Technol.* **B 20**, 338–343 (2002).
19. E. Spiller, "Evaporated multilayer dispersion elements for soft x-rays," *AIP Conf. Proc.* **75**, 124–130 (1981).
20. W. Jark, "Enhancement of diffraction grating efficiencies in the soft x-ray region by a multilayer coating," *Opt. Comm.* **60**, 201–205 (1986).
21. J. C. Rife, W. R. Hunter, T. W. Barbee, Jr., and R. G. Cruddace, "Multilayer-coated blazed grating performance in the soft x-ray region," *Appl. Opt.* **28**, 2984–2986 (1989).
22. R. A. M. Keski-Kuha, R. J. Thomas, J. S. Gum, and C. E. Condor, "Performance of multilayer coated diffraction gratings in the EUV," *Appl. Opt.* **31**, 4529–4531 (1990).

23. J. F. Seely, M. P. Kowalski, W. R. Hunter, et al., "On-blaze operation of a Mo/Si multilayer-coated concave diffraction grating in the 136–142-Å wavelength region and near normal incidence," *Appl. Opt.* **32**, 4890–4897 (1993).
24. P. Naulleau, J. Liddle, E. Anderson, et al., "Fabrication of high-efficiency multilayer-coated gratings for the EUV regime using e-beam patterned substrates," *Opt. Comm.* **229**, 109–116 (2003).
25. B. La Fontaine, A. Pawloski, O. Wood, et al., "Demonstration of phase-shift masks for extreme-ultraviolet lithography," *Proc. SPIE* **6151**, 61510A (2006).
26. P. Mirkarimi, E. Spiller, D. Stearns, V. Sperry, and S. Baker, "An ion-assisted Mo-Si deposition process for planarizing reticle substrates for extreme ultraviolet lithography," *IEEE J. Quantum Electron.* **37**, 1514–1516 (2001).
27. P. Naulleau, K. Goldberg, E. Anderson, et al., "Lithographic characterization of the printability of programmed EUV substrate defects," *J. Vac. Sci. & Technol.* **B 21**, 1286–1290 (2003).
28. F. van Delft, J. Weterings, A. van Langen-Suurling, and H. Romijn, "Hydrogen silsesquioxane/novolac bilayer resist for high aspect ratio nanoscale electron-beam lithography," *J. Vac. Sci. Technol.* **B 18**, 3419–3423 (2000).
29. E. H. Anderson, D. L. Olynick, B. Harteneck, et al., "Nanofabrication and diffractive optics for high-resolution x-ray applications," *J. Vac. Sci. Technol.* **B 18**, 2970–2975 (2000).
30. J. Goldsmith, K. Berger, D. Bozman, et al., "Sub-100 nm lithographic imaging with an EUV 10' microstepper," *Proc. SPIE* **3676**, 264–271 (1999).
31. K. Hamamoto, T. Watanabe, H. Tsubakino, H. Kinoshita, T. Shoki, and M. Hosoya, "Fine pattern replication by EUV lithography," *J. Photopolymer Sci. & Tech.* **14**, 567–572 (2001).
32. P. Naulleau, K. Goldberg, E. Anderson, et al., "Status of EUV micro-exposure capabilities at the ALS using the 0.3-NA MET optic," *Proc. SPIE* **5374**, 881–891 (2004).
33. P. Naulleau, K. Goldberg, J. Cain, et al., "EUV microexposures at the ALS using the 0.3-NA MET optic," *J. Vac. Sci. & Technol.* **B 22**, 2962–2965 (2004).
34. Brunton, J. S. Cashmore, P. Elbourn, et al., "High-resolution EUV imaging tools for resist exposure and aerial image monitoring," *Proc. SPIE* **5751**, 78–89 (2005).
35. H. Oizumi, Y. Tanaka, I. Nishiyama, H. Kondo, and K. Murakami, "Lithographic performance of high-numerical-aperture (NA = 0.3) EUV small-field exposure tool (HINA)," *Proc. SPIE* **5751**, 102–109 (2005).
36. Wavefront data provided by Erik Sohmen, Carl Zeiss SMT AG, Oberkochen, Germany. Private communication.
37. J. Kirk, "Scattered light in photolithographic lenses," *Proc. SPIE* **2197**, 566–572 (1994).
38. P. Naulleau, P. Denham, B. Hoef, and S. Rekawa, "A design study for synchrotron-based high-numerical-aperture scanning illuminators," *Opt. Comm.* **234**, 53–62 (2004).

39. B. Bollepalli, M. Khan, and F. Cerrina, "Imaging properties of the extreme ultraviolet mask," *J. Vac. Sci. & Technol.* **B 16**, 3444–3448 (1998).
40. K. Goldberg, P. Naulleau, P. Denham, et al., "At-wavelength alignment and testing of the 0.3 NA MET optic," *J. Vac. Sci. & Technol.* **B 22**, 2956–2961 (2004).
41. P. Naulleau, J. Cain, and K. Goldberg, "Lithographic characterization of the field dependent astigmatism and alignment stability of a 0.3 numerical aperture EUV microfield optic," *J. Vac. Sci. & Technol.* **B 24**, 1234 (2006).
42. P. Naulleau, J. Cain, and K. Goldberg, "Lithographic characterization of the spherical error in an EUV optic using a programmable pupil fill illuminator," *Appl. Opt.* **45**(9), 1957–1963 (2006).
43. Prolith is a registered trademark of KLA-Tencor Corporation, San Jose, California.
44. Resist provided by G. Wallraff and C. Larson, IBM Almaden Research Center, San Jose, California.
45. P. Naulleau and G. Gallatin, "The line-edge roughness transfer function and its application to determining mask effects in EUV resist characterization," *Appl. Opt.* **42**, 3390–3397 (2003).
46. P. Naulleau, "The relevance of mask-roughness-induced printed line-edge roughness in recent and future EUV lithography tests," *Appl. Opt.* **43**, 4025–4032 (2004).
47. P. Naulleau, "The effect of mask-roughness on printed contact size variation in EUV lithography," *Appl. Opt.* **44**, 183–189 (2004).
48. D. Tichenor, W. Replogle, S. Lee, et al., "Performance upgrades in the EUV Engineering Test Stand," to be published, *J. Vac. Sci. & Technol. B* (2002).
49. D. W. Sweeney, R. Hudyma, H. N. Chapman, and D. Shafer, "EUV optical design for a 100 nm CD imaging system," *Proc. SPIE* **3331**, 2–10 (1998).
50. K. Goldberg, P. Naulleau, J. Bokor, and H. Chapman, "Testing EUV optics with visible-light and EUV interferometry," *J. Vac. Sci. & Technol.* **B 20**, 2834–2839 (2002).
51. N. Beaudry and T. Milster, "Effects of object roughness on partially coherent image formation," *Opt. Lett.* **25**, 454–456 (2000).
52. N. Beaudry and T. Milster, "Effects of mask roughness and condenser scattering in EUVL systems," *Proc. SPIE* **3676**, 653–662 (1999).
53. J. W. Goodman, *Statistical Optics*, Chap. 7, pp. 286–360, John Wiley and Sons, New York (1985).
54. Solid-C is a registered trademark of SIGMA-C GmbH, Thomas-Dehler-Str. 9, 81737 München, Germany.
55. J. H. Underwood and T. W. Barbee, Jr., "Layered synthetic microstructures as Bragg diffractors for X rays and extreme ultraviolet: theory and predicted performance," *Appl. Opt.* **20**, 3027–3034 (1981).
56. D. Stearns, "Stochastic model for thin film growth and erosion," *Appl. Phys. Lett.* **62**, 1745–1747 (1993).

57. D. Stearns and E. Gullikson, "Nonspecular scattering from extreme ultraviolet multilayer coatings," *Physica* **B 283**, 84–91 (2000).
58. Z. Zhengrong, K. Lucas, J. Cobb, S. Hector, and A. Strojwas, "Rigorous EUV mask simulator using 2D and 3D waveguide methods," *Proc. SPIE* **5037**, 494–503 (2003).
59. Erdmann, C. Kalus, T. Schmoller, and A. Wolter, "Efficient simulation of light diffraction from three-dimensional EUV masks using field decomposition techniques," *Proc. SPIE* **5037**, 482–493 (2003).
60. T. Pistor, T. Y. Deng, and A. Neureuther, "Extreme ultraviolet mask defect simulation: Low-profile defects," *J. Vac. Sci. & Technol.* **B 18**, 2926–2929 (2000).
61. E. Gullikson, C. Cerjan, D. Stearns, P. Mirkarimi, and D. Sweeney, "Practical approach for modeling extreme ultraviolet lithography mask defects," *J. Vac. Sci. Technol.* **B 20**, 81–86 (2002).
62. P. Naulleau, "The relevance of mask-roughness-induced printed line-edge roughness in recent and future EUV lithography tests," *Appl. Opt.* **43**, 4025–4032 (2004).
63. S. Hector, "EUVL masks: requirements and potential solutions," *Proc. SPIE* **4688**, 134–149 (2002).
64. P. Mirkarimi, E. Spiller, D. Stearns, V. Sperry, and S. Baker, "An ion-assisted Mo-Si deposition process for planarizing reticle substrates for extreme ultraviolet lithography," *IEEE J. Quantum Electron.* **37**, 1514–1516 (2001).
65. T. Ogawa, M. Ito, H. Yamanashi, H. Hoko, E. Hoshino, and S. Okazaki, "Simulation studies of roughness-smoothing effect of molybdenum/silicon multilayer coating based on resputtering model," *Proc. SPIE* **4688**, 716–724 (2002).
66. International Technology Roadmap for Semiconductors, 2001 edition, <http://public.itrs.net/>.
67. P. Naulleau, "The effect of mask-roughness on printed contact size variation in EUV lithography," *Appl. Opt.* **44**, 183–189 (2004).
68. J. M. Bennett and L. Mattson, Introduction to Surface Roughness and Scattering, Optical Society of America, Washington, D.C. (1989).
69. E. L. Church and P. Z. Takacs, "Specification of the surface figure and finish in terms of system performance," *Appl. Opt.* **32**, 3344 (1993).
70. D. G. Stearns, D. P. Gaines, D. W. Sweeney, and E. M. Gullikson, "Nonspecular x-ray scattering in a multilayer-coated imaging system," *J. Appl. Phys.* **84**, 1003–1028 (1998).
71. E. M. Gillikson, S. Baker, J. E. Bjorkholm, et al., "EUV scattering and flare of 10× projection cameras," *Proc. SPIE* **3676**, 717–723 (1999).
72. M. Born and E. Wolf, Principles of Optics, p. 395, The Macmillan Co., New York (1964).
73. M. Chandhok, S. H. Lee, C. G. Krautschik, et al., "Comparison of techniques to measure the point spread function due to scatter and flare in EUV lithography systems," *Proc. SPIE* **5374**, 854–860 (2004).
74. C. A. Mack, "Measuring and modeling flare in optical lithography," *Proc. SPIE* **5040**, 151–161 (2003).

75. M. Chandhok, S. H. Lee, J. Roberts, B. J. Rice, and H. B. Cao, "Lithographic flare measurements of Intel's microexposure tool optics," *J. Vac. Sci. Technol. B* **24**(1) 274–278 (Jan./Feb. 2006).
76. J. M. Roberts, T. Bacuita, R. L. Bristol, et al., "One small step: world's first integrated EUVL process line," *Proc. SPIE* **5751**, 64–77 (2005).
77. M. Chandhok, E. M. Panning, and M. Goldstein, "Lithographic flare measurements of Intel's microexposure tool optics," *J. Vac. Sci. Technol. B* **24**, 274 (2006).
78. R. L. Brainard, C. Henderson, J. Cobb, and V. Rao, "Comparison of the lithographic properties of positive resists upon exposure to deep- and extreme-ultraviolet radiation," *J. Vac. Sci. Technol. B* **17**, 3384 (1999).
79. S. H. Lee, M. Chandhok, J. Roberts, and B. J. Rice, "Characterization of flare on Intel's EUV MET," *Proc. SPIE* **5751**, 293–300 (2005).
80. E. M. Gullikson, "Scattering from normal-incidence EUV optics," *Proc. SPIE* **3331**, 72–80 (1998).
81. E. M. Gullikson, S. Baker, J. E. Bjorkholm, et al., "EUV scattering and flare of 10× projection," *Proc. SPIE* **3676**, 717–723 (1999).
82. S. H. Lee, P. Naulleau, C. Krautschik, et al., "Lithographic flare measurements of EUV full-field projection optics," *Proc. SPIE* **5037**, 103–111 (2003).
83. S. H. Lee, M. Chandhok, C. Krautschik, and M. Goldstein, "Anisotropic EUV flare measured in the engineering test stand (ETS)," *Proc. SPIE* **5374**, 818–823 (2004).
84. T. Linton, M. Chandhok, B. J. Rice, and G. Schrom, "Determination of the line edge roughness specification for 34 nm devices," *IEDM 2002 Digest International*, pp. 303–306 (2002).
85. F. M. Schellenberg, J. Word, and O. Touban, "Layout compensation for EUV flare," *Proc. SPIE* **5751**, 320–329 (2005).
86. M. Chandhok, S. H. Lee, and T. Bacuita, "Effects of flare in extreme ultraviolet lithography: learning from the Engineering Test Stand," *J. Vac. Sci. Technol. B* **22**(6), 2966–2969 (Nov./Dec. 2004).
87. M. Chandhok, H. Cao, B. J. Rice, R. Bristol, J. Roberts, and D. S. Fryer, *2nd International EUVL Symposium Digest of Abstracts*, Oct. 2003.
88. R. Adam, A. Acheta, I. Lalovic, et al., "Characterization of line-edge roughness in photoresist using an image fading technique," *Proc. SPIE* **5376**, 414 (2004).
89. W. Yueh, H. B. Cao, M. Chandhok, S. Lee, M. Shumway, and J. Bokor, "Patterning capabilities of EUV resists," *Proc. SPIE* **5376**, 434–442 (2004).
90. M. Chandhok, S. H. Lee, C. Krautschik, et al., "Comparison of techniques to measure the point spread function due to scatter and flare in EUV lithography systems," *Proc. SPIE* **5374**, 854–860 (2004).
91. C. G. Krautschik, M. Chandhok, G. Zhang, et al., "Implementing flare compensation for EUV masks through localized mask CD resizing," *Proc. SPIE* **5037**, 58–68 (2003).

92. D. G. Stearns, D. P. Gaines, D. W. Sweeny, and E. M. Gullikson, "Nonspecular x-ray scattering in a multi-layer-coated imaging system," *J. Appl. Phys.* **84**(5), 1003–1028 (July 15, 1998).
93. C. Krautschik, M. Ito, I. Nishiyama, and S. Okazaki, "Impact of EUV light scatter on CD control as a result of mask density changes," *Proc. SPIE* **4688**, 289–301 (2002).



Patrick Naulleau has been involved in EUV lithography since 1997 when he joined Lawrence Berkeley National Laboratory (LBNL) to work in the area of actinic interferometric alignment. Since 2001 he has lead LBNL's EUV Patterning project, starting with the 0.1-NA ETS optics and now the 0.3-NA MET optic. He is internationally recognized for leading EUV patterning studies and his contributions to EUV System designs.



John E. Bjorkholm was a Principal Scientist at Intel Corporation in Santa Clara, California, from 1996 through 2002; his work there was concerned with the development of EUV lithography. Previously, he worked at Bell Laboratories in Holmdel, New Jersey, for 28 years, retiring in 1994 as a Distinguished Member of the Technical Staff. During his Bell Labs tenure he carried out research in a number of areas, including lasers, nonlinear optics, and nonlinear spectroscopy; he was a co-author with Arthur Ashkin and Steven Chu on the first demonstrations of optical molasses and of the optical trapping of atoms; he was also instrumental in the development of the concept of EUV lithography. He received a BSE with highest honors in EE-Physics from Princeton University in 1961, and in 1966 he received a PhD in Applied Physics from Stanford University. John is a Fellow of the OSA and the APS. He served as an OSA Director-at-Large (1988–90) and as the OSA Treasurer (1992–96). He also served as a Trustee of Princeton University (1991–95).



Manish Chandhok received his PhD in EE at the University of Michigan in 1996. He joined the TCAD group at Intel Corporation (Hillsboro, OR) in 1997 as a lithography applications engineer. Dr. Chandhok was responsible for setting up of a photoresist characterization laboratory at Intel to measure parameters for resist models. In 2001, Dr. Chandhok started to work in the EUV lithography program of the Components Research group. He holds several patents and has published over 25 papers in the areas of line edge roughness, EUV patterning, optics contamination, overlay, and flare.

Chapter 12

Lithography Cost of Ownership

Phil Seidel

Contents

12.1	Cost of Ownership Overview	586
12.1.1	SEMATECH lithography CoO historical activities	587
12.1.2	General CoO equations and input relationships	588
12.1.2.1	CoO exposure cell term [Eq. (12.1a)]	589
12.1.2.2	Mask term [Eq. (12.1b)]	590
12.1.2.3	Other costs term [Eq. (12.1c)]	590
12.1.2.4	General high-level CoO impact analysis	591
12.1.3	Lithography global CoO input assumptions (SEMI E35, fab parameters, etc.)	592
12.1.3.1	Scheduled production available timing	593
12.1.3.2	Labor and overhead costs	593
12.1.3.3	Fab floor space rates	594
12.1.3.4	Capital equipment depreciation schedules and values	594
12.1.3.5	Equipment installation cost	595
12.1.4	Lithography-specific product parameters (fields and die per wafer, wafers per mask, etc.)	596
12.1.4.1	Number of exposure fields per wafer	596
12.1.4.2	Wafers per mask	597
12.2	Lithography: Historical Cost and Price Trends	599
12.2.1	Historical completed wafer, die, and function costs to manufacture	599
12.2.2	Historical photolithography exposure tool price trends	601
12.2.3	Historical reticle costs and mask usage trends	601
12.3	Major Lithography CoO Parameter and Productivity Drivers	604
12.3.1	Example of 100-nm lithography patterning Metal 1 level CoO within 90-nm half-pitch logic device manufacturing	604
12.3.2	Exposure tool cell throughput (TPT)	606
12.3.2.1	Stage speeds and accelerations with photoresist speeds as wafer throughput influences	610
12.3.2.2	Exposure tool wafer throughput impacts with laser source power and wafer overhead times	610
12.3.3	Exposure level product requirements (yield, send-aheads, and rework)	611

12.3.4	DUV source consumables and running costs	612
12.3.5	Photoresist cost drivers and photoresist process complexity	615
12.3.6	Reticle cost drivers	617
12.3.7	Lithography cell equipment reliability, availability, and maintainability (RAM)	619
12.4	General Observations on Lithography Cell and CoO Improvements (Past Decade)	622
12.4.1	Exposure tool supplier CoO improvement factors	622
12.4.2	Optical laser source improvements	625
12.4.3	Photoresist and photoresist processing	625
12.4.4	Reticle improvements	626
12.4.5	Fab automation processing and yield controls	627
12.5	CoO Considerations for Future Lithography Technologies	629
12.5.1	193-nm immersion lithography (193i)	629
12.5.2	Extreme ultraviolet lithography (EUVL)	629
12.5.3	Maskless lithography (ML2)	631
12.5.4	Nanoimprint lithography (NIL)	631
12.6	Summary	635
12.7	Appendix: Example Case Studies of Lithography CoO Calculations	635
12.7.1	Example case 1: improved yield at expense of system cost and/or TPT performance	636
12.7.2	Example case 2: slightly improved laser source power at expense of specialty gas costs	636
12.7.3	Example case 3: product lots reroute to different tool vs lot hold	637
	Acknowledgments	638
	References	639

12.1 Cost of Ownership Overview

For almost all manufacturing processes, understanding the cost to manufacture a product compared to the product price that the market will support is pivotal. This holds true for integrated circuit (IC) manufacturing. The ability for IC manufacturers to fabricate high-quality, functioning devices at the lowest possible affordable costs is a major contributor in maintaining IC productivity. This manufacturing cost, plus the profit margin is used to determine the product selling price for customer procurement. If manufacturing costs are not competitive, IC manufacturers may not sell enough products to generate the revenue and profit they need to support their operations. If all IC manufacturing costs are too high, regardless of which manufacturer's processes are used, then this cost will impact the overall growth of IC products in commercial applications and reduce overall IC productivity gains. Therefore, it is essential to understand the cost to manufacture high-quality, functioning IC devices compared to all of the process operating costs. This operating cost is generally referred to as cost of ownership (CoO).

A productivity gain in the IC industry is defined as cost reduction per IC function, which averages from 25 to 29% annually.¹ Half of this average can be attributed to lithography's historic continuous improvements of shrinking feature

sizes.² Yet the evolution of lithography exposure tools and processes continues to be more expensive than previous generations. Lithography costs are 30 to 40% of the entire completed IC device or chip cost.³ Therefore, lithography CoO is always an important metric, not only for current IC manufacturing, but also to calculate the expected operating costs for new lithography technologies in development and to assess cost effectiveness.

There are many CoO definitions, but SEMATECH has adopted the following:

- *Cost of ownership*: The overall cost of a manufacturing system to an organization, including the costs associated with operating and maintaining the system, and the lifetime of operational use of the system.

CoO is also associated with a particular cost metric where the operating cost of the equipment and processes or the cost associated with a particular process step are used. These are some examples of such metrics for lithography cells that include the exposure tool, source, photoresist process, and masks of CoO:

- *Litho cell annual cost (\$/year)*: The total annual amount a facility spends to operate the lithography cell in full manufacturing in dollars per year.
- *Cost per chip (or field) level exposed (\$/GCLE)*: The cost for each “good” IC chip or field exposed from the litho cell in dollars per good chip level exposed.
- *Cost per wafer level exposed (\$/PWLE or \$/GWLE)*: The cost for each “good” wafer level exposure processed from the litho cell in dollars per good wafer level exposed. The term “good wafer” refers to yielded wafers.

In this chapter the metric *cost per good wafer level exposed (\$/GWLE)* will be used extensively because it can be compared to other IC process costs to establish the total completed wafer costs.

12.1.1 SEMATECH lithography CoO historical activities

The SEMATECH CoO model originated in the lithography tool development programs during the late 1980s and was used as an additional tool performance metric during joint development programs with major tool manufacturers. It was used to assess whether system improvements or newer developed tool models would operate cost effectively in the IC fab, given that tool procurement prices could be higher at the expense of improved tool throughput, product yield, or other performances. This model was a simple spreadsheet software that was offered to SEMATECH member companies who funded SEMATECH programs as well as to IC tool manufacturers that were engaged with SEMATECH.

The CoO model became widely adopted by many organizations. It was decided during the early 1990s that the software code should be commercially licensed to Wright Williams & Kelly (W.W.K.) so that it could be adequately supported as a commercial product.⁴ W.W.K., which is one of several commercial companies that offer such software, has continuously improved the original licensed software user

interface and operations of the models, and today it offers many commercial CoO packages. The industry's continued increased use of CoO prompted the need for an accepted standard of calculation methods as well as specific input values for some of the variables. This CoO standard was published through an industry coordination organization called Semiconductor Equipment and Materials Institute (SEMI) under the standard E35.⁵ The E35 standard defines common terms and definitions with broad theoretical cost equations that can be applied to any semiconductor process tool. The E35 standard enabled the industry to use and follow standard methodology with accepted general cost input assumptions to reduce variations in CoO calculations.

SEMATECH uses lithography CoO calculations within a Microsoft Excel program model that is more detailed and specific to lithography processing than the SEMI E35. SEMATECH used its internal CoO model to assess the cost of future manufacturing technologies within a fab environment. Such CoO calculations and analysis were used during the next generation lithography (NGL) activity to compare 193 nm, 157 nm, extreme ultraviolet (EUV), electron-beam projection lithography (EPL), $1 \times$ proximity x-ray, and ion-beam projection lithography (IPL) technologies.^{6–8} SEMATECH continues to utilize lithography CoO to analyze cost impact improvements; returns on investments would be realized if certain exposure technologies or system improvements would be developed. With the most recent developments of 193-nm immersion followed by EUV technology, CoO modeling can be used to help identify IC fab manufacturing issues or to focus further developments on improving technology cost effectiveness. With concerns of EUV source power, collector lifetimes, mask costs, and other items, CoO modeling can be an important tool to show the significance of improving subsystem components to improve IC manufacturing costs.

12.1.2 General CoO equations and input relationships

The CoO equations for IC process manufacturing can vary slightly depending on the application or on the software model that is used. But first-order approximations for lithography CoO calculations can be accomplished easily using Eq. (12.1), which consists of three general terms: the exposure cell term (12.1a), the mask term (12.1b), and the other support processes cost term (12.1c):

$$\text{CoO}\$/\text{GWLE} = \frac{(C_e + C_l + C_f + C_c + C_r Q_{rw} N_c)}{(TUY_p)} + \frac{C_m}{N_{wm}} + C_{other}, \quad (12.1)$$

which can be rewritten simply as

$$\text{CoO}\$/\text{GWLE} = \text{Eq. (12.1a)} + \text{Eq. (12.1b)} + \text{Eq. (12.1c)}.$$

Terms separated by the '+' sign represent Eqs. (12.1a), (12.1b), and (12.1c),

where CoO \$/GWLE = cost per good wafer level exposure (the term “good” refers to “yielded” wafers);

C_e = yearly cost of exposure, coating, and pattern transfer equipment (including depreciation, maintenance, and installation using five-year capital depreciation);

C_l = yearly cost of labor to support equipment tool cell from variable C_e ;

C_f = yearly cost of clean room space occupied or needed to support tools from variable C_e ;

C_c = cost of other consumables (condenser, laser diodes, filters, etc.);

C_r = cost of photoresist or other pattern transfer layers or chemistry [e.g., bottom antireflective coatings (BARC), developer, hexamethyldisilazane (HMDS), etc.];

Q_{rw} = quantity of photoresist and other chemistry used in variable C_r per wafer;

N_c = total number of wafers coated to support production exposure level per year;

T = exposure tool cell throughput;

U = tool utilization;

Y_p = yield of lithography step (e.g., includes yield loss from wafers scrap due to equipment failure, product loss due to defects induced by poor-quality processes, parametric yield loss resulting when product functions below acceptable performance levels but it is not recognized until final product IC tests, and yield loss from infant mortality loss);

C_m = cost of mask or reticle;

N_{wm} = number of wafers exposed per mask (also known as “mask lifetime”); and

C_{other} = other lithography related costs needed to support the specific exposure layer or level [e.g., antireflective coating (ARC) etch, hard mask costs, hard mask etch, post develop cleans, etc.].

12.1.2.1 CoO exposure cell term [Eq. (12.1a)]

The exposure cell term includes the total CoO contributions from the entire exposure cell, which includes the exposure system (stepper or scanner), exposure source [e.g., excimer laser for deep UV (DUV)], photoresist process equipment (known as track to prime, coat, develop, etc., the wafers), and supporting environmental controls. The exposure cell, an example of which is shown in Fig. 12.1, is generally the automation linking of these major tools together in a FAB lithography bay. This linking is needed to support an incoming wafer from a previously completed IC process step and to fully complete the next process step. This term is simply all of the capital, consumables, facility, and labor costs divided by the number of good wafer levels that are produced through the exposure tool cell. Therefore, to lower the CoO, one would want to minimize all of the costs (numerator) and maximize the number of good yielded wafers (denominator). The preferred equipment set can process more wafers (higher throughput) while being reliable enough to maintain production levels (higher uptime or utilization) and produces high-quality product

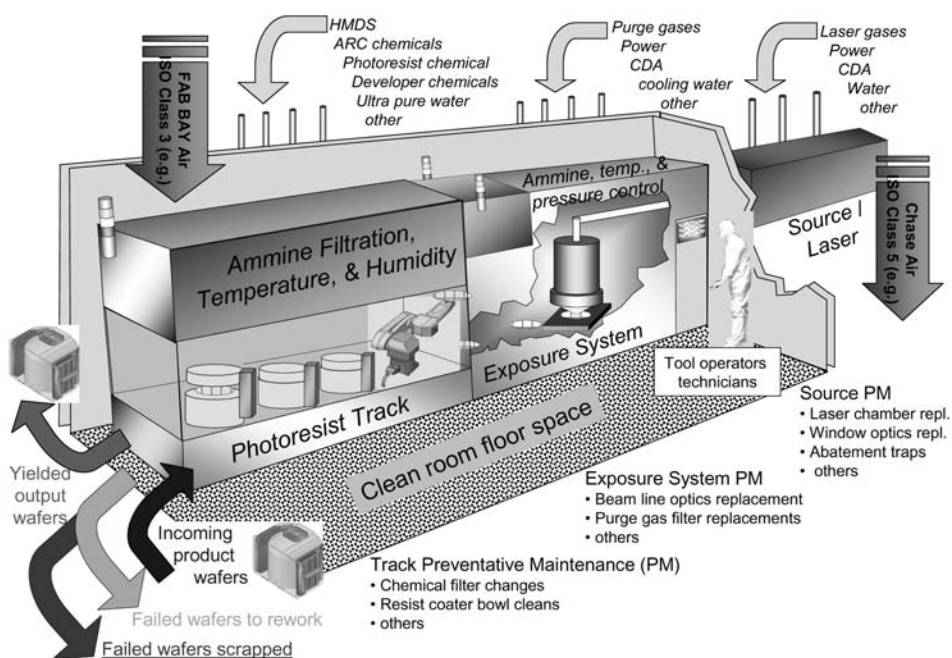


Figure 12.1 Generic example of a lithography-linked exposure cell in a wafer IC FAB that integrates the exposure system body with the source and automated photoresist process track.

(high yield) at similar costs. The following sections will explain why some variables in this term do not produce the same effect.

12.1.2.2 Mask term [Eq. (12.1b)]

The mask term is simply the cost of the patterned mask divided by the number of times it is used to expose the wafer over the lifetime of the mask. A lower-cost mask that is used more often results in a lower CoO. In the past decade, this term has become a much larger contributing cost component to overall wafer level CoO. This term is also very sensitive to what type of IC product is being made. Therefore, wafers per mask amounts can vary depending on the IC product type, but the mask lifetimes are almost always driven by product design obsolescence. When IC product designs are improved and IC products undergo “shrinks,” the current masks ultimately become obsolete and new masks are required to pattern new IC’s. Rarely are masks removed from IC production due to unreparable defects or other failures.

12.1.2.3 Other costs term [Eq. (12.1c)]

The other costs term includes any additional wafer processing cost that is not specifically accounted for in the terms of Eqs. (12.1a) and (12.1b) but that is necessary to complete the wafer level before the product lots are moved to the next “non-lithography” process steps. Sometimes specific process equipment is needed to

support the processing. In some cases, one may need to etch into a multilayer (ML) photoresist system, such as a hard mask or etch stop barrier, that is needed to complete patterning development but that cannot remain on the product once the IC patterns are etched. In such a case, a separate etch process tool like reactive ion etch (RIE) would be required to etch away the unwanted hard mask material. Another example is a top surface imaging (TSI) photoresist system that requires a secondary photoresist chemistry reaction, such as instituting vapor phase silylation to improve the etch bias of the exposed photoresist area on the wafer. Either of these examples would require the addition of a lumped cost per wafer for this term to fully account for the lithography process CoO. In most cases, photoresist systems employing TSI or ML photoresist strategies will have additional processing costs that are captured by this term in Eq. (12.1c).

12.1.2.4 General high-level CoO impact analysis

One can quickly see the different effects that the variables in Eq. (12.1b) have on CoO by using some straightforward assumptions made on a generic lithography exposure cell for CoO calculations and by varying certain parameters. Figure 12.2 shows the sensitivity effects of overall CoO compared to changes in certain input assumptions. The largest impacts occur when product yields are lower. This emphasizes why IC fabs are so concerned with improving product and process yields. Even a one-tenth of one percent yield improvement on a lithography cell can mean \$100,000 savings by the end of a year (based on a 30,000 wafer-start-per-month, 300-mm fab). Exposure cell overall throughput is also a significant CoO driver, followed closely by mask lifetime (mask usages) if all other parameters are held

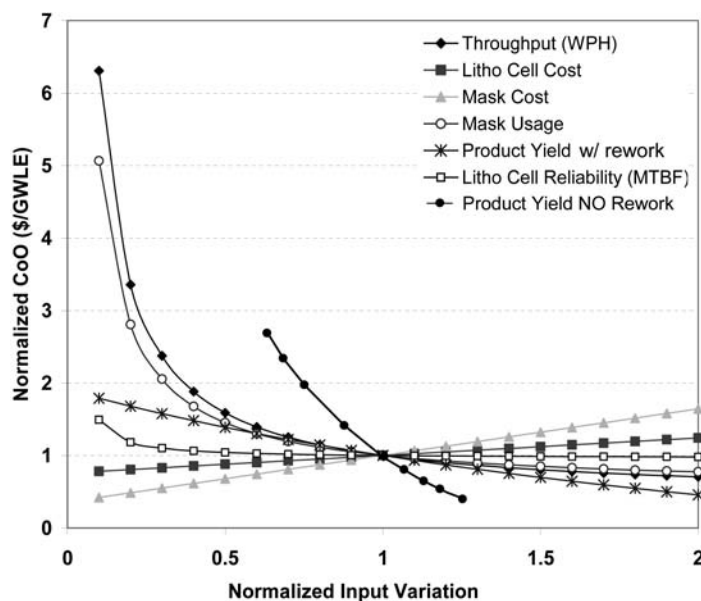


Figure 12.2 The dependency of overall CoO to variations in input performance values.

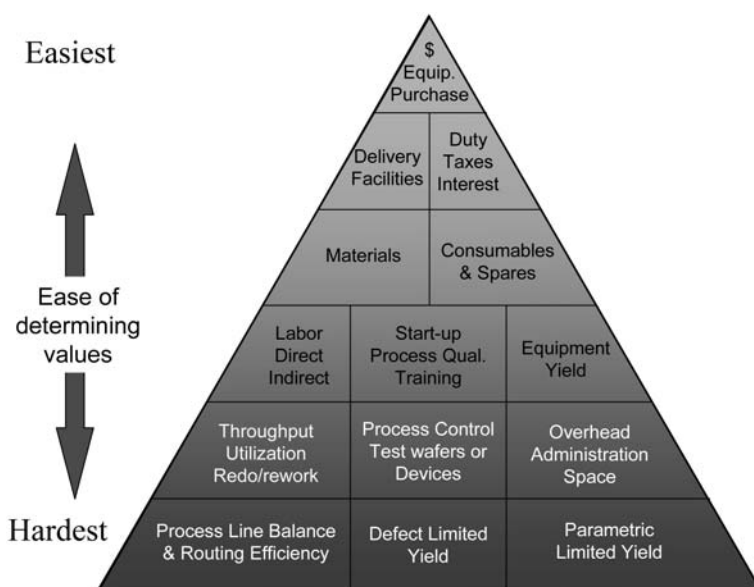


Figure 12.3 The relative scale of difficulty in establishing correct input values in CoO calculations.

constant. Low system throughputs and short mask lifetimes both increase wafer level CoO significantly simply due to the fact that fewer wafers are produced to amortize the exposure tool and to mask costs across the yielded wafer products.

However, one may also find early in CoO analysis that accurately identifying the correct input values or assumptions for certain variables can be very difficult. Figure 12.3 shows a qualitative scale on the ease of identifying the correct values for many of the input assumptions in CoO analysis. Some of the easiest values to accurately identify are tool capital costs, tax rates on facilities, and facility costs. Some parameters that can be difficult to accurately establish are listed at the bottom of Fig. 12.3; they include maintaining adequate line balancing between equipment, products, and yields, especially parametric yield losses. Many parametric yield losses are latent to CoO calculations because poor device performance is not identified until the customer uses the device over a period of time. Tracking such a cost loss is often difficult. Many times IC device functionality assessments using probability models are used to help calculate predicted parametric yield losses.

12.1.3 Lithography global CoO input assumptions (SEMI E35, fab parameters, etc.)

Global input assumptions refer to the support cost items that are dictated by either the IC fab facility, tool operators and technician overhead, and other standard rates. Many of these global or standard rate assumptions are generally fixed values for a given IC fab, IC product type generation, or even the type of process equipment being used in CoO calculations. However, in order to identify the true total CoO costs

of the technology, these standard rates and global assumptions must be included. A complete description for many of these parameters can be found in SEMI E35, but some of these parameters and their influence on a lithography CoO analysis will be discussed here.

12.1.3.1 Scheduled production available timing

For a mature IC fab, most production operations will run at or very near 24 hours a day/7 days a week, with multiple production shifts to cover “around the clock” daily and weekly production operations (a common situation is four or five production shift groups covering a 10- to 11-hour shift period and rotating on a four days on/three days off schedule). SEMATECH CoO calculations generally use the SEMI E35 suggested values for 300-mm wafer production operations that include the following:

Number of hours/week/shift:	42 (amount of time one shift works per week)
Number of shifts/week:	4
Number of hours/day:	24
Number of days/year:	365

As a general rule, the available production time is assumed to be 168 hours per week. However, due to the need to maintain the equipment and verify process controls at shift changes and at weekly, monthly, or quarterly preventative maintenance (PM) cycles, the actual productive time that a lithography exposure cell is exposing and developing wafers is sometimes 70 to 80 hours per week. Those exposure cells, which have minimal PM impact periods, will obviously be processing more wafer product. The scheduled available production time influences how many wafers are able to be processed through the exposure cell tool utilization variable (*U*) in Eq. (12.1).

12.1.3.2 Labor and overhead costs

Usually labor and overhead costs are the total corporate burdened costs for either salary or hourly paid employees that support the equipment in the fab and are direct inputs to the variable term *C_l* in Eq. (12.1). Included in these burdened costs is any health, retirement, profit sharing, or other human resources benefits. Each worker usually supports more than one piece of equipment during a shift, so the labor and overhead contributions are normally spread over many tools in the fab. As an example, tool operators can support two to three different exposure cells during one shift. SEMI E35 suggested these values for labor and overhead costs:

Engineering personnel total costs:	\$111,000 USD/year
Supervisor personnel total costs:	\$111,000 USD/year
Operator personnel total costs:	\$25 USD/hour
Maintenance and technician personnel total cost:	\$30 USD/hour

Table 12.1 CoO cost contributions for occupied fab clean-room floor space of process equipment compared to class level clean-room performances.

Traditional U.S. class	Worldwide ISO class	Cost (\$USD/sq. ft./year)	Number of particles contained in 1 cubic meter of air			
			$\geq 0.1 \mu\text{m}$	$\geq 0.2 \mu\text{m}$	$\geq 0.3 \mu\text{m}$	$\geq 0.5 \mu\text{m}$
Class 0.01	ISO class 1	~\$750 (estimated)	10	2	—	—
Class 0.1	ISO class 2	~\$550 (estimated)	100	24	10	4
Class 1	ISO class 3	\$400	1,000	237	102	35
Class 10	ISO class 4	\$250	10,000	2,370	1,020	352
Class 1000	ISO class 5	\$100	100,000	23,700	10,200	3,520
Class 10,000	ISO class 6	\$50	1,000,000	237,000	102,000	35,200

12.1.3.3 Fab floor space rates

Fab equipment for submicron IC processing requires “clean room” environments. In these clean rooms, incoming air to the fab area is filtered to remove airborne particulates that could cause defects and IC device failures if the particles landed on the product wafers. This air is also routed into the fab to produce a downward laminar airflow to further reduce defect generation. Additional antistatic measures are often employed to reduce static discharge that could cause catastrophic damage to small IC devices. All of these air and environment preparations add costs to the overall wafer production. These costs are identified in the term C_f in Eq. (12.1). They are generally assigned as costs to the process equipment for the floor space that they occupy. The class rates of clean-room space specifications are defined as having no more than a certain number of particles of a certain size in a cubic volume of air. Clean-room space costs get more expensive as the cleanliness level increases. Costs for fab floor space are generally in the metrics of dollars per square foot or square meter per year. A traditional U.S. class 1 clean room requires controlled air to have less than 1 particle of size $0.5 \mu\text{m}$ or larger per 1 cubic foot of air.

As shown in Table 12.1, significant cost variations exist for different clean room levels that will affect CoO. For many types of equipment that tend to have larger footprints or support service equipment (examples: process chamber vacuum pumps, fluid delivery systems, etc.), it is common practice to place only the most critical part of the process equipment in the highest performance clean-room space and to locate many service items in lower-class areas. Such strategies are often termed “bay and chase” fab architecture because critical process chamber openings are located in the cleanest process bay areas and the service units are placed in the chase areas to reduce overall operating costs.

12.1.3.4 Capital equipment depreciation schedules and values

The total toolset costs are used in the CoO calculation, but depreciation is done over multiple years. Due to the significantly higher capital costs of most leading-edge lithography exposure process tools, equipment should be fully utilized over

multiple IC product generations spanning many years. Each time a company prepares its financial statements, it records a depreciation expense to allocate a portion of the cost of the buildings, machines, or equipment it has purchased to the current fiscal year. For business tax and company asset declarations as well as CoO calculations, the cost of the exposure toolset is spread over many years, usually over five years, of depreciation. After the fifth year, IC companies can declare that the tools no longer have capital value. Also, the overall lifetime of exposure toolsets is now averaging seven years since older equipment can be reused to support other less-critical exposure levels in new products. These costs are identified in the term C_e in Eq. (12.1).

For lithography CoO calculations, tool costs are spread evenly over what is called a “straight line” depreciation schedule. For example, a lithography tool whose initial procurement price capital value is \$20,000,000 can be depreciated \$4,000,000 per year until it reaches the salvage value (which may be \$0 for lithography tools) after the fifth year. Other depreciation schedules can be used such as “double declining” methods, where more capital value is depreciated in the early years versus final years of its depreciation life at a rate of two times the straight-line method. In the SEMATECH CoO model and analysis, one can identify the wafer level CoO (\$/GWLE) after the first year, third year, or fifth year of operation. SEMATECH uses the following tool depreciation schedule as identified in SEMI E35:

Life of the equipment:	7 years
Depreciation life:	5 years
Salvage value of equipment:	\$0
Depreciation schedule:	Straight line

12.1.3.5 Equipment installation cost

For accurate accounting of the full CoO costs, proper installation costs must be added to the term C_e in Eq. (12.1). Installation costs can vary dramatically for different IC process tools. Installations costs for fab wafer metrology tools often are the lowest cost to install since they require mainly house gas, electricity, chilled water, and other standard services. Lithography tools tend to be the second most expensive tool type as a percentage of equipment purchase cost to install into a fab. These tools usually require specialty-grade tube gases for excimer laser chambers, high purity nitrogen purging for optics protection, and exposure tool and photore-sist track special temperature, humidity, and airborne ammine filtration systems, in addition to standard house facility services. On an installation percentage level, the most expensive tool types tend to be multi-wafer/multi-process chamber etching systems. These process tools require a tremendous number of separate high-purity process gases to support chamber reactions that must be delivered to the tool. These are needed to support the various materials of IC device films that are deposited, imaged, etched, and cleaned. For some multi-chamber process dry-etch tools, there can be as many as 20 or 30 separate high-purity gas delivery systems that all need

to be interfaced from the facility to the tool. Their installation costs can reach 15% of the overall procurement capital tool value. SEMATECH uses the following installation costs as a percentage of the capital procurement costs:

Lithography exposure and process equipment:	8%
Metrology equipment:	5%
Other equipment:	12%
Multiple-chamber dry-etch process equipment:	15%

12.1.4 Lithography-specific product parameters (fields and die per wafer, wafers per mask, etc.)

This section will briefly discuss the specific IC device size, exposure field size, and the number of actual exposures required to complete the full wafer area. The total number of exposure fields needed per wafer will directly translate in the exposure tool throughput. Also, the mask lifetime, which is directly proportional to the total amount of IC device product, will be discussed. These variables are considered “specific product parameters” that have a significant impact on overall exposure cell throughput, mask cost contributions, and the frequency of mask exchanges needed between wafer lots.

12.1.4.1 Number of exposure fields per wafer

A major factor for exposure tool throughput is the number of exposure fields that are needed to complete a full wafer. This parameter varies with the IC device area and size aspect ratios, which determine how many individual IC device chips or “die” can be placed within the reticle field. Having multiple die per reticle field multiplies the number of die that are exposed per wafer exposure field. Most leading-edge exposure scanner tools have a maximum field size at the reticle (or mask) using a $4\times$ demagnification that is $132\text{ mm} \times 104\text{ mm}$. This translates to a physical wafer field size of $33\text{ mm} \times 26\text{ mm}$. The IC device design and process implementation engineers optimize the cost of the mask driven by the patterned area on the mask with how many IC die can be exposed in one field. The aspect ratios of the die impact such optimization. Traditional dynamic random access memory (DRAM) die aspect ratios tend to be 2:1 length versus width. Microprocessor logic chips historically have had aspect ratios of near 1:1, but recently, with microprocessor chip designs including additional digital signal processor (DSP) functions, aspect ratios of 1:1.25 and up to 1:1.50 have been seen. Several methods can be used to quickly calculate how many exposure fields per wafer exist for a given IC product. Equation (12.2) can be used, which is simply the area of the wafer divided into the area of the exposure field:⁹

$$N_{ExpFields} = \frac{\pi d^2}{4a_{ExpField}}, \quad (12.2)$$

where d is the diameter of the wafer and $a_{ExpField}$ is the area of the exposure field.

A simple example of Eq. (12.2) is a square 25 mm × 25 mm exposure field at the wafer using a 300-mm-diameter wafer, which would require 110 exposures. Although this may be a reasonable first-order approximation, this equation does not take into account two items: the optimized packing of field sizes with aspect ratios other than 1:1, and the partial fields at the edge of the wafer that would not yield full exposure fields and functioning IC die.

Equation (12.3) is a modest improvement to better estimate the number of exposure fields, based again only on the exposure field area and the wafer diameter but with the second term subtracting those partial fields around the wafer edge:

$$N_{ExpFields} = \frac{\pi(d/2)^2}{(2a_{ExpField})} - \frac{\pi d}{(2a_{ExpField})^{0.5}}. \quad (12.3)$$

If the same example used previously of a 25 mm × 25 mm field size and a 300-mm wafer is used in Eq. (12.3), the effective number of exposure fields is calculated to be 84. Although this is an improvement, it does not account for exact optimized field placements on the wafer, especially with variations in field aspect ratios.

More exact calculations for the number of fields per wafer that consider aspect ratios are generally conducted using assumed field placement calculations, with iterations to determine the optimal number of fields possible. This offset is calculated by using software that examines a number of prospective offsets between the center of one of the die and the center of the wafer. The number of available die is calculated for each such offset, and the offset that maximizes the available fields and die from the wafer is determined. Several available modest software packages support this approach.^{10,11} Figure 12.4 shows a calculated exposure and the dies per wafer map from such a software program. Table 12.2 illustrates how the calculated fields per wafer can vary significantly among the three methods, especially when aspect ratios of the fields move further away from 1:1.

12.1.4.2 Wafers per mask

As discussed in Sec. 12.1.2.2, mask lifetimes are determined mostly by when new IC products are introduced to the fab (that includes IC “shrinks”). Compared to other IC products, DRAM IC devices tend to have much longer mask lifetimes, lasting for 5,000 to 20,000 wafers. Logic or microprocessing unit (MPU) IC devices have an average mask lifetime lasting from 1,000 to about 5,000 wafers (on rare occasions MPU mask lifetimes have reached 40,000 wafers). Application specific integrated circuits (ASIC) devices such as DSP or video ICs sometimes have masks with only a 100 to 1,000 wafer exposure lifetime. There are two reasons why some ASIC product lines have much shorter mask lifetimes than DRAMs or MPUs. First, ASIC products tend to be optimized for only one or two customers compared to the higher-volume DRAM or MPU devices, so the total volume of products needed is smaller. The second reason is that many ASIC die sizes are smaller than DRAM or MPU sizes, making the number of printed die per wafer more efficient than DRAMs or MPUs.

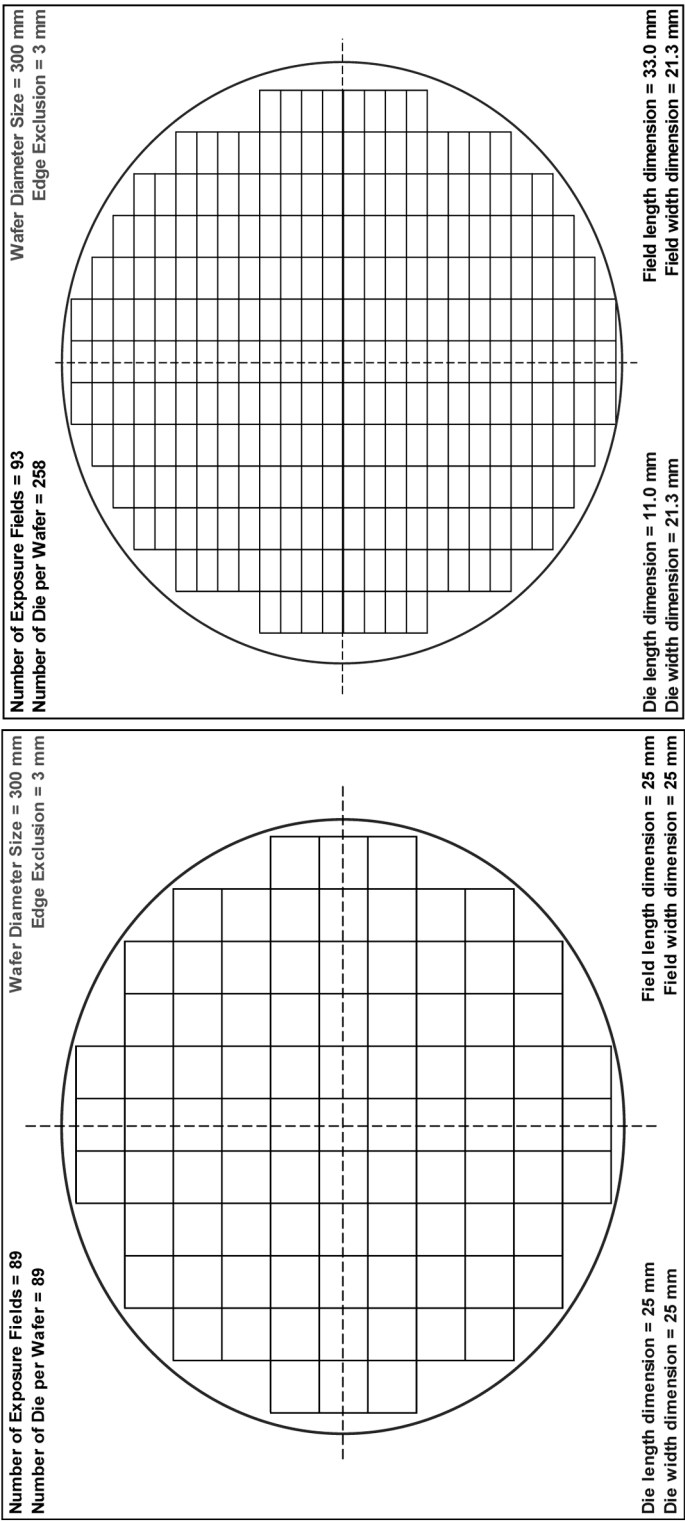


Figure 12.4 Graphical map showing the maximum number of available exposure fields for a 300 mm wafer calculated using SEMATECH Die per Wafer software.¹⁰ Left map uses a 25 mm × 25 mm field size with one die per field. Right map uses 33.0 mm × 21.3 mm field size with 11.0 mm × 21.3 mm die size.

Table 12.2 Comparison of total exposure fields per wafer and die per wafer using different calculation methods.

Exposure field size at wafer (mm × mm)	IC die size at wafer (mm × mm)	IC die per exposure field	Total fields and IC die per 300-mm wafer					
			Simple area method		Improved area method		SEMAETCH die per wafer method ⁹	
			Eq. (12.2)		Eq. (12.3)			
			Fields/ wafer	Die/per wafer	Fields/ wafer	Die/per wafer	Fields/ wafer	Die/per wafer
25 × 25	25 × 25	1	110	110	84	84	89	89
33 × 26	33 × 26	1	80	80	58	58	64	64
21.3 × 33	21.3 × 11	3	98	294	73	219	93	258
25 × 24	12.5 × 8	6	115	690	88	528	117	621

12.2 Lithography: Historical Cost and Price Trends

The IC lithography process and materials sectors have continued to be major enablers by supporting the traditional 30% annual productivity gains seen in semiconductors. However, in the drive to expose and print smaller features comes an increased manufacturing cost, with more advanced technologies needed that have increased productivity as much as an order of magnitude over the past several decades. But with both the process tool and material suppliers increasing productivity in certain areas as well as the IC manufacturers consistently shrinking both feature size and die size, greater IC device performance has continued at the same or lower prices.

This section highlights some of the major historical costs of lithography tools and materials, balanced by the die and transistor unit function cost over time. The CoO observed over time with completed wafer costs, estimated area, and unit function costs is discussed briefly. Additional discussions are made on the lithography exposure tools and mask costs and their impacts to increased lithography manufacturing costs.

12.2.1 Historical completed wafer, die, and function costs to manufacture

SEMATECH and its associated International SEMATECH Manufacturing Initiative (ISMI) consortia periodically monitor the current IC generation wafer manufacturing costs and model future-generation completed costs of IC manufacturing.^{12,13} A small sample of these comparisons can be seen in Table 12.3. It is clear that total lithography costs for completed wafers are increasing due to the device complexity and the number of levels needed to support the completed wafer. As shown in Table 12.3, a 90-nm half-pitch (HP) logic device can use as much as 28 separate lithography steps, which will require 28 separate masks and potentially, at least three different generations of lithography exposure tools (I-line/365-nm wavelength, 248 nm, and 193 nm dry). This is significantly more costly to support

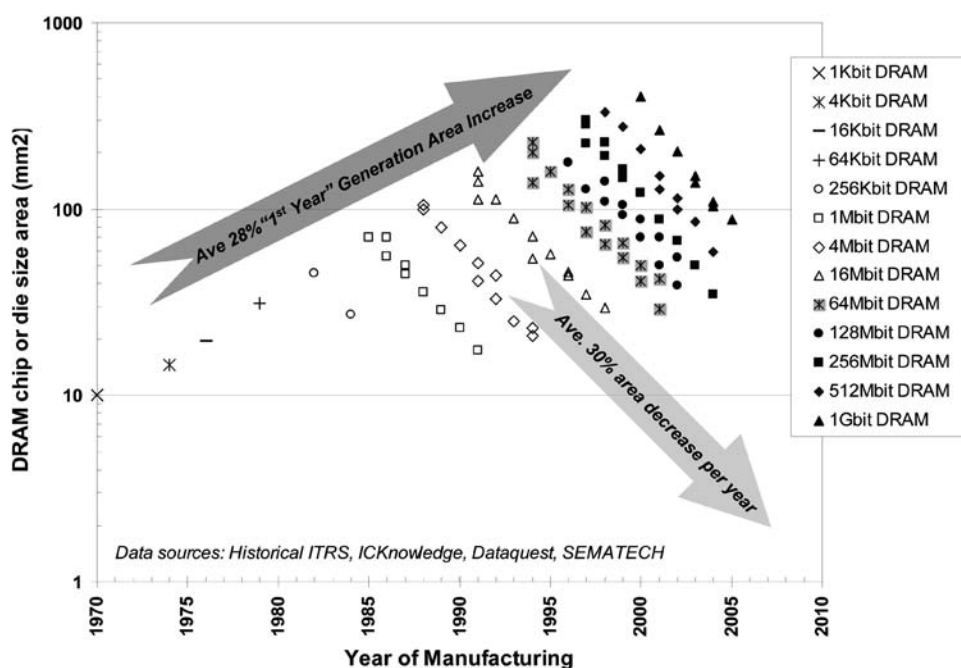


Figure 12.5 Historical DRAM chip area size trends seen over a 30-year period with 13 different DRAM generations where annual die area shrinks 30% within any given generation.

than previous generations. Ten years ago, 350-nm-device generations required only 15 lithography mask patterning levels and averaged four metal levels. In the early 1980s, 1500-nm-device (i.e., 1.5- μm) generations needed only 10 lithography levels, only two of which were metal interconnect levels. The number of patterning levels needed ultimately drives the total lithography cost per completed wafer in IC manufacturing, which is now reaching 35% of the overall wafer costs.

Historically, the size of the IC die or chip appeared to be growing at an average trend of $1.14\times$ per year over a period of 30 years (1970s thru mid-1990s). This was largely based on DRAM and MPU size growths. However, this chip size growth trend has slowed over the past 10 years as a result of attaining higher productivity gains through feature size shrinks, wafer sizes, and other factors (i.e., the 2005 ITRS chip size model discussion on flattening chip size increase rate).¹ Also, the introduction and market growth of many smaller ASIC products (such as DSP) as well as the slowing of MPU size growth has reduced the die size growth, which relies more on improved transistor packing or functional cell layout density. Memory products have a characteristic annual productivity improvement: although the first year of a new-generation DRAM may have a die area 25 to 30% larger than its predecessor (i.e., 1991 16-Mbit vs 1994 64-Mbit DRAM), each year there is an average 30% die size reduction within each DRAM generation. Figure 12.5 illustrates these trends clearly using data from multiple sources.^{14–16} Generally, this pattern reinforces the drive to increase the number of die per wafer.

Table 12.3 Comparison of several different logic IC device generations with associated average completed wafer costs using the lithography costs from SEMATECH and ISMI. Note that although the completed wafer and lithography costs consistently increase, there is a net decrease in cost-per-unit function (i.e., cost per transistor).

IC design	250 nm	180 nm	130 nm	90 nm	65 nm*	45 nm*
IC process/materials used	Al/SiO ₂	Al/SiO ₂	Cu/LoK	Cu/LoK	LEL	LEL
200-mm wafer size	\$1,500	\$1,700	—	—	—	—
300-mm wafer size	—	\$2,681	\$2,752	\$2,950	\$3,600	>\$4,200
No. of metal levels	—	—	7	9	10	12
No. of litho mask levels	19	21	25	28	32	35
Litho cost per wafer	—	\$730	\$744	\$1,063	\$1,290	\$1,500
Total cost per area (U.S.\$/cm ²)	—	—	3.89	4.37	5.05	>5.90
Cost per transistor (U.S. cents)	—	0.17	0.11	0.08	0.04	0.03

*Cost of projected future device generations by ISMI factory modeling. LEL = Leading Edge Logic device.

The lithography industry has significantly contributed to shrinking geometries. Some additional average annual productivity gains include the following:

- Average number of transistors per DRAM chip device increases by about $1.6\times$ per year.
- Average number of transistors per MPU chip device increases by about $1.4\times$ per year.
- The cost per transistor function has decreased by an average of 30% per year.

12.2.2 Historical photolithography exposure tool price trends

The ability of exposure tool suppliers to continue to deliver new technology platforms with increased productivity has contributed greatly to the lithography industry's contributions to overall reduced cost per device function. Although stepper and scanner tool prices have consistently increased over time, due to new more-expensive technology platforms (i.e., G-line, I-line, 248 nm, and 193 nm), scanner throughputs and other productivity gains have enabled cost-effective wafer-level CoO. Figure 12.6(a) shows SEMATECH's historical tracking of exposure tool prices. However, the increased productivity in higher throughput and tool uptime (utilization) while maintaining adequate yields has contained term Eq. (12.1a) for normalized areas, as shown in Fig. 12.6(b). This is significant because more die per wafer were enabled at similar or slightly higher throughputs on much larger wafer sizes.

12.2.3 Historical reticle costs and mask usage trends

The largest increases seen in the lithography wafer-level CoO has been a result of both the steady increase in reticle costs for each IC feature size shrink coupled with

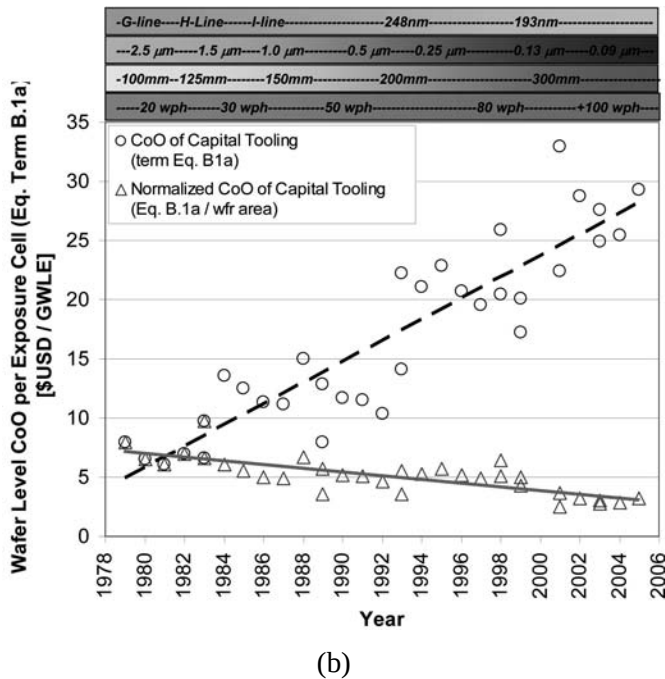
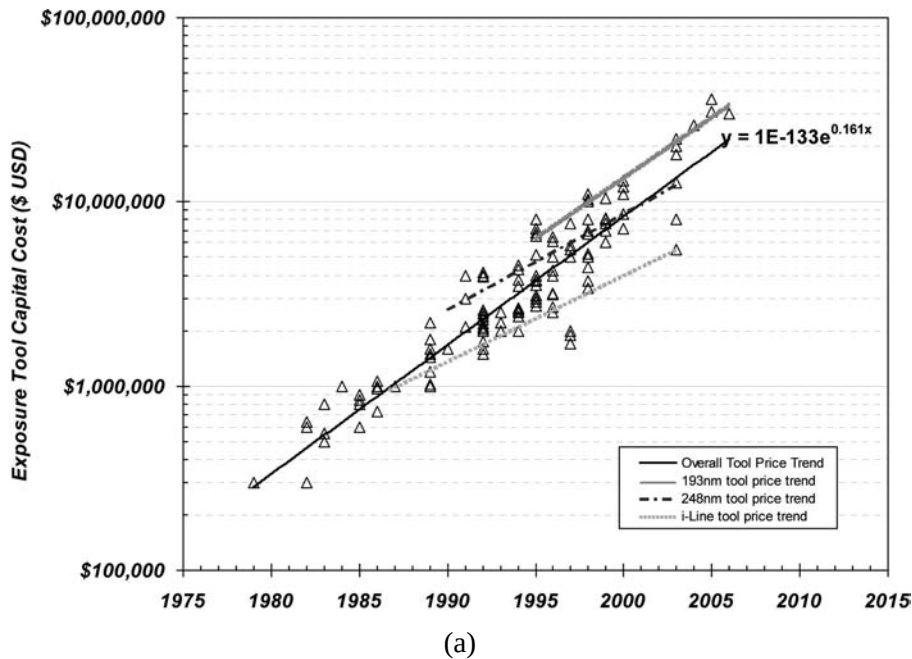


Figure 12.6 (a) SEMATECH historical lithography exposure tool price with general trends and average increase trends for I-line, 248 nm, and 193 nm dry exposure systems compared to (b) the general historical capital tooling critical level exposure cell wafer CoO and normalized wafer CoO with wafer area.

the overall reduction in average mask lifetimes. As identified earlier, the reticle cost contributor to the overall lithography CoO is provided by term Eq. (12.1b); therefore, this term easily escalates when reticle costs increase and usage decreases. For the overall mask costs for a given node over the lifetime of a given node, there is a modest decrease in cost from about 7 to 10% annually, which is the result of mask manufacturing process improvements.¹⁷ However, there have been steady increases for mask costs for each successive smaller IC feature generation. Increased complexity of binary chrome on glass (BIN COG) traditional reticles, of alternating phase shift masks (Alt. PSM), and of attenuated phase shift masks (Att. PSM) have added to the cost increase over time. In some cases, first-year mask costs at the next feature node size mask can be as much as double the cost of previous-generation mask sets. From 1995 to 1997, 250-nm reticle costs were \$10,000 to \$14,000 depending on the needed CD, IP, and defect requirements. By the year 2000, leading-edge 130-nm HP optical reticle costs were as much as \$44,000 compared to the \$19,000 cost for the previous 180-nm generation HP reticle.¹⁸ Currently, 90-nm HP masks have reached \$100,000 for binary masks and \$124,000 for Alt. PSMs.¹⁹ There are many reasons for the increases, which will be discussed in detail in Sec. 12.3.

Process tooling costs for mask manufacturing have increased just as the costs of lithography exposure tools have increased. However, mask writing technology productivity has not increased as dramatically as the wafer exposure tools, due primarily to the “pixel explosion” effect: the need to write much more complex assist features on the mask. As with the general decrease in lithography imaging—the k_1 factor below 0.70 seen in the early 1990s is now to 0.40 or lower today—there is an exponentially larger number of reticle assist features such as line biasing, hammer heads to reduce line shortening, additional serifs for corner fidelity, and scattering bars. All these features are used to reduce reticle diffraction effects. The dramatic increase in pixel counts challenges both optical laser and e-beam mask writers to pattern masks with good image fidelity at process times that often reach 15-hour write times for 90-nm HP generation masks, or even more for certain critical-level masks.²⁰ Also, a significant factor in the reticle cost increases is due to a different business sector model where there are fewer mask process tools and mask process tool customers than in the wafer exposure tool sectors.

With the fairly recent transition in IC manufacturing to many more product lines and more ASIC-type devices coupled with a general industry trend to shrink die sizes at a faster rate, average mask lifetimes have decreased over the past 20 years. The overall wafers per mask (WPM) average for DRAM, MPU, and ASIC at different points in history show a steady decrease in the average wafers per mask. By 1990 the average mask usage was about 7,000 WPM, which was driven by the additional DRAM products. By 1995, MPU product proliferation increased together with early ASIC growth. The WPM average decreased to around 3500. By 2000, the ASIC market share had increased dramatically, especially with DSP chips for cell phones and small handheld devices (PDA), and the DRAM market had become more efficient with die sizes. Also by the year 2000, the average WPM

had further decreased to around 2500. Figure 12.7(a) shows the historical reduction in WPM usage as IC product introductions increased but with a significant decrease in product lifetime.²¹ Figure 12.7(b) also shows the cumulative prices for the complete masks set needed to support a full IC product through all of the exposure and patterning steps in the IC fab.²² A complete mask set for a 90-nm HP logic MPU that requires 28 mask levels can run between US\$1 million and US\$1.5 million.

12.3 Major Lithography CoO Parameter and Productivity Drivers

This section will review in more detail some of the parameters that affect the lithography wafer-level CoO by highlighting most of the major productivity drivers that the lithography supplier and IC manufacturing community have been concentrating on for continuous improvements. Several elements on the exposure scanner or stepper tools will be looked at in addition to reticle and photoresist processing cost impacts. To further illustrate the effects of changes to certain exposure tool cells or material cost impacts, a baseline case will be established with a reasonable, current, leading-edge exposure level for a 90-nm HP logic MPU product. This example will be for a 100-nm line width feature lithography patterning level for the first metal interconnect level (i.e., “Metal 1”), which is needed to support a 90-nm HP MPU product. Once this baseline case is established, several impact scenarios will be discussed that illustrate the effect of key equipment and materials costs, performance, and yield drivers.

12.3.1 Example of 100-nm lithography patterning Metal 1 level CoO within 90-nm half-pitch logic device manufacturing

An example of a 90-nm HP MPU product with associated exposure and patterning levels is taken from one of many SEMAETCH and ISMI factory model studies.¹³ Table 12.4 shows the complete lithography exposure levels needed to complete the full product where the gate level calls for an isolated line feature of 50 nm. Many other exposure levels are needed. For the specific baseline case, this section will describe the assumptions needed for the 100-nm feature length for Metal 1. It is assumed for the Metal 1 CoO wafer level exposure baseline case that a 193-nm dry exposure scanner is being used with $NA = 0.85$. The complete lithography cluster cell is considered to cost \$24.8 million (U.S.) including the exposure scanner, a 40-W 193-nm excimer laser source, and the photoresist processing track. The exposure tool and track also have special environmental enclosures for temperature, humidity, and ammine acid controls to protect the chemically amplified photore-sist (CAR) generally used in DUV. It is also assumed that the wafers are 300 mm in diameter and the exposure area is 26 mm $\times$ 33 mm, which provides for 64 exposure fields per 300-mm wafer. These production assumptions, along with additional baseline assumptions for this exposure wafer level listed in Table 12.5 and 12.6, equal a total CoO wafer level cost of \$59.44/GWLE. With these parameters the CoO Eq. (12.1) or any other CoO software programs (such as SEMATECH’s

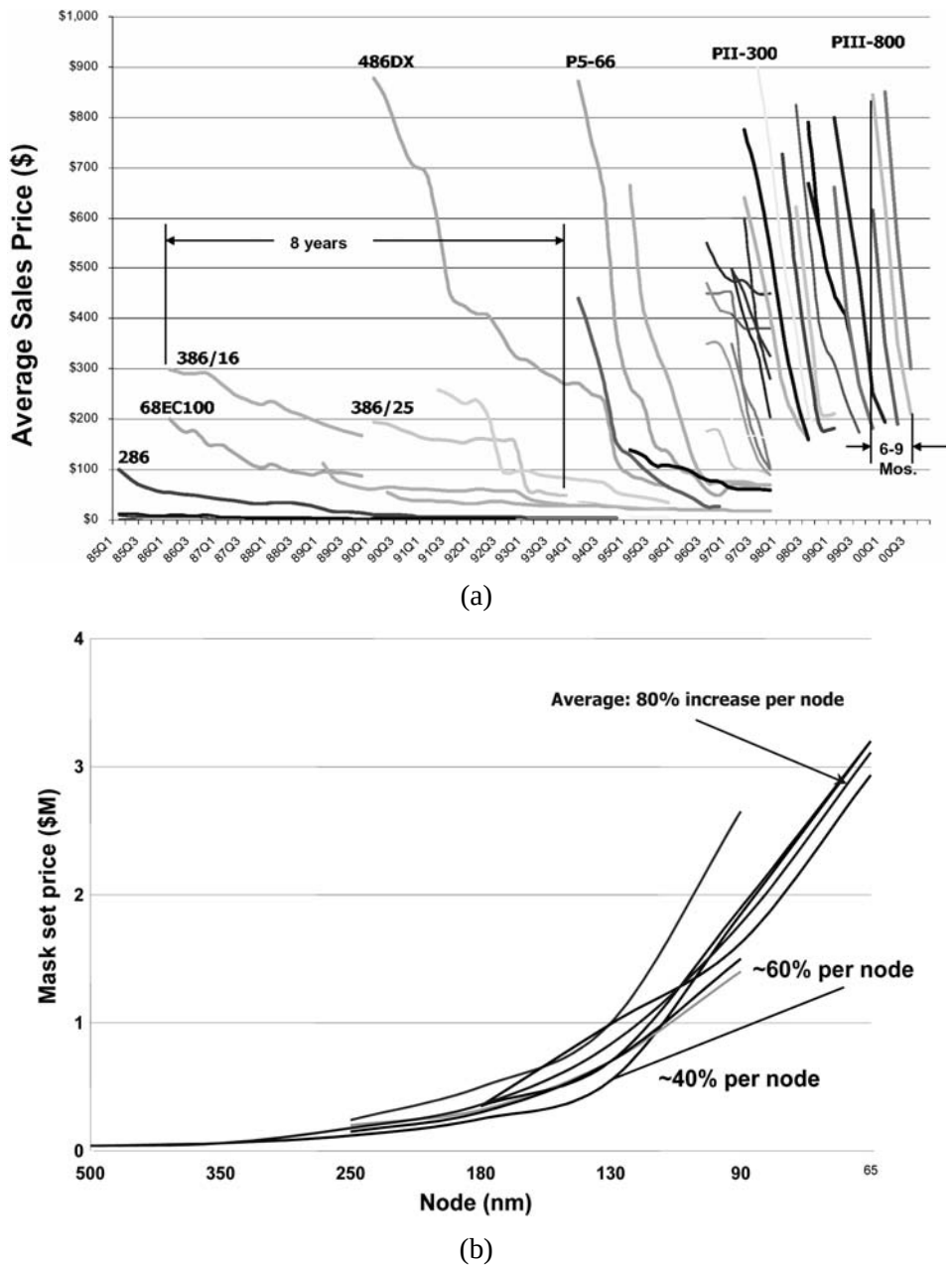


Figure 12.7 (a) Historical trend in the average device sales price over time, which illustrates the increase in IC product introduction with decreased lifetimes. (Reprinted from Ref. 21.) (b) The historical cumulative costs for complete reticle sets for various IC MPU products needed to support the full lithography exposure levels in the IC FAB. (Reprinted from Ref. 22.)

Table 12.4 Lithography exposure and patterning layers needed to support a generic 90-nm HP MPU device that includes a minimum 50-nm feature size isolated gate and a 100-nm feature length Metal 1 interconnect.

90-nm CMOS logic flow (operation description)	CD nm	Pitch nm	Lithography step	Mask cost	CoO (\$/GWLE)	Throughput (wph)	
						Raw	Effective
Expose active level	140	n/a	193-nm binary	\$90,000	\$57.30	112	43
Expose N-well level: hi-speed PMOS low Vt	400	n/a	I-line binary	\$2,500	\$20.02	105	58
Expose gate level	50	220	193-nm PSM	\$175,000	\$94.55	65	27
Expose N-ext level: low Vt NMOS	400	n/a	I-line binary	\$2,500	\$20.02	105	58
Expose contact level	100	220	193-nm binary	\$100,000	\$59.44	112	43
Expose Metal 1 level	100	210	193-nm binary	\$100,000	\$59.44	112	43
Expose via level	100	210	193-nm binary	\$100,000	\$59.44	112	43
Expose Metal 2 level	100	220	193-nm binary	\$100,000	\$59.44	112	43
Expose via level	110	220	193-nm binary	\$100,000	\$59.44	112	43
Expose Metal 3 level	130	265	193-nm binary	\$90,000	\$57.30	112	43
Expose via level	130	265	193-nm binary	\$90,000	\$57.30	112	43
Expose Metal 4 level	155	310	193-nm binary	\$75,000	\$54.05	112	43
Expose via level	155	310	193-nm binary	\$75,000	\$54.05	112	43
Expose Metal 5 level	230	460	248-nm binary	\$25,000	\$33.84	127	51
Expose via level	230	460	248-nm binary	\$25,000	\$33.84	127	51
Expose Metal 6 level	275	550	248-nm binary	\$15,000	\$31.67	127	51
Expose via level	275	550	248-nm binary	\$15,000	\$31.67	127	51
... (several layers removed from table) ...							
PAD (last layer)	3000	660	I-line binary	\$750	\$19.63	105	58
Total lithography CoO per completed wafer \$1,063.22							

lithography exposure tool CoO suites) can be used to itemize the cost elements contributed for the equipment, mask, photoresist process consumables, and other factors. Most CoO models are also able to identify cost impacts due to unproductive time. The SEMATECH lithography CoO model calculates both the raw tool cell throughputs as well as the average effective cell throughputs. Effective throughputs can be as much as 50% less than the raw system throughput (sometimes considered the advertised throughput) due to a myriad of time detractors that reduce the system utilization (U) efficiency from 100%, including unscheduled downtime due to failures, scheduled downtime for PM, engineering time for experiments or new process developments, and wafer and die losses due to yield hits. Even at an effective throughput (TPT) of 43 wafers per hour (wph) versus 112 raw WPH, the lithography cell is able to produce more than 1000 complete wafer levels or “turns” per 24-hour period.

12.3.2 Exposure tool cell throughput (TPT)

An important parameter for lithography exposure cell CoO, second only to yield in its impact, is system throughput. With lithography production equipment capital costs steadily increasing over time, throughput improvements have provided higher productivity and contained CoO costs. Over a 20-year time span, lithography expo-

Table 12.5 Various production assumptions for a 193-nm exposure cell made to develop the baseline CoO case for the 100-nm Metal 1 wafer level exposure, which resulted in a level CoO of \$59.44/GWLE.

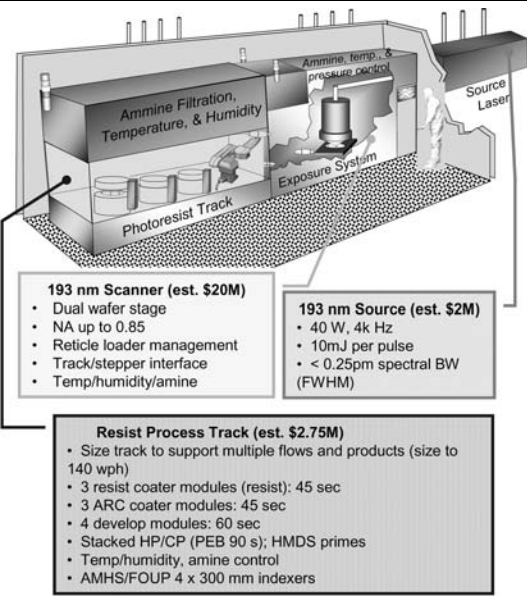
	Parameter	Value
 193 nm Scanner (est. \$20M) • Dual wafer stage • NA up to 0.85 • Reticle loader management • Track/stepper interface • Temp/humidity/amine 193 nm Source (est. \$2M) • 40 W, 4k Hz • 10mJ per pulse • < 0.25pm spectral BW (FWHM) Resist Process Track (est. \$2.75M) • Size track to support multiple flows and products (size to 140 wph) • 3 resist coater modules (resist): 45 sec • 3 ARC coater modules: 45 sec • 4 develop modules: 60 sec • Stacked HP/CP (PEB 90 s); HMDS primes • Temp/humidity, amine control • AMHS/FOUP 4 x 300 mm indexers	193-nm laser source power/Hz	40 W/4 kHz
	Cell cost (scanner, laser, track, partial automated material handling systems [AMHS] and reticle stocker)	\$24.8M
	Raw wafer system throughput	112.12
	Wafer size	300 mm
	Product field size at wafer	26 mm × 33 mm
	Exposure fields per wafer	64
	Photoresist sensitivity	10 mJ/cm ²
	Power at wafer plane	731 mW
	Wafer overhead time (wafer load/unload, alignments, etc.)	5.0 sec.
	Mask cost (CD = 100-nm BIN w/optical proximity correction (OPC))	\$100,000
	Mask usage (leading-edge logic)	5000
	Wafer/mask stage acceleration	1.5 G/6.0 G
	Stage step and scan speed	50 cm/sec
	Wafer overhead (OH)	5.0 sec
	Stage settle time	0.05 sec
	Scheduled maintenance for cell	13 hrs/wk
	Engineering usage of cell	13 hrs/wk
	Standby time of cell	13 hrs/wk
	Photoresist cost for level	\$3.5 k/gal
	ARC cost for level	\$1.5 k/gal
	Level yield at Metal 1	98%
	300-mm wafer cost	\$225

Table 12.6 Detailed wafer-level CoO and effective tool cell TPT for the 100-nm Metal 1 wafer level exposure, which resulted in a level CoO of \$59.44/GWLE. These values are taken over a five-year capital depreciation.

Production requirements (starts/wk)	7470
Net lithography cell throughput (39% raw)	43.51
# good wafers out (wafers/wk)	7309
# good wafers out/day	1044
Life of equipment inflated	5 Years
Cost per good wafer (\$)	CoO/GWLE
Lithography cluster equipment	\$14.39
Lithography chemical consumables	\$6.95
Arc etch and other patterning processing	\$3.97
Masks cost (tooling, AMHS, PM)	\$21.70
Utilities, support/services, materials	\$0.52
Maintenance	\$3.01
Labor	\$0.55
Scrap and product loss	\$5.51
Administrative costs	\$2.84
TOTAL	\$59.44

sure tools have increased raw throughput almost 10 times, even with larger wafer diameter sizes. Given that wafer and die yields remain consistent, higher TPT levels allow more wafers to be produced over the lifetime of the equipment toolset, thus spreading the large capital costs over more products.

Lithography exposure tool cells are most often optimized to allow the exposure tool to run at the highest throughput possible. Therefore, the photoresist process tracks, wafer indexers, and interfaces, as well as the reticle handler TPT, are nearly always configured to allow the exposure tools to operate at maximum run rates. It is not uncommon for photoresist tracks to employ four or more photoresist coater modules and four to five developer modules, supported by 10 or more thermal hot plate and chill plate modules, in one system to handle high exposure tool throughputs. Usually photoresist tracks and wafer or reticle handler TPTs are optimized to handle about 20% higher capacity for both process improvements and the potentially higher exposure tool TPT that may result when product designs are changed or optimized. As shown in Fig. 12.8, the exposure tool cell TPT can dramatically reduce overall wafer-level CoO. Many factors that affect exposure tool cell TPT are illustrated in the fishbone diagram of Fig. 12.8.

A fairly straightforward equation can quickly calculate exposure scanner TPT. Equation (12.4) shows that exposure scanner TPT is related to the number of fields per wafer, exposure time, stage movement time per field, and other additional wafer overhead movement times:

$$\text{TPT}_{\text{Raw}} = \frac{3600 \text{ seconds}}{f_w(m_s + e_t + a_f) + w_{l/ul} + a_w + a_m + w_{OH}}, \quad (12.4)$$

where TPT_{Raw} = raw throughput of the scanner or stepper in wafers per hour,
 f_w = number of fields per wafer that needs to be exposed,

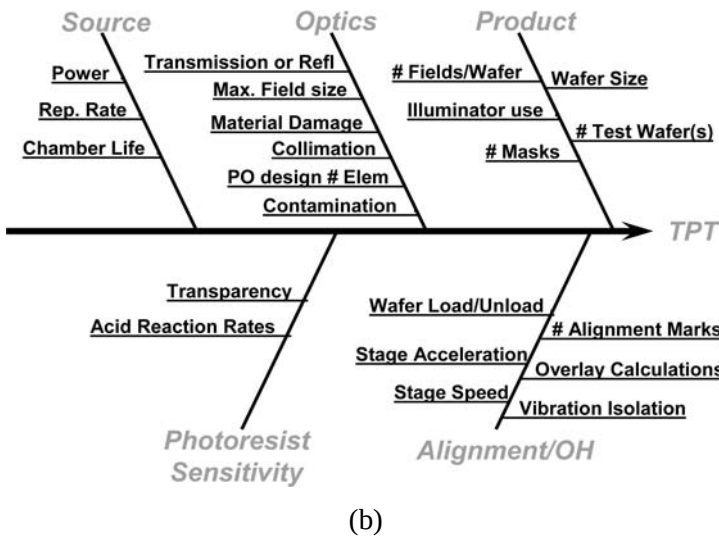
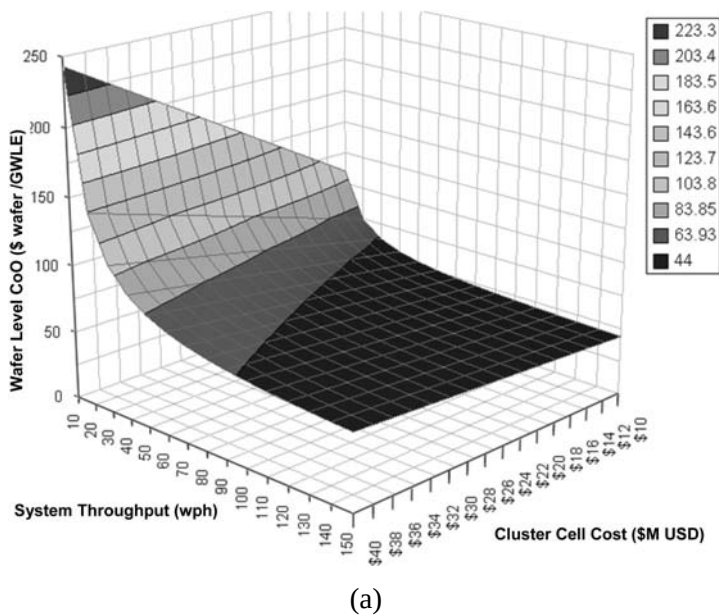


Figure 12.8 The effect of total exposure tool cell throughput on the overall wafer level CoO and what are the contributing factors to the exposure scanner or stepper throughput: (a) shows sensitivity CoO analysis based on the earlier Metal 1 100-nm MPU exposure level baseline case. (b) shows that the source power, optics transmission, IC product requirements, photoresist sensitivity (i.e., photospeed), as well as the stage performances all contribute to overall exposure tool throughputs.

m_s = stage movement time in seconds from previous field to the next field,
 e_t = exposure time per field in seconds (time needed to expose photoresist),
 a_f = any field alignment time in seconds needed per field prior to exposure,
 $w_{l/ul}$ = time for wafer loading and unloading in seconds,

a_w = global alignment time of the wafer in seconds,
 a_m = alignment time needed for the mask in seconds for each wafer or mask exchanges, and
 w_{OH} = any additional wafer overhead in seconds.

12.3.2.1 Stage speeds and accelerations with photoresist speeds as wafer throughput influences

Both exposure tool suppliers and photoresist suppliers have been able to incrementally improve the efficiency of their products to improve IC fab exposure productivity while maintaining or slightly improving yield. Photoresist suppliers present a special case due to the complex relationship between maintaining photoresist imaging fidelity (CD control and line edge roughness [LER]) and photospeed. Depending on the type of photoresist polymer and photo acid generator (PAG) chemistry, there is a direct inverse relationship between improving photospeed and maintaining adequate feature CD control with good LER control. Most of the critical-level production photoresists for 248 nm and 193 nm have photoresist speeds in the range 10 to 40 mJ/cm². For less-critical levels utilizing I-line exposure, the I-line photoresist speeds are slower, averaging about 150 to 200 mJ/cm².

For the exposure scanners or steppers, overall TPT can be improved by designing stages with faster travel and higher acceleration to reduce the overhead times needed to step and scan the wafer field to expose the photoresist. Current leading-edge exposure tools operate at a 4× demagnification, in which mask images are 4× larger than printed features. In these scanners the wafer stage scan velocities are 50 mm/sec at an acceleration of 1.5 G and have precision calibrations with the mask stage that operate at 4× the velocity of the wafer stages (i.e., scan speeds of 200 mm/sec and accelerations of 6.0 G). Figures 12.9(a) and (b) show the sensitivity analysis of the overall exposure tool wafer TPT as scan speed, scan accelerations, and photospeeds are varied.

12.3.2.2 Exposure tool wafer throughput impacts with laser source power and wafer overhead times

Two other major influences in overall lithography exposure tool CoO are the available source power and time spent aligning the wafer to the mask with the optical system. DUV excimer laser source power and laser pulse repetition rates have been improving over the years, and today commercial suppliers are able to offer higher power sources of 60 W or more for 193-nm systems. In the early 1990s laser sources for 248-nm DUV and 193-nm lasers were as low as 5 to 10 W. Wafer overheads also have been systematically reduced over the years to allow more productive time while delivering exposure energy to the photoresist at the wafer and limiting lost time due to wafer loading and unloading or alignments. Figure 12.10 shows the effects on overall system TPT of increasing laser power or reducing wafer loading and alignment times.

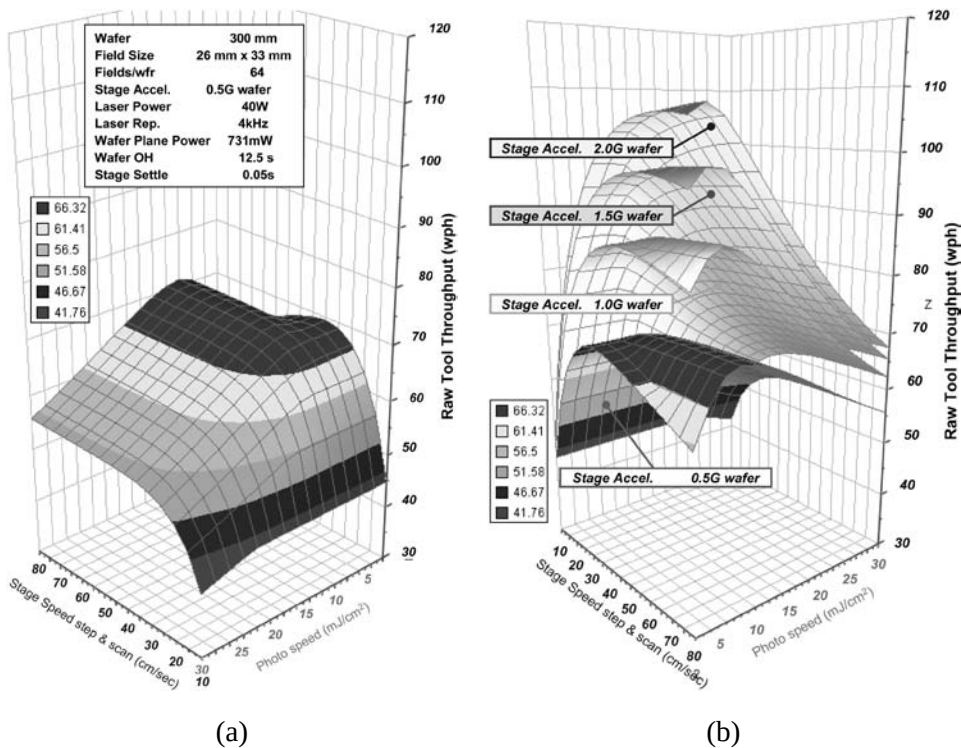


Figure 12.9 The overall exposure tool throughput variation with wafer and mask stage scan speed and accelerations compared to photoresist sensitivity: (a) shows response curve using the baseline assumptions but at a 0.5 G acceleration. (b) shows larger TPT gains if stage accelerations are increased. Stage acceleration increases can provide moderate throughput gains when photospeeds are less than 25 mJ/cm².

12.3.3 Exposure level product requirements (yield, send-aheads, and rework)

An often overlooked parameter for lithography CoO is the complexity of the IC product being manufactured and the required process measures needed to check current tool settings. In order to maintain reasonable yields, IC fabs often implement sample test runs on a single wafer and measure the results before committing the lot or multiple lots to exposure. In this process, termed a “send-ahead” (SAHD), one wafer is sent ahead and processed in the lithography cell and then inspected on critical performance metrology tools to verify whether CD control, overlay performances, or defect levels have been met. Although this is a fairly good process-control measure, it takes time to send a single wafer through the exposure tool cell. Also, the tool cell must remain idle until metrology inspection is completed and the operators or technicians determine if the wafer level performance is adequate. If the wafer metrology results are poor, then extra time is required to either make small process recipe changes or to hold the lot and run other product levels. This can add more idle time while the process modules are stabilized if temperature set-

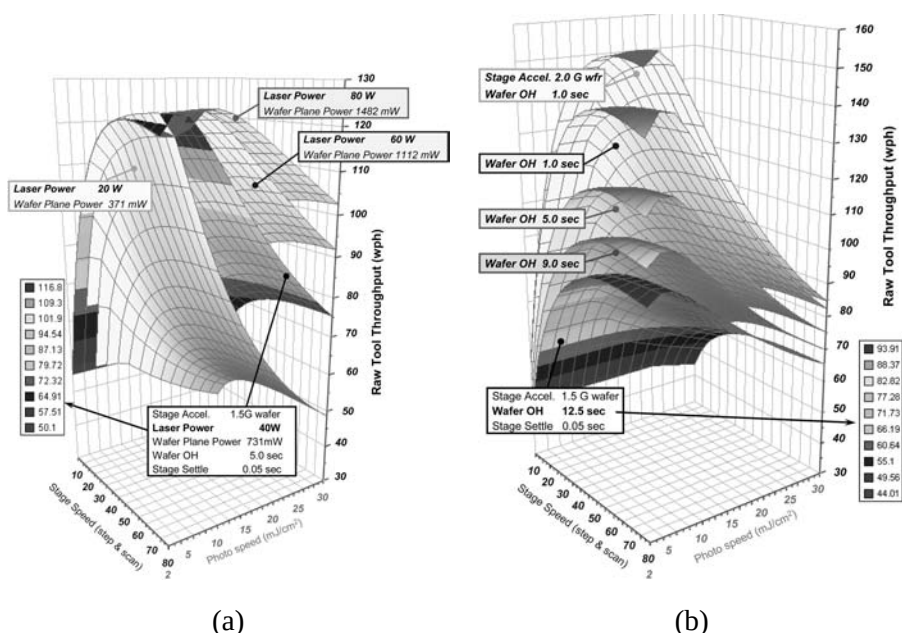


Figure 12.10 The overall exposure tool throughput variation with (a) laser source power levels and (b) reduction in wafer stage overheads. Current 193-nm laser sources are being offered at 60 W power. Current exposure scanner suppliers have optimized stage designs to support lower than 5.0 sec overhead times per wafer.

tings on the photoresist bake plates must be changed. Figure 12.11 shows the effect of the number of SAHDs used per number of lots processed, and the “mean time to test” (MTTT) of the SAHD as an impact to overall CoO.

The most dramatic impacts to CoO, which may be very dependant on the IC product level complexity, are yields. In general, yields tend to be lower for more immature products or the more critical IC levels in the product flow. Since yields have such a dramatic effect on CoO and overall profitability, oftentimes individual wafers or whole lots are sent to rework the layer that was just completed. When deciding whether to rework a layer, the operators, technicians, or production engineers need to balance the costs of reworking the level against the estimated gain in yield and the added value of the wafer product at that process level. Figure 12.12 shows the effects of yields, rework costs, and total lost product levels on the value level of the wafer product to that point.

12.3.4 DUV source consumables and running costs

In the early to mid-1990s, laser-based sources were introduced for production beginning with 248-nm excimer systems. Consequently, overall lithography CoO levels increased over the much-simpler mercury arc lamp broadband sources used in G-line, H-line, and I-line exposure tools. Since both 248-nm and 193-nm excimer laser sources have increased power levels, with power reaching 60 W, the cost to

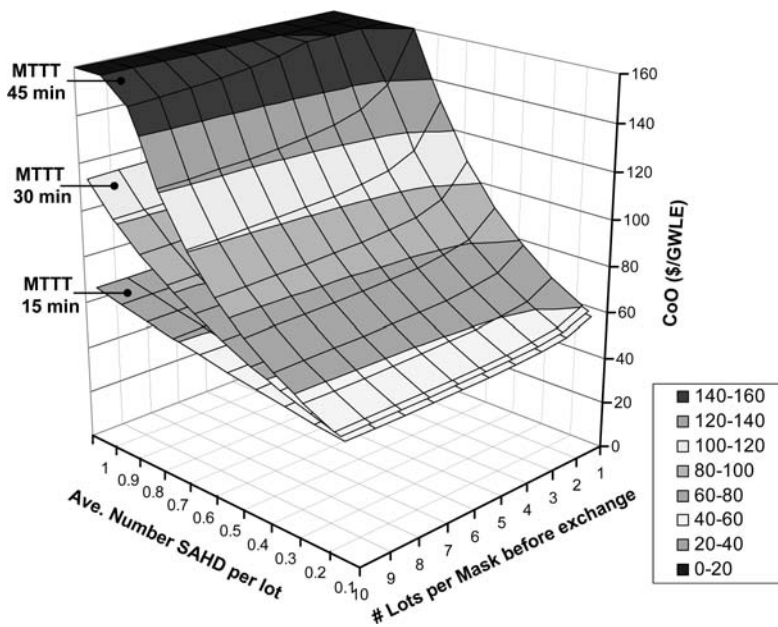


Figure 12.11 The CoO increases for longer wait times while a SAHD wafer is being analyzed compared to the number of lots processed before a mask exchange is preformed.

maintain these sources for maximum exposure tool productivity is not trivial. With high-volume exposure tools operating at >100 wph and sources operating between 4 and 6 kHz, excimer laser production can easily reach a total of 10 to 15 billion pulses per year, delivering hundreds of pulses per exposure field depending on the field size. In optical lithography systems, the source often includes all of the components and beam-delivery optics along the path to the exposure tool. The procurement costs of these sources are generally included in the exposure tool scanner costs and can reach \$1.5 to \$2 million per source system for a leading-edge 193-nm system. Annual maintenance and replacement costs of the source components, often referred to as “running costs,” can total \$250,000 to \$500,000.

Among the highest costs for the DUV laser sources are the replacement costs for laser tubes whose gas-charging efficiency degrades with use. Almost all of the laser components are rated by the supplier in pulse count levels. Those exposure systems that are running at near-maximum TPT at high tool utilizations tend to have higher running costs as pulse counts increase. Laser suppliers also rate their laser systems in operating costs per billion pulses as a metric. This cost can range from \$25,000 to \$35,000 per billion pulses depending on the complexity of the laser source. Many of the beamline optics and laser windows need scheduled replacement due to the very high 193-nm fluencies that cause material damage through increased absorption centers or compaction. For the baseline case developed in Sec. 12.3.1, the high throughput 193-nm exposure tool cell laser source system running costs were calculated to be \$550,000 per year to operate. This is based on 7470 wafer starts per week with 64 fields per wafer, which must ex-

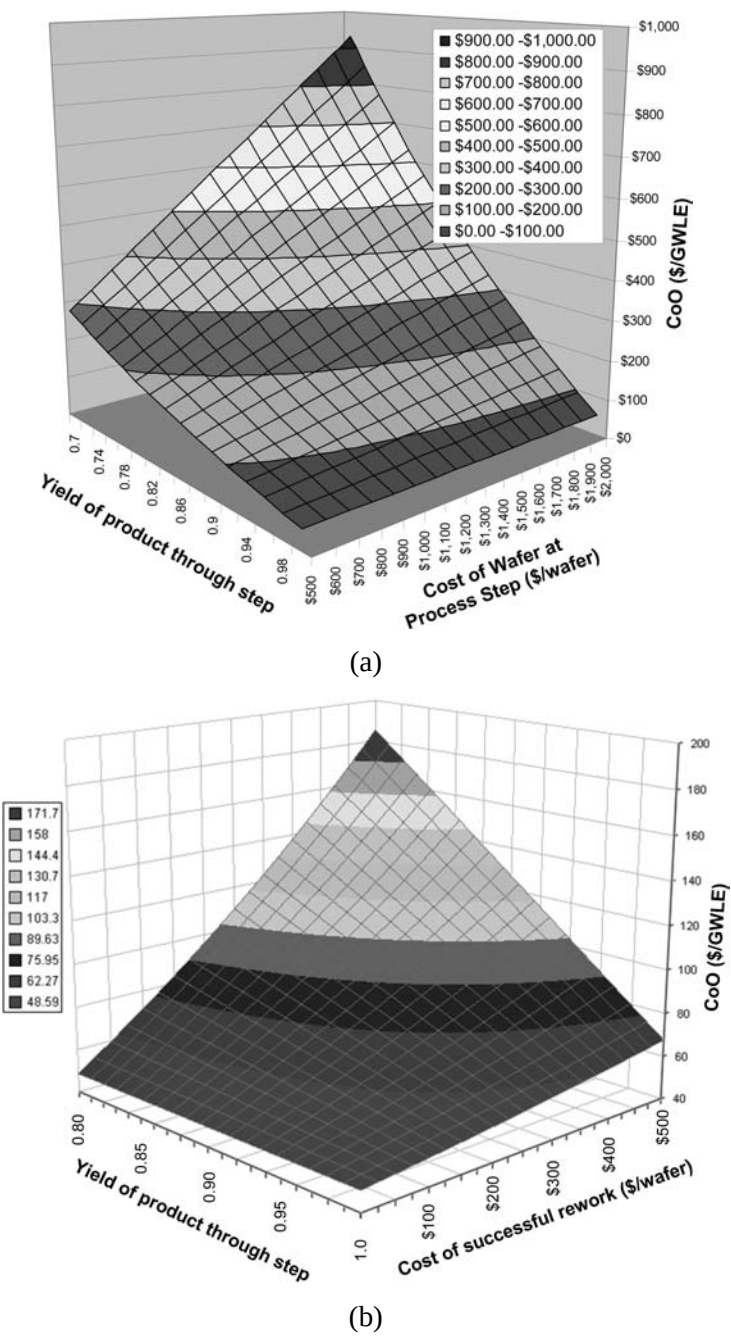


Figure 12.12 The effect of yield, cost of rework of that IC product level, and the value of the wafer at that point in the manufacturing process to overall CoO: (a) shows yield impacts are significant even at lower product values. (b) shows the value of lower rework costs to the overall CoO.

Table 12.7 Example of running costs for the 193-nm laser source in the baseline case for the 100-nm Metal 1 CoO assumption. The use of 14.18 billion pulses per year drives the \$550,000/year cost.

Item	Value	Replacement period (per billion pulses)	Replacements per year	Comments
Source capital cost	\$2,000,000	n/a	n/a	laser + new starting chambers (3)
Source and beam delivery unit footprint (\$/sq. ft.)	\$30	n/a	n/a	chase + subfloor footage
Laser chamber oscillator	\$50,000	5	2.84	rotating refurbished tube cost
Laser chamber amplifier	\$50,000	5	2.84	rotating refurbished tube cost
Chamber windows/mirrors (front/back)	\$25,000	7	2.03	replacements
Line narrowing module/components	\$30,000	7	2.03	replacements
BDU components/couplers/other	\$15,000	5	2.84	replacements
Abatement/F2 trap – scrub	\$10,000	10	1.42	replacements
High-purity gas charge mixtures (\$/cylinder)	\$2,000	0.015	926 charges	replacements
Other consumables/filters	\$15,000	10	1.42	replacements
Laser service contract (yr)	\$75,000	n/a	n/a	annual maintenance contract
TPT (300-mm wph)	112.12	n/a	n/a	
Wafers exposed/week	7470	n/a	n/a	
Replacement cost per year	\$548,298.46	n/a	n/a	
# 10 ⁹ pulses per year	14.18	n/a	n/a	
Laser running cost per billion pulses	\$38,654.58	n/a	n/a	

pose 10 mJ/cm² photoresist over 52 weeks of operation. This roughly translates to about 570 laser pulses per field. Therefore, several replacement cycles are needed for many of the components in the source. Average commercial laser source information and estimated replacement costs are shown in Table 12.7.

12.3.5 Photoresist cost drivers and photoresist process complexity

Costs are incurred with the special chemicals used to produce the exposed images as well as the process equipment needed to deposit the highly uniform films with low defectivity and to develop the photoresists after exposures. The vary-

ing complexities of the photoresist imaging systems used, whether I-line Novolak-based systems or DUV CAR systems, cause photoresist processing costs to vary significantly depending on the feature size and type. Multiple-level photoresist processes can help improve imaging fidelity, but they add complexity and costs. DUV photoresists, which employ CAR, need special environmental controls to filter out latent acid that can cause premature chemical diffusion in the photoresist. The use of special activated-charcoal filtration units is required, especially over the photoresist processing track. In addition to the photoresists, additional ARC films are used to suppress the standing waves created in the exposed photoresist films due to the wavelength reflections off of the wafer surface. Most often these ARC films have different chemistries than the photosensitive photoresists and need a dedicated patterning or etching step to remove the unwanted ARC. The amount of photoresist materials used to uniformly spin coat onto the wafer is between 2.0 and 3.0 ml per 200-mm wafer coat and between 3.0 and 4.0 ml per 300-mm wafer coat.

Photoresist costs have scaled in proportion to the exposure technology as the exposure tool costs have increased. At the time of technology introduction, production-worthy 193-nm photoresists ran as high as \$8,000 to \$10,000 per gallon. Usually photoresist costs are higher in the first year of technology introduction. As the chemistry processing improves and supply volumes increase, photoresist chemistry manufacturing improves and usually decreases in cost for the same photoresist chemistry product. Current 193-nm photoresists can cost as much as \$4,000 to \$7,000 per gallon, 248-nm photoresists can cost as much as \$1,500 to \$2,500 per gallon, and I-line photoresists can cost from \$500 to \$700 per gallon. In general, the photoresist costs will increase for customer-specific performance and can even vary for specific applications. Most photoresist suppliers have several product variations within the same product family, where one formulation may be optimized for IC gate features, another for contact or via patterns, and another for metal layers. Each formulation has its own chemistry manufacturing requirements and different costs.

The photoresist itself is a cost consideration. As an example, a modest 193-nm DUV photoresist that costs \$3,000/gallon and uses 3 cm³ to coat a wafer will cost \$2.38 per wafer alone. However, additional costs incurred for processing the photoresists are attributed to the track equipment or additional equipment for ML photoresist etching. Some of the major operating costs for photoresist tracks are described here:

- *Photoresist coater modules:* These process modules coat the wafer with photoresist or ARCs and remove the edge bead of the photoresist. These modules are generally wet processes in which consumables such as photoresists, ARCs, and edge bead solvents are expended. More solvent may be employed to reduce the amount of photoresist needed to coat the wafer. Additional solvents are required for periodic coater bowl cleaning so that excess photoresist does not build up and cause particle contamination on the wafer. All of the expended photoresists, ARCs, and solvent wastes require hazardous waste

disposal costs. Usually photoresists and ARCs are incompatible at the liquid stage and require the application of separate coater bowls. The precision photoresist dispense pumps require periodic replacement of filters.

- *Developer modules*: These process modules develop the post-exposure wafer to remove the unwanted exposed photoresist materials. The bulk of the consumables for this wet-processing module is the developer chemistry that can consume as much as 90 cm³ per wafer development step (utilizing single- or double-puddle developer). These developer chemistries are usually aqueous-based so waste disposal is not as costly as that of the solvent photoresists or ARCs. Additional ultra-pure water is another consumable within this module. The precision developer dispense pumps require periodic replacement of filters.
- *Vapor prime module*: These modules are modified hot or bake plates that drive off water molecules to enhance the adhesion performance of the photoresist. HMDS chemicals and higher wafer temperatures are expended to drive off the water species on the wafer prior to photoresist coatings.
- *Chemistry delivery cabinet*: The chemical bottles or packages are usually integrated into a storage and delivery unit located either in the process bay chase area or less-clean gray floor space area. Pre-filters for all of the chemicals must be replaced frequently.
- *Ammine control and HEPA local filtration*: As mentioned earlier, many DUV photoresist chemistries employ chemically amplified photoresists in which the initial acid is generated through the excimer laser energy on the photoresist. Further acid diffusion occurs into the photoresist film to complete the cross-linking reactions. These types of photoresist are very sensitive to any background airborne ammine and ammonia (as low as ≤ 10 ppb) that would cause premature acid catalyzing of the photoresist film, causing “T” topping. To protect against this expense, activated-charcoal filtration units are used. Annual maintenance is usually required, but an accidental local acid chemical spill or release could render the activated charcoal filters totally useless. Replacement of the filter units is expected and can cost \$1,000 per panel section. Depending on the track area needing protection, there can be up to 12 filters per system. Localized additional particulate air HEPA filter controls over the track may be used depending on the fab design; therefore, periodic replacement of the HEPA filters is required.

12.3.6 Reticle cost drivers

SEMATECH has made significant assessments of manufacturability costs for lithography masks, including detailed mask CoO models. The impact of overall wafer CoO on the use of masks is dictated by Eq. (12.1b), which is simply the cost of the mask amortized over the usage lifetime in number of wafers. Another large impact of wafer CoO due to the mask is any increased yield loss due to poorer mask quality with respect to CD, image placement, and defect levels that cause wafer

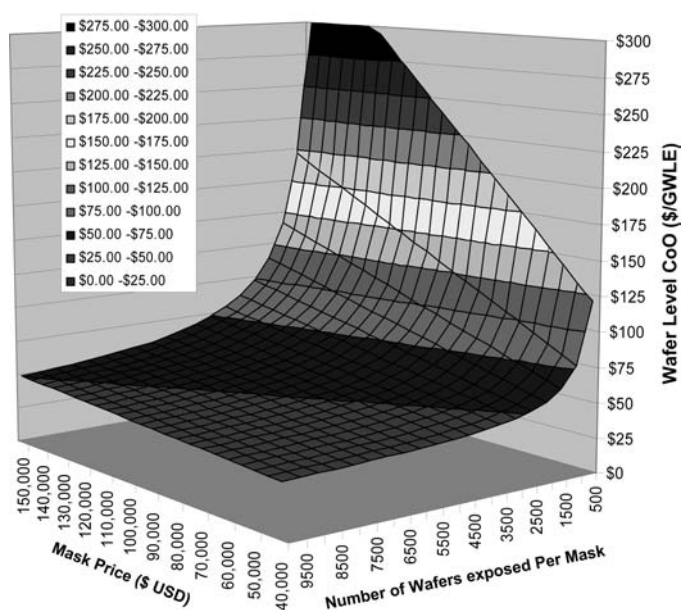


Figure 12.13 Overall effect of wafer level CoO impact as a function of reticle cost and wafers per reticle usage.

or die loss. Additional mask costs are incurred with needed servicing, including mask cleaning, mask repair, pellicle repair, and other storage overhead costs. Figure 12.13 shows the overall impact of mask cost and usage to wafer-level CoO.

Many factors determine the overall costs of lithography reticles, which can result from the mask technology being utilized (BIN COG, Alt. PSM, Att. PSM, etc.) and the complexity of the mask design. This chapter cannot address all of the possible impacts on mask costs and overall complexity. Articles by A. Balasinski and M. Mason are excellent references for this topic.^{23,24} The cost drivers relating to the mask technology type used are usually determined by the cost and quality of the materials and the process steps needed. COG masks utilize cheaper binary chromium (Cr) on high-purity fused silica (HPFS), where a ready-to-write blank can cost \$1,700. An Att. PSM ready-to-write blank that utilizes thin films of chromium-oxygen-nitrogen (CrON), molybdenum-silicon (MoSi), zirconium-silicon-oxygen (ZrSiO), or calcium (C) can cost \$4,500 to produce the weak transmission and phase-shifting properties. Although Att. PSM and Alt. PSM masks allow significantly higher printing resolution capability than BIN chrome on glass (COG), this capability comes with an increased manufacturing cost as well as potential exposure tool throughput limitations if a double-exposure Alt. PSM is followed by a BIN COG “trim” mask. Alt. PSM masks usually need two separate mask-writing steps: one for the CDs at the 0-deg plane followed by a second writing step for the ± 180 -deg plane to create the phase-shift effect. Tri-tone Att. PSMs employ an additional Cr absorber layer on top of the attenuating material to add

resolution with improved CD control, but they need additional processing for the Cr patterning and etch with tight IP control.

In addition to the mask technology type, the mask feature complexity will significantly impact the overall mask cost. Mask-patterning systems that utilize either e-beam direct writing or laser writing play a major role in the cost. Current leading-edge e-beam mask writer tool costs are reaching \$3,000 per hour of write time; some critical-level masks can take as long as 10 to 14 (or more) hours to write. Write time costs usually account for up to 50% of the overall mask cost compared to 20% for inspection costs, 20% for material costs, and 5% each for data prep time and pellicle costs.²⁵ Write time and inspection cost percentages of the final mask cost can vary.²³ As subwavelength optical lithography imaging has progressed, the write time for BIN COG has increased dramatically to compensate for the added assist features that are required when operating at low k_1 regimes. Spence et al. estimated that the needed writer “shot” (pixel) count increased at $2.5\times$ per IC generation.²⁶ The number of shots or pixels needing to be written has increased between 2 and 4 times per technology node. Table 12.8 shows the general trends over the past several IC feature-size generations for mask complexity and related mask cost drivers.

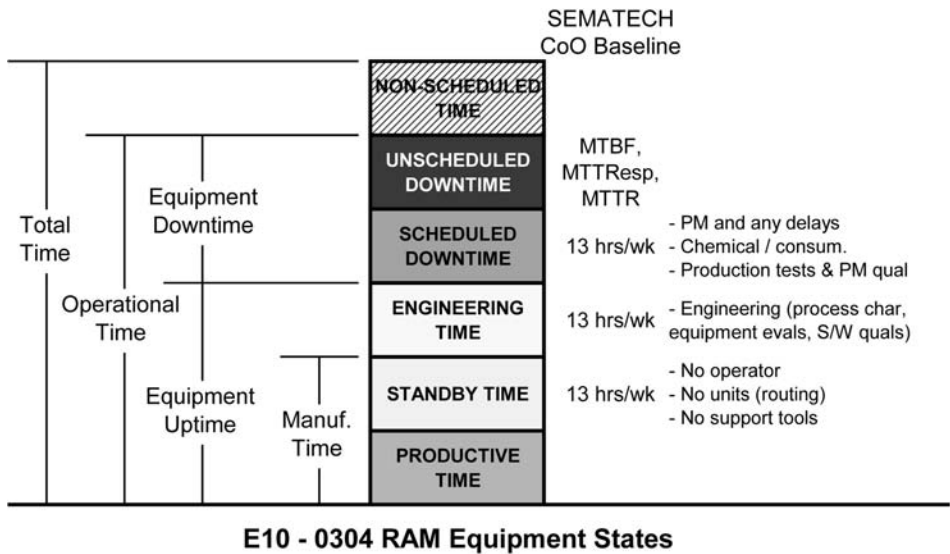
12.3.7 Lithography cell equipment reliability, availability, and maintainability (RAM)

The IC manufacturing must support the tools within the fab so it can run at the highest utilization possible while maintaining high yield, which can significantly reduce the overall wafer-level CoO. Tools that exhibit higher reliability and availability will help produce wafers with greater yield, thus reducing wafer costs. However, since IC production tools are often very complex systems, users must schedule PMs and continually monitor the system product quality. PMs help to maintain the system yields and guard against more frequent system failures. The industry has adopted several standardized conventions on process tool reliability and overall equipment effectiveness. One of these convention systems, called equipment “reliability, availability, and maintainability” (RAM), is fully described by the E-10 SEMI standard.²⁷ Clear definitions of mean time between failure (MTBF), mean time to repair (MTTR), equipment uptime, equipment productive time, and various other “states” are defined. Figure 12.14(a) shows the appropriations of such times as a portion of overall available time. A sizable component of either scheduled downtime or engineering time is shown in Fig. 12.14(b) for the typical tests and times that are needed to complete the qualification tests for an advanced lithography exposure tool.

Additional effectiveness standards conventions for IC process equipment manufacturing are identified through the SEMI E79 standard, which further defines productivity metrics for process tools.²⁸ Whether one adopts SEMI E10, E79, or both methodologies, it becomes fairly clear that any tool suffering from lower utilization rates for any reason is less cost-effective, which makes the product more

Table 12.8 General mask complexity increase over time with average mask cost impacts.

IC design rules	250-nm HP mask feature	180-nm HP mask feature	130-nm HP mask feature	90-nm HP mask feature
Lithography k_1 factor	0.68–0.75	0.60–0.68	0.50–0.60	0.40–0.50
Desired IC contact feature on wafer				
Representation of needed OPC/RET mask layout to print a contact feature at the node size (Generalization of feature layout)				
Type of mask OPC used and methods	Target reticle size adj., simple iso./dense bias	Rule-based OPC sizing iso./dense bias; use of line extensions, hammerheads, and serifs	Rule-based OPC iso./dense bias; hammerhead and serifs; model-based OPC poly; sub-resolution assist features (SRAF); Att PSM for poly or vias	Majority model enhanced OPC; hammerhead and serifs; SRAF; use of scattering bars; Att. PSM for via; Alt. PSM for poly
Average mask file size for die field	0.35–1.0 GB	1.0–8.0 GB	≤15.0 GB	≤50.0 GB
ITRS full-field maximum file size	10.0 GB	60 GB	100 GB	200 GB
Nominal leading-edge mask write time	4–5 hrs	4–6 hrs	7–10 hrs	10–13 hrs
Typical leading-edge BIN COG cost	\$ 12,000	\$ 16,000	\$ 42,000 ²⁵	\$ 100,000 ¹⁹
Typical leading-edge Alt. PSM cost	\$ 33,000	\$ 45,000	\$ 70,000	\$ 118,000 ¹⁹
Typical leading-edge Att. PSM cost	\$ 24,000	\$ 42,000	\$ 65,000	\$ 124,000 ¹⁹



(a)

Representative Tool Qualification Testing

Qual. Name	Frequency		
	Shift	monthly	post PM
Autocal	X		X
Uniformity	X		X
Grating	X		X
Coater thickness			X
Stage accuracy			X
Overlay			X
CD uniformity			X
Focus		X	
Scatter		X	
Gas Fill	auto refills (tool specific)		
E0		X	
Coating particles			X
totals (minutes)	30 - 45	60 - 75	120 - 180

(b)

Figure 12.14 The impact of unproductive time needed to support lithography exposure cell systems in IC manufacturing: (a) shows that unscheduled (system failures), scheduled, engineering, and standby time takes away from product exposure productive time. (b) shows representative qualification testing and times needed to re-qualify the system after shift changes or scheduled PM.

expensive to manufacture. However, nonproductive time is essential for many reasons, two of which are to perform routine PMs and to run certain experiments to validate new products, system upgrades, or process improvements (all considered “engineering time”). An optimum amount of engineering time is needed for quality improvement cycles on existing product or process learning for test products that are scheduled for future production. Figure 12.15 shows the effect on CoO from several nonproductive events that lithography exposure tool cells experience. For the baseline case example in Sec. 12.3.1 that uses the 100-nm Metal 1 level, the assumption of 13 hours per week is attributed to scheduled downtime, engineering time, and standby time. These RAM states essentially have a near-linear relationship to increase CoO, as shown in Fig. 12.15(a), where an increase in 1 hour/week of engineering time or scheduled maintenance increases the wafer level CoO by about \$0.19 per GWLE for the baseline case.

System reliability and repairability have a strong impact on overall wafer-level CoO, as shown in Fig. 12.15(b). Exposure tool cells with MTBFs lower than 200 hours tend to suffer from large CoO increases. If both the MTBF and the time to recover MTTR are long, the impact on CoO is compounded because unscheduled failures occur more frequently and longer repairs significantly inflate the nonproductive time. Equipment suppliers now develop and market process tools with MTBFs of 1000 hours, which the IC manufacturers demand to increase utilization. A lithography exposure cell’s total MTBF will be a reliability product of the photoresist process track, exposure tool scanner, laser system, and any additional automated material handling systems. For higher-capital process tooling such as lithography systems, the ability to respond quickly to system issues and failures to minimize reaction time and repair times is pivotal. Therefore, IC fabs routinely operate with on-site supplier field service engineers or local supplier field service centers to reduce response times.

12.4 General Observations on Lithography Cell and CoO Improvements (Past Decade)

The lithography community has continued to improve CoO in many areas. Almost every sector within the lithography supply chain has provided significant productivity improvements over the past 10 years. Although the critical-level wafer exposure CoO has generally increased for both IC feature size and exposure technology, the dramatic increase in device feature size (packing density) over larger areas (increased wafer sizes) with reasonable yields has more than offset these increases. This section will list the major sectors within the lithography community and some of the improvements seen over the past decade that have manifested lower effective CoO per IC function.

12.4.1 Exposure tool supplier CoO improvement factors

The exposure tool suppliers have driven resolution improvements as well as productivity gains, especially in TPT, while maintaining or increasing wafer yields.

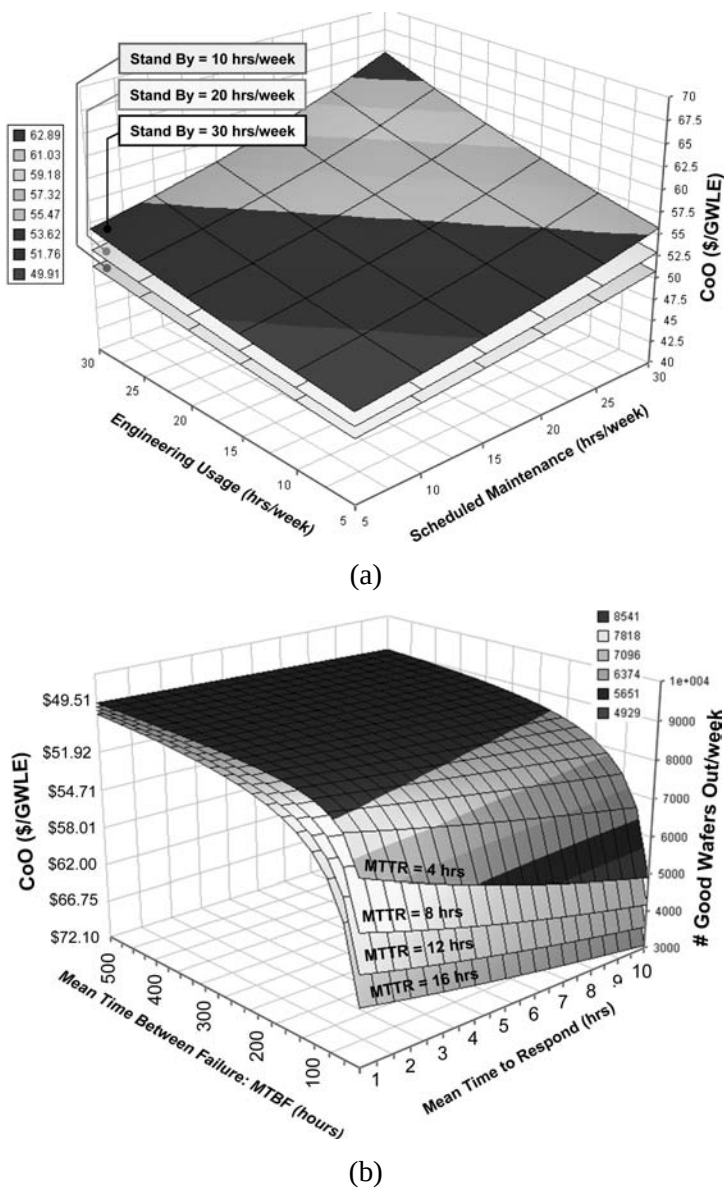


Figure 12.15 The wafer level CoO impacts due to various non-productive system events: (a) shows an almost linear effect due to the increase in lost time due to engineering, PM, and standby. (b) shows the significant impact in CoO with poor exposure cell reliability or time to repair.

With the combination of faster wafer and reticle stages, newer stage architectures, optical transmission improvements, and system setup or qualification reductions, system productivity improvements have been able to offset the annual average US\$1 million to US\$1.2 million exposure tool cost increase seen from 1995 to 2005.

- *Stage speeds and accelerations*: Significant improvements in stage speeds and accelerations have lowered both wafer overheads and exposure scan times. By 1995, wafer and reticle stage accelerations were 0.5 G and 2.0 G, respectively, but since then they have increased three-fold: currently they are at 1.5 G and 6.0 G, respectively, with reduced stage settling times. Current stage designs employ sophisticated, large counter-balance masses on the stage to reduce the acceleration and deceleration oscillations. Currently, some wafer stage scan velocities can reach 500 mm/sec synchronized with mask stages that can reach 2000 mm/sec.
- *Implementation of “dual wafer stages”*: In the past five years, wafer loading, unloading, and alignment overhead times have been decreased dramatically with the use of two wafer stages. The wafer stages work together so one is used to load, unload, and align the wafer before exposure while the other stage is already exposing the wafer. The stages automatically switch so that the pre-aligned wafer is under the exposure optical column. Stepper suppliers employ such strategies, termed “twin scan dual-stage,” for ASML platforms, and Nikon employs a similar strategy termed “tandem stage.” Wafer overheads have almost been eliminated while the quality of overlay alignment has increased with the use of two stages. ASML has stated that there is no TPT penalty in using an alignment registration of up to 16 marks.²⁹ Previously this number was 3 to 4 marks for single stages. This 4- to 5-time increase in registration mark alignments means greater overlay performance and higher wafer yields. The introduction of the two-stage system architectures was one of the most important factors for the lithography community to transition to 300-mm wafers and to attain 80 to 100 wph or more.
- *Improved off-axis illumination transmissions*: Although off-axis illumination (OAI) has been a resolution enhancement technique (RET) for many years, mainstream adoption of the technique was slower due to the large exposure light loss using simple aperture stops to create annular, dipole, quadrupole, or other similar variations. Use of these aperture stops decreased TPT as much as 30 to 50%. Now exposure tool suppliers have designed and employed OAI focusing systems that are an optical subsystem able to use the full exposure light energy and refocus it into the desired OAI configuration. Some light is lost due to the additional transmission OAI focusing system, but it is a much lower energy loss than the previous generation of simple aperture stops.
- *Improved system qualification testing*: Exposure tool suppliers have reduced the time required to re-qualify the tools or run shift monitor wafer tests with the use of special reticles and in-situ dose monitors that eliminate the need to expose, develop, and inspect wafers to determine dose to clear (E_0) and other tests. Such strategies reduce the engineering or scheduled maintenance E10 RAM states.

12.4.2 Optical laser source improvements

Within the DUV excimer laser source community (248 nm and 193 nm), both the overall average power and repetition rates have increased dramatically over the past 10 to 15 years. Around 1977, 248-nm excimer lasers for semiconductor use were introduced, and improvements by 1983 had provided systems with a 10- to 20-W average and repetition rates from 200 to 1000 Hz (0.2 to 1 kHz). The first 193-nm lasers were commercially available for lithographic stepper applications around 1990, with an average power of 3 to 4 W at 300 Hz. By 1995 to 1996, laser suppliers had a mature 248-nm laser and they introduced 193-nm lasers for high-volume production lithography 193-nm tools. Newer ≤ 1 picometer (full width half maximum) 193-nm sources were averaging 3 to 4 W at 1000 Hz, with chamber gas lifetimes of about 20 million pulses by 1996. By 2000–2001, krypton-fluorine (KrF) 248-nm excimer laser improvements provided 20-W average powers, operating at 2 kHz for 10 mJ/pulse. Within the same year, 193-nm lasers were also operating at 20-W averages but repetition rates increased to 4 kHz. By the end of 2006, 193-nm excimer laser system products reached 60 W with a 6-kHz repetition for 10 mJ/pulse. Currently, several suppliers now offer 193-nm excimer laser systems that can operate at 90 W with a 6-kHz repetition for a 15 mJ/pulse. The ability to deliver a higher frequency of laser energy has improved overall exposure cell throughputs over the years.

The laser source suppliers have also significantly improved gas lifetimes between gas refill changes as well as the lifetime of the chamber before refurbishing is required. The running costs for 248 nm and 193 nm have significantly decreased by a factor of 3 to 4 compared to their earlier generation systems. In the early 1990s, 248-nm running costs were as high as \$75k to \$80k per billion laser pulses. This was about the same level for 193-nm lasers when they were adopted in 1995. By 1995, 248-nm running costs were as low as \$25k per billion pulses, and today 193-nm laser running costs also have significantly decreased to about \$25k to \$30k per billion pulses.^{30,31} Much of the reduction in running costs has been attributed to innovative laser chamber and system designs that utilize dual chambers with master oscillator–power amplifiers (MOPAs) compared to earlier single-chamber systems.

12.4.3 Photoresist and photoresist processing

Photoresist chemical suppliers have improved the resolution and image fidelity for their product lines over time. Costs for 193-nm photoresists have been reduced over the past ~ 5 years, from \$8k to \$10k per gallon in 2000 to \$3k to \$3.5k today. Incremental improvements to photoresist formulations have also decreased the level of defectivity associated with imaging photoresists, which translates to increased yields. With DUV photoresists that operate using CARs, the photopolymer cross-linking mechanisms are increased with photo acid generators (PAGs). Unfortunately, elevated airborne ammine levels will cause T-topping. Just a few

ppb of amines in the air could cause catastrophic wafer yield loss. The suppliers of the localized chemical filtration systems used by the stepper, photoresist track, and fab to reduce and eliminate the airborne amine levels have greatly improved the capture efficiency of their activated-charcoal filtration systems to operate at or better than 1 ppb amine levels. Events that took place in the early to mid-1990s of fab shutdowns and activated chemical filtration fouling caused by neighboring livestock farming or petrol-chemical facilities producing high levels of amines have been greatly reduced or eliminated with system protection improvements using these activated filtration systems. The purity of the photoresists within the track system at the dispense “point of use” has also been better preserved with technology advancements in membrane micropore filtration technology. Microbubbles and trace impurity levels have been significantly reduced with these newer membrane filters to reduce wafer defects and increase yields.

The photoresist processing tracks, which have always been configured to support maximum exposure tool throughputs, have also improved their system designs to handle higher scanners or steppers throughputs. Although the conventional wet coating and developing photoresist processes times have remained somewhat constant over time (30 to 45 seconds needed to spin coat wafers with photoresists and 90 to 120 seconds for wet development times), the parallel wafer processing and wafer routing architectures within the track have been improved to limit footprint increases. Track suppliers moved away from serial process modules of sequential prime, cool, coat, and soft bake to more sophisticated multiflow wafer tools. Track process module size reduction, as well as module stacking in the vertical direction and multiple-wafer transfer robotics, have greatly improved throughputs without a large footprint increase. Chemical usage within the process modules has been optimized, especially for the expensive photoresists. Implementation of improved dispense systems or solvent-rich wafer prewetting decreases the necessary amount of photoresist material dispensed to coat the wafers. Average photoresist consumption per a 300-mm wafer has decreased from 6 to 7 ml/wafer to 2 to 3 ml/wafer. Track suppliers have also been able to demonstrate photoresist dispenses as low as 1.0 ml/wafer over 300-mm diameters.

12.4.4 Reticle improvements

The efficiency gains in the mask industry have resulted largely from cost-containment strategies instituted by mask makers and mask users. Like the exposure tool costs, mask costs have increased from one IC HP node to the next node but at a much higher rate, as shown in Table 12.9. The higher costs have been attributed to greater assist feature densities with only marginal improvement in mask-patterning TPTs. Within the first year of manufacturing masks using new design rules, the total yield of a critical-level mask may be only 20 to 40%. Mask yields do increase after process and tooling development improvements within the second to third year, but by that time the next critical-level masks are at the next shrink. Another factor in the increased mask cost is the process and metrology

tool cost increases that result from meeting design rules for smaller feature sizes. Pattern-defect inspection tools can be equal to or even more than the cost of the mask writer.

Both mask makers and IC manufacturers have contained mask costs over the past decade using the following strategies:

- *Vector-shaped beam (VSB) and cell projection (CP) writer optimization:* E-beam mask writers are utilized for the most critical mask layers while a lower-cost/higher-throughput laser beam mask pattern generator is used for less-critical mask levels. Mask suppliers have adopted more VSB pattern generators versus raster scan e-beam systems. The VSB tools are much more efficient in stage movement overhead because much more time is devoted to actual exposure of the mask surface rather than rastering over unwritten areas while the blanker is activated, as is done in a raster tool. The use of CP pattern generators can also improve mask write time. Certain redundant mask features and levels are more conducive to CP writers, such as DRAM cells versus more-random logic feature layouts. DRAM mask costs can benefit by the use of CP on these repetitive patterns.
- *Mask specification optimization:* Costs can be controlled by identifying and optimizing the yield metrics that are the most important for any particular level. Mask prices can be reduced somewhat if defectivity within a certain localized area or CD control is not as important as image placement. Optimizing IP while eliminating the specification for either CD or defectivity can provide cost relief.
- *Reduce field size of masks:* Reducing the area and patterns to be written on the mask obviously reduces mask costs. Write-time costs of masks at \$3,000 to \$3,500 per hour for a mask requiring 10 hours of write time can account for over 50% of the total mask cost. The decrease in mask field size will help to bring down mask costs, but it will be at the expense of exposure-tool TPT reduction since the total exposure field is not being utilized.
- *Amortize costs over more wafers:* Many ASIC and foundry IC manufacturers will group multiple layers of smaller field sizes on the same mask. This is called “bussing” or “shuttling” in the foundry sector. By having multiple layers on the same mask, many more wafers will be used in the mask’s lifetime. Therefore, the total wafer-level CoO cost component of the mask term can be significantly reduced by the number of additional levels the mask may use. Each additional layer is a multiplier in the denominator of Eq. (12.1b).

12.4.5 Fab automation processing and yield controls

Since yield has such a dramatic effect on CoO and overall productivity in manufacturing, many systems and tasks once conducted by experienced operators, technicians, or product engineers have been replaced or enhanced through the implementation of the following automation, software controls, and software decision systems:

- *Automated recipe cascading*: Many process tools in the IC fab use automated software job setup and queue the changes to the product wafer level automatically. In the case of transitioning from one product lot (e.g., Poly) to another (e.g., Metal 1) system recipes and tool settings are automatically loaded into the process tool once the last wafer of the previous lot is finished. The term “cascading” refers to the ability of the system controller to seamlessly queue up multiple recipe changes one after another so the tool can “cascade” through job setups. Before this adoption operators or technicians had to spend time calling up recipes and loading them.
- *Automated material handling systems (AMHS)*: Fabs routinely implement AMHS with both wafers and with the lithography reticles. Automated carriers, which are usually elevated above the tools, transport wafers from one tool or process sector to the next, thereby reducing the need for operators to carry the wafers. This is especially beneficial in the 300-mm generation fabs where wafer front-opening unified pods (FOUPs) can be heavy. Reticle stockers are also implemented to store and retrieve the needed reticles at the time of use to the photo cell.
- *Automated integrated product scheduling (IPS) systems*: It is common for most of the larger wafer fabs to produce hundreds of different IC product lines at the same time. An improvement in overall equipment utilization is needed and a reduction in the lost “standby” time when a high-capital tool is ready to process wafers but no product has been delivered. IPS optimizes the product flow to the available process tools to increase productive tool time.
- *Knowledge-based automated process control (APC)*: The use of knowledge-based APC software systems improves overall wafer yields. APC utilizes the past performance of product lots or wafers to assess tool-to-tool differences. As an example, it is commonplace in fab lithography bays to match exposure tool overlays. Some combinations of exposure tools can produce lower overlay yields and are avoided on certain levels. The term “knowledge-based” refers to the increased learning that more statistical data provide as a product’s development progresses. APC systems apply complex decision criteria that can include “weighting” the statistical process control (SPC) data heavier for newer versus older SPC data, then routes certain products to certain tools based on current statistical process control performance levels to maximize yields. These systems are used for overlay (OL), CD, and other metrology process monitors. Many journal papers have been published that show the dramatic yield improvements and increased productivity using such systems.^{32–34} APC databases built in a fab can also rapidly increase yield learning on a newly introduced IC product that has levels, layouts, and requirements similar to other products. Measurable results—such as 50% improvements in product OL yields, exposure tool-to-tool OL matching reduced to <0.1 ppm, and CD control reduced to less than 2.5%—are examples of gains achieved from APC implementation.

12.5 CoO Considerations for Future Lithography Technologies

As new lithography technologies are developed to attain finer CD features and meet industry requirements (*ITRS*) for continued productivity gains, CoO will always be a key consideration of the technology. If the new technology is too expensive for affordable IC manufacturing, then the CoO will be cost-prohibitive for the industry. The most accurate CoO calculations that can be done are for current technologies operating “on the floor” with known performance, costs, and yields. But CoO modeling is very helpful to understand future technology operations and fab productivity. If new lithography technologies in development use subsystems or materials vastly different than those used in current optical lithography technology, some CoO assessments can be prepared based on assumptions that were made. CoO modeling for these technologies in development can identify areas to improve operations, system costs, and maintainability. This section will review some of the major items that can or will impact several of the future lithography technologies that are now under consideration.

12.5.1 193-nm immersion lithography (193i)

An extension of conventional dry 193-nm lithography is 193i, which utilizes liquid media (termed as high-refractive-index fluid) between the wafer surface and the final lens of the optical conjugate to dramatically increase the exposure effective NA. This technology already has early pilot line tools in use or being shipped by the major stepper suppliers to IC customers. The 193i technology is expected to meet the 45-nm HP 2009 roadmap requirements and potentially meet some 32-nm HP 2011 requirements. Many successful technical advances have occurred to enable pilot systems in the field, yet additional improvements are needed as well as an understanding of this technology’s potential limitations on extension capability to meet the 32-nm HP. With the introduction of a liquid media for increased effective NA, there are further issues that may impact the CoO attributes of this technology. Table 12.9 lists some of the CoO factors in comparison to current leading-edge 193-nm dry technology and provides brief comments on each parameter. The use of hyper-index fluids will increase depth of field (DOF) and exposure latitude (EL), thus providing gains in wafer CD control; however, some potential CoO effects for 193i include issues with increased potential of wafer defect printing and potential reticle cost increases to maintain far more stringent image placement for double patterning (DP).

12.5.2 Extreme ultraviolet lithography (EUVL)

The overall EUVL exposure tool technology has been amply described in other chapters in this book. Although EUVL has some similarity to optical lithography, there are significant differences that will or may impact this technology in manufacturing with respect to overall CoO and productivity. The overall system capital tool costs will be significantly more expensive than 193-nm dry systems since

Table 12.9 System parameters or subsystem factors that are or may be CoO impacts of 193i technology compared to 193-nm dry exposure technology.

CoO parameter	CoO effect vs 193-nm dry “+” = CoO increase, “−” = CoO decrease	Reason for impact/comments
Ultimate resolution	− −	High NA allows greater feature resolution, improves overall chip packing density.
Exposure system capital cost	+	Cost increase due to added high purity fluid delivery and wafer–optic column integration (first 193i systems list price ≤\$30 million).
CD yield	− −	Large improvement in DOF translates to higher focus exposure latitude and CD control → higher yield.
Stepper TPT	None to + +?	Minor TPT decrease due to fluid delivery and fluid mechanics (maintain fluid on wafer); if DP, large TPT reduction (30 to 40% less)—but two masks are needed.
Defect yield	+	Fluid purity and homogeneity levels within wafer–lens gap shows initial added defect levels (bubble, water mark, particles, micro-bridges); further improvements possible. ³⁵
Reticle cost for CD/IP control	Unknown (+/−)?	Hyper NA for 45-nm HP provides EL and polarization effects that can relax mask CD tolerances ³⁶ —but mask IP tolerances tightening by 2× may be needed for DP. ³⁷
Reticle cost for RET	+	General mask cost increase for assist feature increases to meet 45-nm, 32-nm nodes. ³⁸
Photoresist costs	+	Improvements to photoresist polymers needed to match high index properties. ³⁸

ultra-high-vacuum systems and expensive, large, precision reflective optics integration is required. Completely different EUVL sources are needed for either the discharge-produced plasma (DPP) or laser-produced plasma (LPP) approach and can be significantly more expensive than their 193-nm excimer laser source counterparts. Recently preproduction capital costs have been publicized to be more than \$50 million.³⁹ To reach cost-effective levels for post 45-nm HP use, there are two major challenges and additional lesser challenges for this technology. The first major challenge is overall system TPT, especially to offset the high capital costs. A 100+ wph production tool is needed, which will depend on having the ultimate source power during steady, long-term pulse counts, and EUVL photoresists that can provide the ultimate resolution at reasonable photospeeds to enable a high TPT but do so without yield impacts such as CD control and defect levels. The other ma-

jor challenge is for the industry to deliver cost-effective EUVL reticles. With the need for a reflective mask operating under high power fluxes of more than 6 W at the reticle plane, low thermal expansion materials (LTEMs) must be used in place of HPFS mask substrates. The added cost to provide defect-free MLs on the EUV blank will also challenge overall EUVL mask costs, as well as keep the finished mask clean from additional defects without the use of a conventional pellicle. There will be some areas of CoO relief for EUVL due to the much higher k_1 process margin factor of 0.5 to 0.7, versus 0.35 or less for 193-nm dry or 193i options. Mask costs will not be largely affected by added costs for the RET subresolution features on the mask because only mild to low OPC will be required. Also, the higher k_1 should help relieve larger CD yield hits compared to the 193 dry or 193i wafer patterning. Table 12.10 shows EUVL-specific CoO potential impact areas.

12.5.3 Maskless lithography (ML2)

Generally ML2 technology refers to the multiple approaches of using “direct writing” IC patterning without a conventional transmission or reflective photomask.^{40–42} With the use of e-beams, ion beams, or direct laser writing patterning, the photoresist can be written and exposed directly on the wafer surface. Thus, there are no large costs associated with photomasks for the use of ML2 technology. The optical mask-making community uses either e-beam or laser pattern generators to write masks. The general approach is to utilize similar charged-particle or laser energy at much higher TPTs to directly write the IC features on the wafers. To do so cost-effectively at the HVM IC fab’s tool, the TPT needs to be much higher than the one photomask per 6 to 12 hours used in mask houses. Such system designers have developed system concepts with huge arrays of micro-columns operating simultaneously to write small cell areas within the IC chip. The success of these types of technologies depends on the development of massive column arrays (some systems have thousands of micro-columns) to operate repeatedly and reliably without dropping data sections or miswriting features. Charged-particle versions of these systems will also suffer from particle interactions in close proximity as a function of current. The higher particle charges required for a higher TPT produce a repelling phenomenon termed “coulomb interactions” that can blur the charged-particle beams and impact the wafer CD. Table 12.11 lists some of the CoO impacts of ML2 technologies compared to 193-nm dry lithography.

12.5.4 Nanoimprint lithography (NIL)

NIL technology refers to the use of an “imprint” mold or $1\times$ patterned template to either imprint features on the wafer or imprint a UV curable media on the wafer to create the IC features.^{43–45} This technology is somewhat similar to the current technique used by the compact disc media industry, where micro-sized features are stamped into the compact disc and then cured. The potential CoO benefit is that the patterning system does not need any precision transmission optics, large surface reflective optics, or massive parallel charged-particle arrays. It relies solely

Table 12.10 System parameters or subsystem factors that are or may be CoO impacts of EUVL compared to 193-nm dry exposure technology.

CoO parameter	CoO Effect vs 193-nm dry “+” = CoO increase, “-” = CoO decrease	Reason for impact/comments
Ultimate resolution	- - -	13.5-nm wavelength drives better ultimate resolution to meet 45-nm to 22-nm HP. Greater IC packing density vs 193-nm dry. Currently 40-nm dense lines and spaces on alpha tool demonstrated.
Exposure system capital cost	+ +	Exposure tool and source cost larger increase, early alpha and preproduction tools $\geq$ \$50 million. Large reflective precision optics, high vacuum controls, and source costs drivers.
Stepper TPT	None to +?	>180 W long-term in-band power needed for >100 wph, ability for source community to meet ultimate cost-effective power requirements. 22-nm HP node may require even higher power sources for additional reflective surfaces to meet $NA \geq 0.35$.
System utilization	+ ?	Largely unknown due to optics lifetime, source maintainability, and consumables, and longer system pump down and other recovery times following PMs.
System operation	+	Expect higher operating costs due to source facility power, vacuum pumps, etc.
CD yield	-	Improved CD control due to much higher k_1 process (~ 0.7 to 0.5 vs 0.30 for 193i).
IP yield	+ ?	Reflective mask technology requirements and “as chucked” flatness can be an issue.
Defect yield	+ ?	Potential increased defect yield loss due to nonconventional mask pellicle solution.
Reticle material cost	+	Larger cost for substrate and ML-coated blanks could be 3 to $5\times$ vs 193-nm Att. PSM.
Reticle cost for RET	-	Mask assist features are greatly reduced vs low k_1 193-nm dry or wet mask RET needs.
Photoresist costs	+ ?	Largely still unknown, significant photoresist development to balance photospeed, LER, and ultimate resolution. Use of ultra-thin photoresist with hardmask will add costs.

Table 12.11 System parameters or subsystem factors that are or may be CoO impacts of ML2 technologies compared to 193-nm dry exposure technology.

CoO parameter	CoO effect vs 193-nm dry “+” = CoO increase, “−” = CoO decrease	Reason for impact/comments
Ultimate resolution	− −	Resolution capability of ≤ 20 -nm HP at very low currents. Greater IC packing density vs 193-nm dry.
Exposure system capital cost	−/+ ?	Largely unknown. Tools will not have expensive optical components but will have large quantities of massively parallel arrayed columns and data paths could effectively be just as expensive as 193-nm dry tools.
Stepper TPT	+ + +	<i>Author opinion:</i> ML2 TPTs have always been the major challenge for this technology. A system TPT of 10 wph or less may be the best TPT. Although ML2 tool developers have shown reasonable TPT scaling roadmaps, a > 1 wph TPT has never been achieved.
System utilization	+ ?	Largely unknown due to unproven production-scale operational reliability of massive parallel e-beam or other laser beam direct-write columns operating simultaneously.
System operation	−/+ ?	System consumables appear to be less vs 193-nm dry excimer laser sources.
CD yield	−/+ ?	Unknown in HVM. CD control can be very good at very low e-beam current levels, but CD control will be a factor of coulomb stochastic and chromatic blurs vs TPT.
IP yield	+	Large scale of subfield overlay or stitching required from micro-column to micro-column. Large potential of OL drift causing IP yield hits.
Defect yield	+ ?	Difficult to quantify reliability of micro-columns writing identically from cell to cell. Potential of miswrites or dropped data bits from all of the micro-columns.
Reticle cost	− − −	There are no physical mask costs and term Eq. (12.1b) is essentially zero. Some costs need a data fractioning GDS file structure to be compatible with ML2 data paths.
Photoresist costs	+ ?	Some photoresist developments are needed on the base technology of e-beam CAR photoresists. Photoresist optimization between photospeed, resolution at $1\times$, and defectivity needed.

Table 12.12 System parameters or subsystem factors that are or may be CoO impacts of NIL compared to 193-nm dry exposure technology.

CoO parameter	CoO effect vs 193-nm dry “+” = CoO increase, “−” = CoO decrease	Reason for impact/comments
Ultimate resolution	−/+ ?	Ultimate resolution capability in production unknown. 50- to 60-nm features demonstrated on development tools. ⁴⁵ 10-nm feature produced in research labs. ⁴⁶ Resolution limited to quality of 1× mask. Feature packing density may not be as great at 193-nm dry.
Exposure system capital cost	− −	System cost probably lower than 193-nm dry systems. No expensive optical POs or source maintainability issues. Clear potential for system with 3D templates to eliminate multiple exposure steps (such as replacing dual damascene processes).
Stepper TPT	−/+ ?	Ultimate TPT unknown in HVM. Dependencies will be on the alignment ability of the 1× template to the wafer fields and other potential in-situ process controls.
System utilization	−/+ ?	Unknown due to potential issues with 1× template overheads or system alignments.
System operation	−	System appears to have fewer consumables vs 193-nm dry systems.
CD yield	−/+ ?	CD control directly related to CD control of 1× templates and imprint media (UV curable photoresists) to retain edge fidelity. Greater linear mask-to-feature CD control.
IP yield	+	Overlay control may be complicated with unproven magnification control. Ability of 1× template to employ simple magnification, barrel, pin cushion OL control is an issue.
Defect yield	−/+ ?	Will depend on 1× template quality. Any small template defect will print, subresolution optical mask defects do not print (there is no defect bandpass optical filter). Some data show 1× templates are self-cleaning over time/usage.
Reticle cost	+ + ?	1× masks/templates always difficult to manufacture for full-field critical-level CDs. Conventional 4× mask pattern generators have difficulty meeting minimum feature size (MFS) of less than 100 nm on a 4× mask. 1× NIL template lifetimes are unknown.
Photoresist costs	− −	Imprint media or UV curable photoresist should have lower costs than DUV photoresists.

on the ability for a high-quality $1\times$ template to be accurately positioned and imprinted onto the wafer surface. Although an attractive feature of NIL is its potentially lower-cost tool with a reasonable overall TPT, the technology has some challenges in becoming widely accepted in HVM for critical-level IC manufacturing, such as unknown ultimate resolution capability and the cost-effective $1\times$ template manufacturing. Table 12.12 highlights some of the potential CoO impacts of NIL compared to 193-nm dry lithography.

12.6 Summary

The lithography community is a major contributor in supporting the overall IC productivity annual gains of 28%. The lithography cell CoO cost contributions have kept pace with supporting productivity gains that now reach about 0.06 μ cents/transistor for 90-nm HP devices. Yet lithography costs are reaching 40% of wafer costs and are consuming about 60% of overall wafer cycle time. How is this possible with lithography process tooling cost increases, reticle cost increases, and higher development costs? The answer has two parts that, coupled together, effectively lower the cost per function. The first partial answer is the straight-forward technical ability to image smaller features for smaller transistor features that operate faster due to the smaller features. This also helps to improve packing density (more functionality per area). The second partial answer is the lithography industry's ability to reduce image sizes at both reasonable yields and higher productivity because both are a component of wafer CoO.

This chapter has shown that wafer yields are the most influential parameter to CoO and productivity. What may seem to be a minor yield impact of 0.1% can translate to several hundred thousand dollars per year from one exposure tool cell. To the IC fab operations, yield often becomes an over-riding factor. The cost of the equipment toolset must be balanced between high wafer TPT and high tool utilization. This balance allows more of the system costs to be amortized over many more "yielded" good wafers, which drives down the CoO per wafer. System cost escalation may be absorbed if yield, TPT, and utilization could trade-off, especially now that exposure tool cells are reaching US\$30 million each or more. Mask costs and reduced mask usage have increased CoO significantly over the years and have even influenced IC layout designs and exposure system selections in low-volume, high-part-count ASIC IC fabs.

12.7 Appendix: Example Case Studies of Lithography CoO Calculations

The following example cases serve to further illustrate the effect of CoO impacts and potential improvements on operation costs, reduced CoO, or improved productivity. As a baseline CoO level case, the "Metal 1" CoO calculation will be used in hypothetical cases to demonstrate the effect of certain changes or decisions on overall CoO.

Table 12.13 Data for example case 1.

	Baseline case	Option 1: no TPT decrease	Option 2: 5% TPT TPT decrease
System TPT (raw)	112.1 wph	112.1 wph	106.5 wph
System cost (\$USD)	\$24.8 million	\$25.0 million	\$24.9 million
Scheduled maintenance (averaged hrs/week over annual period)	7	8.3	8.3
Level yield through step	98.0%	98.5%	98.5%
CoO (\$/GWLE)	\$59.44	\$58.29	\$58.82
# wafers yielded per day	1044	1037	1007
Cost savings per day	\$0.00	\$1,192.55	\$624.43
Cost savings per week	\$0.00	\$8,347.85	\$4,370.38
Cost savings per year	\$0.00	\$434,088.20	\$227,259.76

12.7.1 Example case 1: improved yield at expense of system cost and/or TPT performance

Situation background: An improvement to the CD performance of the Metal 1 layer has been studied. Device performance can be improved if certain features on the Metal 1 layer have better CD control. The engineering study shows that an effective 0.5% overall yield in the wafer level can result. The engineering team has received a cost proposal from the exposure tool supplier with two options for the OAI focusing system: one option will cost \$200,000 with no TPT decrease, and the other option is a \$100,000 system that decreases TPT by 5%. The system upgrades and a total tool downtime of three days are needed for both options.

Problem statement: Which of the system upgrade options will be most cost-effective? Or should the system be maintained until product lifetime ends?

Discussion: It appears that the more expensive upgrade option is more cost effective, and the CoO reduction savings for Option 1 would more than recoup the investment in six months' time based on wafer yield alone. In practice, the savings would probably be much more than in this case, because the fab would schedule the upgrade on top of a regular annual or quarterly system PM cycle so there would be almost no additional tool downtime. However, the implementation may be delayed by the ability to minimize downtime via increasing tool utilization by scheduling the upgrade with a regularly occurring PM cycle. This would improve Option 1 by another \$100,000 annual savings.

12.7.2 Example case 2: slightly improved laser source power at expense of specialty gas costs

Situation background: An excimer laser source supplier offers a brand-new modified gas mixture for the laser chamber tubes that will effectively increase the average power from 40 to 41 W. However, this comes with a 50% increase in gas

Table 12.14 Data for example case 2.

	Baseline case	+1 W at 150% gas cost and 90%	+1 W at same gas cost and lifetime (six months later)
Average laser power (W)	40	41	41
System TPT (raw)	112.1 wph	112.71 wph	112.71 wph
Gas mixture cost per canister	\$2,000	\$3,000	\$2,000
Gas charge pulse lifetime before re-injection	15 million	13.5 million	15 million
CoO (\$/GWLE)	\$59.44	\$ 59.41	\$59.39
# wafers yielded per day	1044	1047	1047
Cost savings per day	\$0.00	\$31.41	\$52.35
Cost savings per week	\$0.00	\$219.87	\$366.45
Cost savings per year	\$0.00	\$11,433.24	\$19,055.40

injection costs and the gas lifetime within the chamber is only 90% at the current gas mixture ratio. The laser supplier has also communicated that the new modified gas mixture costs and charge life will be improved to meet the current product cost and durations in about six months. Although there is an effective increase in energy per pulse, the laser supplier says that there will be no decrease in dose control.

Problem statement: Should the IC fab consider switching immediately to the more expensive gas mixture or wait until the supplier has reached the same costs and charge life that they plan to offer in another six months?

Discussion: It appears that either option will provide a cost reduction and an additional three yielded wafers per day. In this example, even an increase in gas costs at a slightly lower gas charge lifetime will provide some gains. Since the relative scale of the margin reduction is between \$0.03 and \$0.05, any small deviation from the original performance parameters should be reviewed carefully. In this case the production engineer may feel that either output increase or potential laser dose stability variations due to a gas mixture change may be too risky to transition to the new mixture.

12.7.3 Example case 3: product lots reroute to different tool vs lot hold

Situation background: A photocell tool has just gone down due to a system failure that impacted a critical product with tight delivery requirements. The product lots have a baseline yield of 98% through the Metal 1 step using the photocell that just went down due to having optimized tool-to-tool overlay matching from the APC knowledge base. It may be possible to re-route these product lots to another photocell in order to meet the product delivery, but yield may be lowered to 96%. The yield may be improved at or near the baseline 98% case by acquiring more alignment registration marks, but this will impact the tool TPT. The tool and production engineering staff estimate that an additional three alignment marks are

Table 12.15 Data for example case 3.

	Baseline case	Re-route lots through other tool at lower yield	Re-route lots through other tool using added alignment
Yield through the Metal 1 process level	98%	96%	98%
System TPT (raw)	112.1 wph	112.1 wph	104.2 wph
Number of global alignment marks per wafer	3	3	6
Global alignment time per wafer	3.21 sec	3.21 sec	5.65 sec
CoO (\$/GWLE)	\$59.44	\$65.89	\$60.30
# wafers yielded per day	1044	1023	1001
Cost savings (impact) per day	\$0.00	−\$6,598.35	−\$860.86
Cost savings (impact) per week	\$0.00	−\$46,188.45	−\$6,026.02
Cost savings (impact) per year	\$0.00	−\$2,401,799.4	−\$313,353.04

needed to bring the yield up to the original 98%. Due to the tight delivery timing, the product will need to move through the re-routed photocell.

Problem statement: Based on CoO analysis, should the additional alignment marks be implemented and the TPT reduction accepted, or should the lots be processed at the same TPT?

Discussion: Based on CoO impact, the results obviously support re-routing the lots to the other tool and adding the three alignment marks to preserve yields. This example illustrates how important yield can be. A simple 2% yield decrease in this case would mean close to \$2.5M in lost product annually. For this specific example, additional factors could affect the choice because the overall number of product lots represents the final product to the customer. In the case of a low-volume ASIC product, yield could play a more important role to maximize yield on the wafer because the total volume to the customer may be difficult to make up by running more wafer starts.

Acknowledgments

My gratitude to Heather and Evan for their support during the creation of this chapter.

To the many individuals who have added value to SEMATECH's lithography CoO: Paul Ackmann, Vivek Bakshi, James Beach, Karen Brown, John Canning, Will Conley, Patrick DeJager, Kim Dean, Giang Dao, Gary Escher, Gene Feit, John Frank, Gene Fuller, Brian Grenon, Gerhard Gross, Doug Guenther, Scott Hector, Dan Holladay, Kevin Kemp, Byrol Kuyel, Scott Mackay, Mark Mason, Gordon McMillian, Michael Lercel, Lloyd Litt, Ed Muzio, Shane Palmer, Victor Pol, Gra-

ham Pugh, Andy Rudack, Tom Seidel, Gil Shelden, Keith Standiford, Tony Tryba, Walt Trybula, Robert Wright, Stefan Wurm, and Tony Yen.

References

1. *International Technology Roadmap for Semiconductors, 2005 Edition*, Executive Summary chapter, www.itrs.net/Links/2005ITRS/ExecSum2005.pdf, Semiconductor Industry Association (SIA), San Jose, CA (1995).
2. K. H. Brown, "SEMATECH and the national technology roadmap: Needs and challenges," *Proc. SPIE* **2440**, 33–37 (1995).
3. *International Technology Roadmap for Semiconductors, 2005 Edition*, Lithography chapter, <http://www.itrs.net/Links/2005ITRS/Litho2005.pdf>, Semiconductor Industry Association (SIA), San Jose, CA (1995).
4. *Decision Tools for Productivity and Cost Management*, Wright, Williams & Kelly, Inc. (<http://www.wwk.com>), Pleasanton, CA.
5. *Guide to Calculate Cost of Ownership (CoO) Metrics for Semiconductor Manufacturing Equipment*, SEMI E35-0305, Semiconductor Industry Association (SIA), San Jose, CA.
6. P. K. Seidel and E. G. Muzio, "NGL and Optical CoO Analysis Update," 3rd NGL Workshop, Colorado Springs, CO (Dec. 1999).
7. E. G. Muzio and P. K. Seidel, "Mask cost of ownership for advanced lithography," *Proc. SPIE* **4066**, 73–83 (July 2000).
8. E. G. Muzio, P. K. Seidel, G. Shelden, and J. Canning, "An overview of cost of ownership for optical lithography at the 100 nm and 70 nm generations," *Semiconductor Fabtech* **11**, 191–194 (June 2000).
9. B. Kyrol, "SEMATECH Cost of Ownership Model," TTID: 91020473B-GEN, SEMATECH (1991).
10. Gross and Net Die Calculator, ICKnowledge (www.icknowledge.com), Georgetown, MA (2006).
11. G. Popham, DIE/WAFER Calculator Software Program, TTID: 94012165A-XFR, SEMATECH (Feb. 17, 1994).
12. R. Wright, "Equipment Case Studies," Economic Analysis Workshop, Arlington, VA 27, (May 2004).
13. R. Wright, "Total Wafer Costs—Industry Economic Model," IEEE Lithography Workshop, Vancouver, BC, Canada (July 27, 2004).
14. *International Technology Roadmap for Semiconductors, 1998–2005 Edition*, Lithography, Semiconductor Industry Association (SIA), San Jose, CA (2005).
15. S. W. Jones, *Die Size Trends*, ICKnowledge (www.icknowledge.com), Georgetown, MA (2000–2003).
16. A. Allan, "DRAM design rule/die size, 200 mm/300 mm wafer fab demand transition," in *The 1997 National Technical Roadmap for Semiconductors (NTRS)*, Semiconductor Industry Association (SIA), San Jose, CA (1997).
17. K. Kimmel, "Photomask supply partnership to optimize cost and value," *Future Fab Intl.* **14** (Feb. 2003).

18. D. Hutchenson, "VLSI's reticle forecast," *Autumn 2000 Yield Management Solutions Magazine, A Focus on Reticles* **3** (2000).
19. B. Grenon and S. Hector, "Mask costs, a new look," *Proc. SPIE* **6281**, 62810H (June 2006).
20. C. Spence et al., "Mask data volume—historical perspective and future requirements," *Proc. SPIE* **6281**, 62810H (June 2006).
21. W. Trybula, "Financial impact of technology acceleration on semiconductor masks," *Proc. SPIE* **4562**, 321–328 (2002).
22. W. Trybula, "A common base for mask cost of ownership," *Proc. SPIE* **5256**, 318–323 (2003).
23. A. Balasinski, "Optimization of sub-100-nm designs for mask cost reduction," *J. Microlithography, Microfabrication, and Microsystems* **3**(2), 332–331 (April 2004).
24. M. Mason, "The real cost of RET's," *Microlithography World* **12**(2), 8–20 (May 2003).
25. K. Rygler, "Photomask costs: damming the rising tide," *Future Fab Intl.* **17**, 75–78 (June 21, 2004).
26. C. Spence, et al., "Mask data volume—explosion or damp squib?" *Proc. SPIE* **5992**, 599211 (2005).
27. *Specification for Definition and Measurement of Equipment Reliability, Availability, and Maintainability (RAM)*, SEMI E10, Semiconductor Industry Association (SIA), San Jose, CA.
28. *Specification for Definition and Measurement of Equipment Productivity*, SEMI E79-1106, Semiconductor Industry Association (SIA), San Jose, CA.
29. P. Alibrandi, "Exposing the Limits of ArF Lithography," DNS Lithography Breakfast Forum (July 15, 2003).
30. R. Patzel and V. Pfeufer, "The new generation of excimer lasers for subquarter-micron lithography," in *Semiconductor Fabtech, Edition 5*, IGC Publishing Ltd., p. 219 (1996).
31. H. Meiling, "EUV Source Cost of Ownership," *SEMATECH EUV Source Workshop*, San Jose, CA, www.sematech.org/meetings/archives/litho/euvl/20050227 (Feb. 2005).
32. C. P. Ausschnitt, et al., "Industrial strength lithography APC," *Proc. SPIE* **5044**, 1–11 (2003).
33. J. Fenner, et al., "Stepper registration feedback control in 300 mm manufacturing," *Proc. SPIE* **5044**, 44–51 (2003).
34. D. Crow, et al., "Enhancement of photolithographic performance by implementing and advanced process control system," *Proc. SPIE* **5378**, 44–51 (2004).
35. Y. Wei, et al., "193 nm immersion-related defects and strategies of defect reduction," *Future Fab. Intl.* **22**, 65 (2007).
36. K. Iwase, K. Ozawa, and F. Uesawa, "Mask specifications for 45-nm node: the impact of immersion lithography and polarized light imaging," *Proc. SPIE* **6283**, 628337 (2006).

37. K. Monahan, "Addressing 32 nm half-pitch challenges with double-patterning lithography," *Solid State Technology* **49**(12) (Dec. 2006).
38. A. Grenville, "Prospects for immersion lithography at the 45 nm half-pitch and beyond," *Future Fab. Intl.* **20**, 75 (2005).
39. E. Meurice, "Tool order: ASML receives 2 more orders for EUV lithography tools," *Semiconductor Fabtech News*, January 17, 2007.
40. P. Buck, et al., "A mask manufacturer's perspective on maskless lithography," *Proc. SPIE* **5992**, 599225 (Nov. 2005).
41. H. C. Pfeiffer, "The history and potential of maskless e-beam lithography," *Microlithography World* **14**(1), 4 (Feb. 2005).
42. C. Brandstatter, et al., "Projection maskless lithography," *Proc. SPIE* **5374**, 601–609 (May 2004).
43. F. Xu, et al., "Development of imprint materials for the step and flash imprint lithography process," *Proc. SPIE* **5374**, 232–241 (May 2004).
44. F. Reuther, et al., "Mix and match of nanoimprint and UV lithography," *Proc. SPIE* **4343**, 802–809 (Aug. 2001).
45. R. Pelzer, et al., "Nanoimprint lithography: full wafer replication of nanometer features," *Proc. SPIE* **5650**, 256–259 (Feb. 2005).
46. K. Kincade, "Imprint lithography challenges EUV for next generation chip manufacturing," *Laser Focus World* **43**(7), 97–104 (July 2007).



Phil Seidel is a senior member of the technical staff and a project manager for the EUV Strategy Program at the SEMATECH consortia located in Austin, Texas. In his 17 years working for SEMATECH, he has contributed to technology developments for I-line, 248 nm, 193 nm, EUV, electron projection lithography (EPL), ion beam projection lithography (IPL), and $1\times$ proximity x-ray ($1\times$ x-ray). For the past eight years Seidel has contributed to EUV mask material developments and overall lithography CoO analysis. Additional contributions include developments with SEMATECH for EUV and optical lithography projection optics manufacturing processes.

Appendix

Reference Data for the EUV Spectral Region

Eric M. Gullikson and David Attwood

Contents

A.1 Introduction	643
References	663

A.1 Introduction

Basic equations and data for the interaction of EUV radiation with materials is presented. The complex refractive index and penetration of EUV radiation into materials is presented in terms of the real and imaginary parts of the atomic scattering factors for various atoms of common interest. These scattering factors are presented graphically as a function of photon energy, with sample tabulated values. Full access for all elements, and sample calculation routines for compound materials, are referred to the CXRO website. Basic physical constants from the NIST website are also given. Tabulations of electron binding energies and characteristically emitted photon energies are presented in tables for all natural elements.

Table A.1 Optical constants and absorption data for extreme ultraviolet wavelengths.^{1,2}

$n(\omega) = 1 - \delta + i\beta$	$\frac{I}{I_0} = e^{-\rho\mu x}$
$\delta = \frac{n_a r_e \lambda^2}{2\pi} f_2^0(\omega)$	$\mu = \frac{2r_e \lambda}{Am_u} f_1^0(\omega)$
$\beta = \frac{n_a r_e \lambda^2}{2\pi} f_2^0(\omega)$	

Table A.1 (continued)

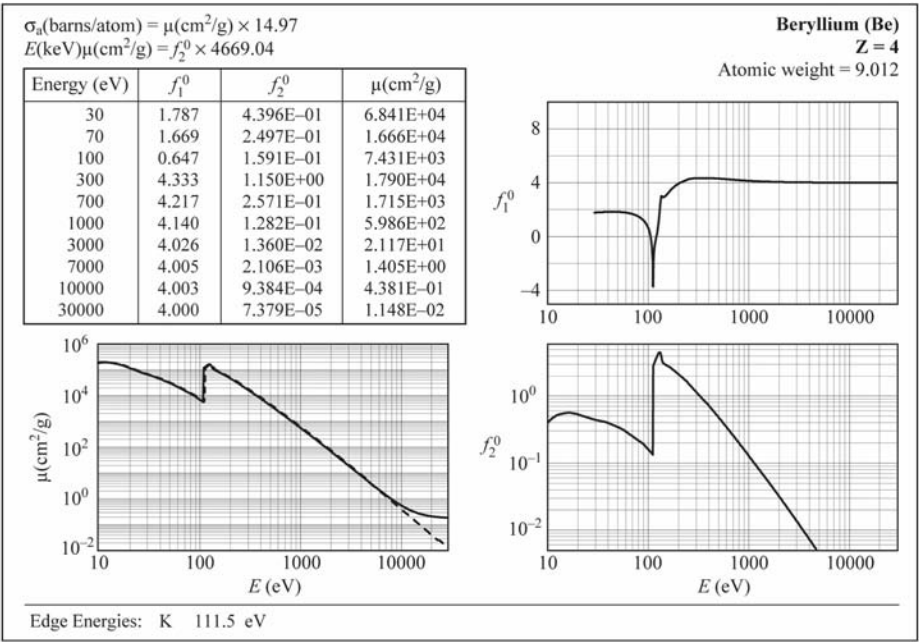


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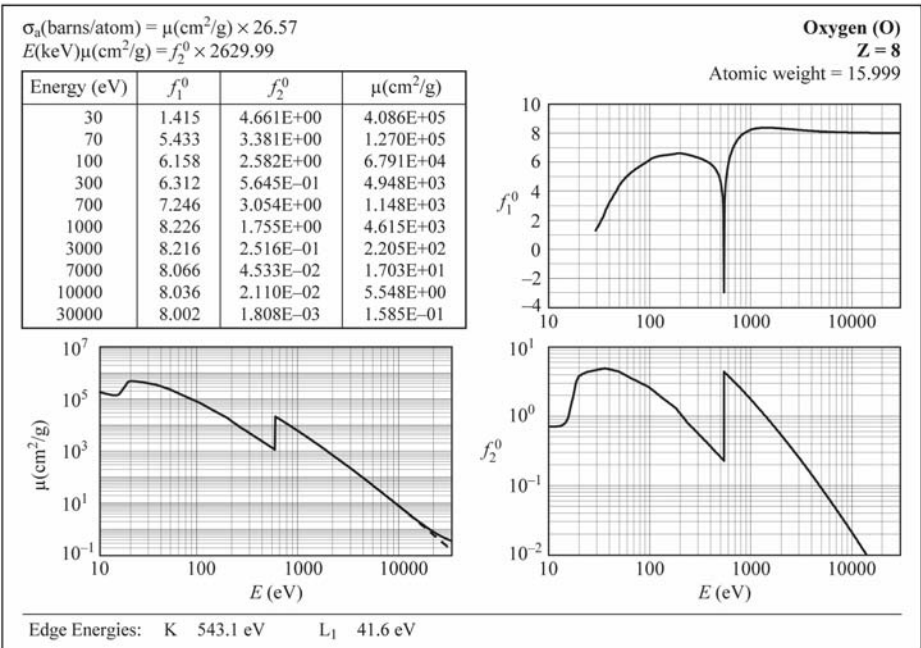
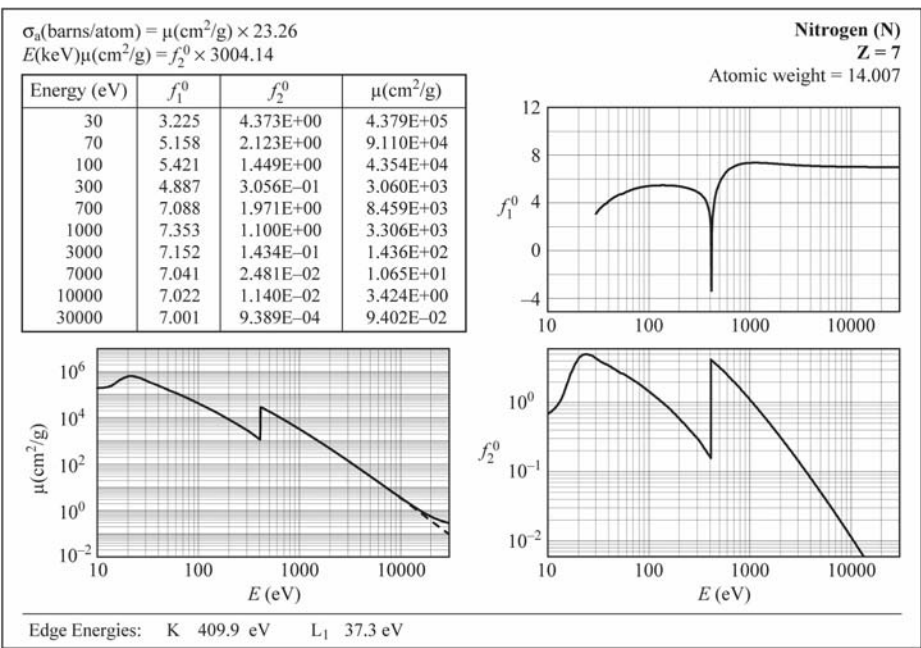


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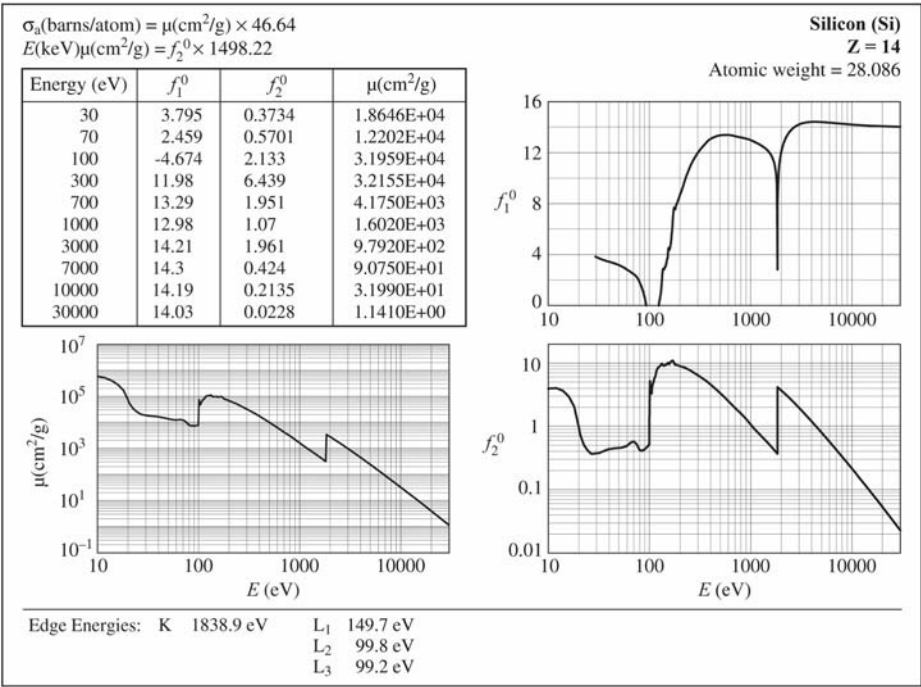
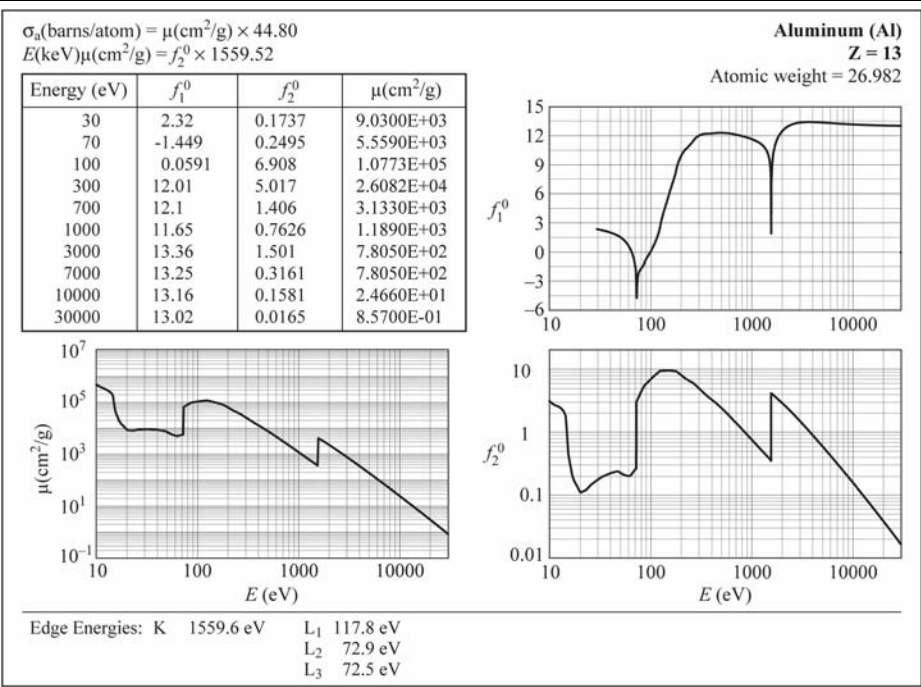


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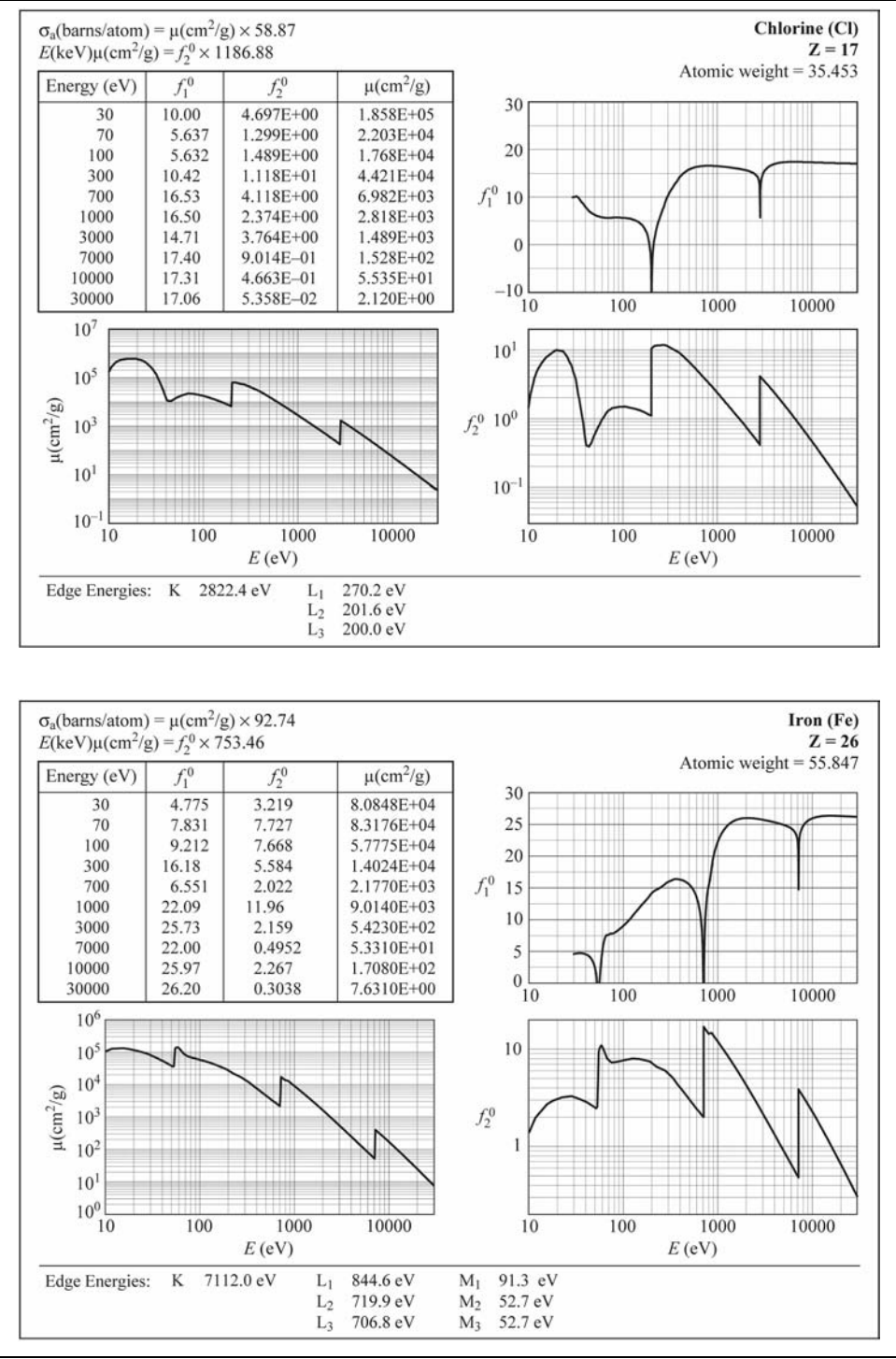


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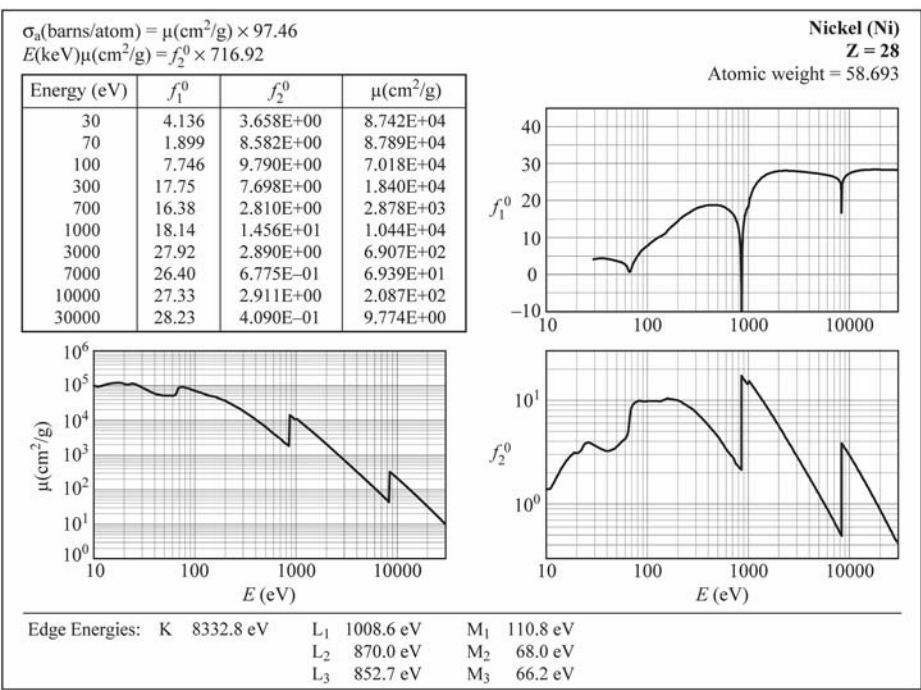


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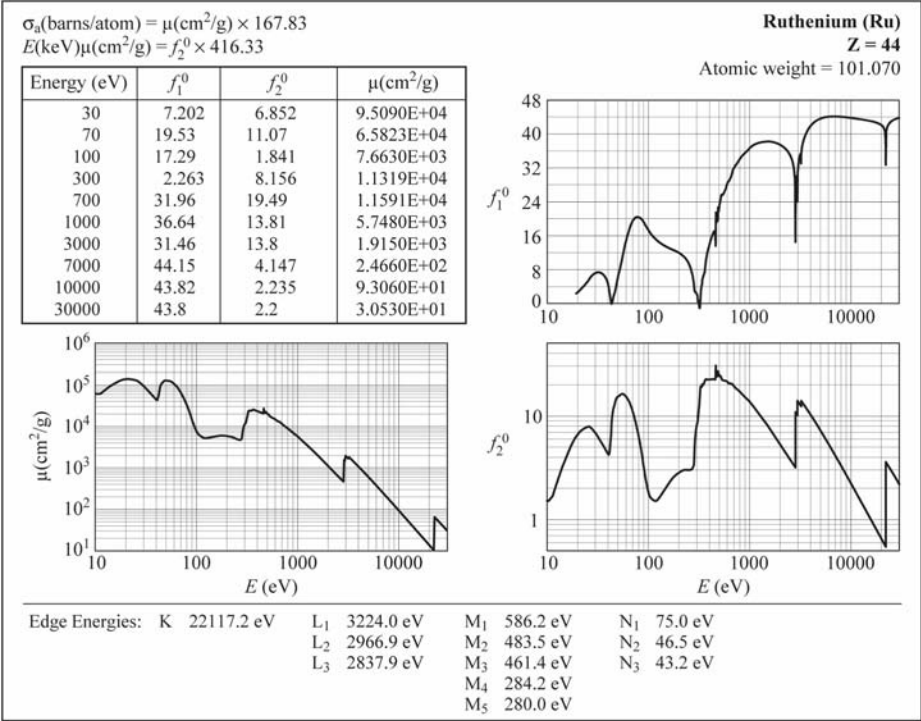
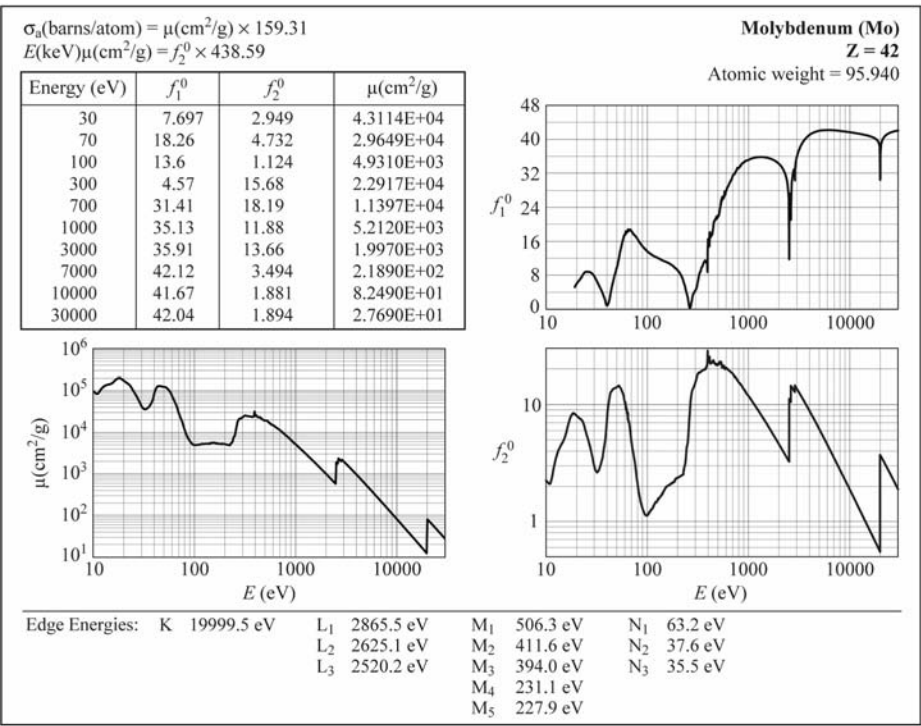


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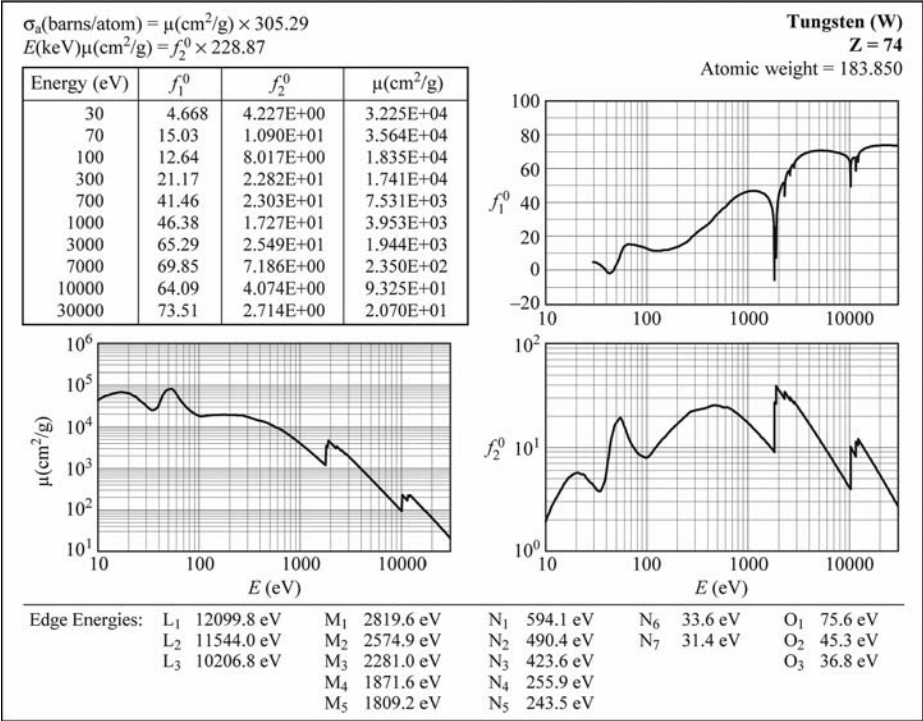
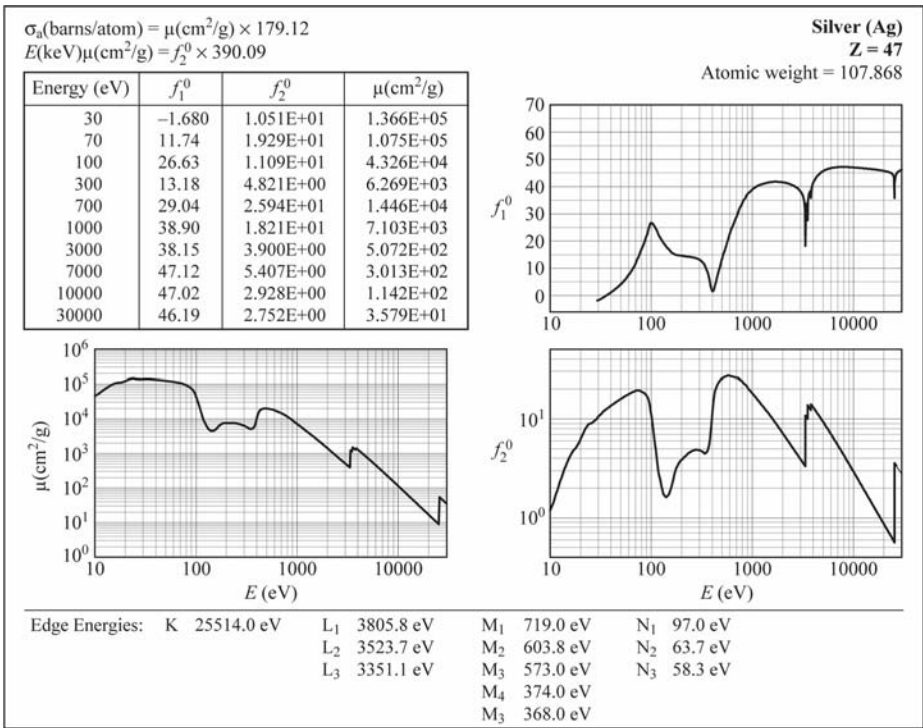


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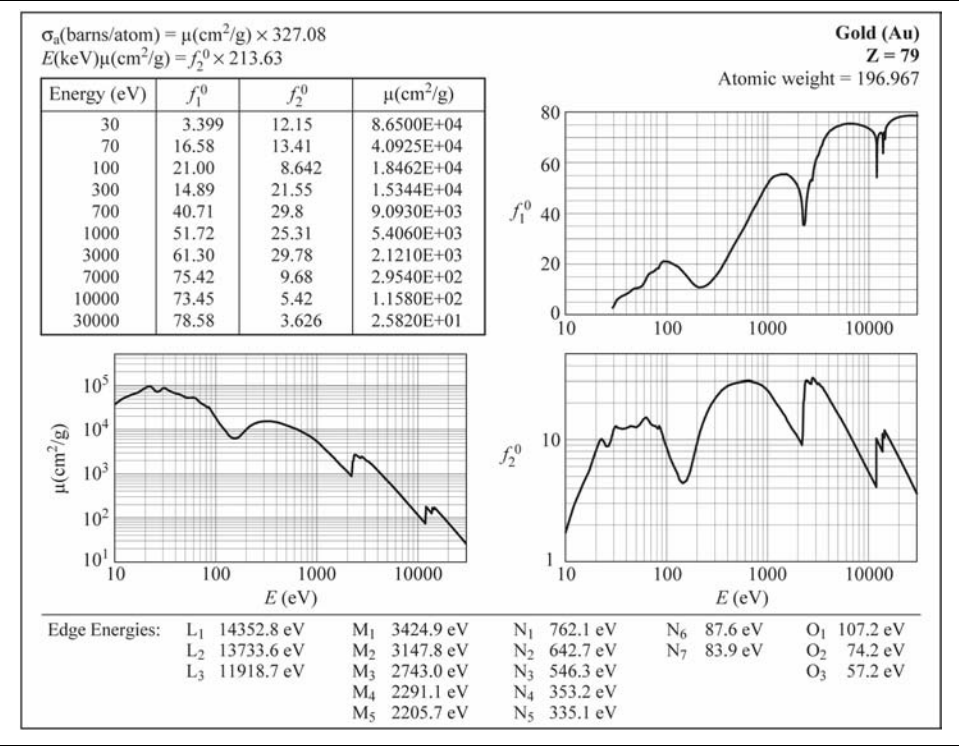


Table A.2 Physical constants.^{3,4}

Quantity	Symbol	Value*	Units
Speed of light in vacuum	c	299,792,458 (exactly)	$\text{m} \cdot \text{s}^{-1}$
Permeability of vacuum	μ_0	$4\pi \times 10^{-7}$ (exactly)	$\text{N} \cdot \text{A}^{-2}$
Permittivity of vacuum	ϵ_0	$1/(\mu_0 c^2) = 8.854, 187, 817 \dots$	$10^{-12} \text{ F} \cdot \text{m}^{-1}$
Planck's constant	h	4.135,667,33(10)	$10^{-15} \text{ eV} \cdot \text{s}$
Planck's constant/ 2π	$\hbar$	6.582,118,99(16)	$10^{-16} \text{ eV} \cdot \text{s}$
Electron charge	e	1.602,176,487(40)	10^{-19} C
Electron mass	m	9.109,382,15(45)	10^{-31} kg
Electron rest energy	mc^2	0.510,998,910(13)	MeV
Proton mass	m_p	1.672,621,637(83)	10^{-27} kg
Neutron mass	m_n	1.674,927,211(84)	10^{-27} kg
Atomic mass unit [$m(^{12}\text{C})/12$]	m_u	1.660,538,782(83)	10^{-27} kg
Rydberg constant ($me^4/32\pi^2\epsilon_0^2\hbar^2$)	$R_\infty hc$	13.605,691,93(34)	eV
Bohr radius ($4\pi\epsilon_0\hbar/me^2$)	a_0	0.529,177,208,59(36)	10^{-10} m
Classical electron radius ($e^2/4\pi\epsilon_0 mc^2$)	r_e	2.817,940,2894(58)	10^{-15} m
Thomson cross section ($8\pi r_e^2/3$)	σ_e	0.665,245,8558(27)	10^{-28} m^2
Fine-structure constant ($e^2/4\pi\epsilon_0\hbar c$)	α	7.297,352,5376(50)	10^{-3}
Compton wavelength (h/mc)	λ_C	2.426,310,2175(33)	10^{-12} m
Bohr magneton ($e\hbar/2m$)	μ_B	5.788,381,7555(79)	$10^{-5} \text{ eV} \cdot \text{T}^{-1}$
Nuclear magneton ($e\hbar/2m_p$)	μ_N	3.152,451,2326(45)	$10^{-8} \text{ eV} \cdot \text{T}^{-1}$
Avogadro's number	N_A	6.022,141,79(30)	10^{23} mol^{-1}
Boltzmann constant (R/N_A)	κ	8.617,343(15)	$10^{-5} \text{ eV} \cdot \text{K}^{-1}$
Stefan-Boltzmann constant [$(\pi^2/60)\kappa^4/\hbar^3 c^2$]	σ	5.670,400(40)	$10^{-8} \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-4}$
Universal (Molar) gas constant	R	8.314,472(15)	$\text{J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1}$
Molar volume (ideal gas) (RT/P) (at 273.15 K, 101,325 Pa)	V_m	22.413,996(39)	$10^{-3} \text{ m}^3 \cdot \text{mol}^{-1}$
Loschmidt's number (N_A/V_m)	n_L	2.686,777,4(47)	10^{25} m^{-3}
Photon energy-wavelength product	hc	1239.8418(04)	$\text{eV} \cdot \text{nm}$

*The numbers in parentheses indicate the uncertainties in the last digits. For example, $h = 4.1356692(12)$ is equivalent to $h = 4.1356692 \pm 0.0000012$.

Table A.3 Electron binding energies in electron volts for the elements in their natural forms.⁵

Element	K 1s	L ₁ 2s	L ₂ 2p _{1/2}	L ₃ 2p _{3/2}	M ₁ 3s	M ₂ 3p _{1/2}	M ₃ 3p _{3/2}	M ₄ 3d _{3/2}	M ₅ 3d _{5/2}	N ₁ 4s	N ₂ 4p _{1/2}	N ₃ 4p _{3/2}
1 H	13.6											
2 He	24.6 ^b											
3 Li	54.7 ^b											
4 Be	111.5 ^b											
5 B	188 ^b											
6 C	284.2 ^b											
7 N	409.9 ^b	37.3 ^b										
8 O	543.1 ^b	41.6 ^b										
9 F	696.7 ^b											
10 Ne	870.2 ^b	48.5 ^b	21.7 ^b	21.6 ^b								
11 Na	1070.8 ^c	63.5 ^c	30.4 ^c	30.5 ^b								
12 Mg	1303.0 ^c	88.6 ^b	49.6 ^c	49.2 ^c								
13 Al	1559.6	117.8 ^b	72.9 ^b	72.5 ^b								
14 Si	1838.9	149.7 ^b	99.8 ^b	99.2 ^b								
15 P	2145.5	189 ^b	136 ^b	135 ^b								
16 S	2472	230.9 ^b	163.6 ^b	162.5 ^b								
17 Cl	2822.4	270.2 ^b	202 ^b	200 ^b								
18 Ar	3205.9 ^b	326.3 ^b	250.6 ^b	248.4 ^b	29.3 ^b	15.9 ^b	15.7 ^b					
19 K	3608.4 ^b	378.6 ^b	297.3 ^b	294.6 ^b	34.8 ^b	18.3 ^b	18.3 ^b					
20 Ca	4038.5 ^b	438.4 ^c	349.7 ^c	346.2 ^c	44.3 ^c	25.4 ^c	25.4 ^c					
21 Sc	4492.8	498.0 ^b	403.6 ^b	398.7 ^b	51.1 ^b	28.3 ^b	28.3 ^b					
22 Ti	4966.4	560.9 ^c	461.2 ^c	453.8 ^c	58.7 ^c	32.6 ^c	32.6 ^c					
23 V	5465.1	626.7 ^c	519.8 ^c	512.1 ^c	66.3 ^c	37.2 ^c	37.2 ^c					
24 Cr	5989.2	695.7 ^c	583.8 ^c	574.1 ^c	74.1 ^c	42.2 ^c	42.2 ^c					
25 Mn	6539.0	769.1 ^c	649.9 ^c	638.7 ^c	82.3 ^c	47.2 ^c	47.2 ^c					

Table A.3 (continued)

Element	K 1s	L ₁ 2s	L ₂ 2p _{1/2}	L ₃ 2p _{3/2}	M ₁ 3s	M ₂ 3p _{1/2}	M ₃ 3p _{3/2}	M ₄ 3d _{3/2}	M ₅ 3d _{5/2}	N ₁ 4s	N ₂ 4p _{1/2}	N ₃ 4p _{3/2}
26 Fe	7112.0	844.6 ^c	719.9 ^c	706.8 ^c	91.3 ^c	52.7 ^c	52.7 ^c					
27 Co	7708.9	925.1 ^c	793.3 ^c	778.1 ^c	101.0 ^c	58.9 ^c	58.9 ^c					
28 Ni	8332.8	1008.6 ^c	870.0 ^c	852.7 ^c	110.8 ^c	68.0 ^c	66.2 ^c					
29 Cu	8978.9	1096.7 ^c	952.3 ^c	932.5 ^c	122.5 ^c	77.3 ^c	75.1 ^c					
30 Zn	9658.6	1196.2 ^b	1044.9 ^b	1021.8 ^b	139.8 ^b	91.4 ^b	88.6 ^b	10.2 ^b	10.1 ^b			
31 Ga	10367.1	1299.0 ^b	1143.2 ^c	1116.4 ^c	159.5 ^c	103.5 ^c	103.5 ^c	18.7 ^c	18.7 ^c			
32 Ge	11103.1	1414.6 ^b	1248.1 ^b	1217.0 ^b	180.1 ^b	124.9 ^b	120.8 ^b	29.0 ^b	29.0 ^b			
33 As	11866.7	1527.0 ^b	1359.1 ^b	1323.6 ^b	204.7 ^b	146.2 ^b	141.2 ^b	41.7 ^b	41.7 ^b			
34 Se	12657.8	1652.0 ^b	1474.3 ^b	1433.9 ^b	229.6 ^b	166.5 ^b	160.7 ^b	55.5 ^b	54.6 ^b			
35 Br	13473.7	1782.0 ^b	1596.0 ^b	1549.9 ^b	257 ^b	189 ^b	182 ^b	70 ^b	69 ^b			
36 Kr	14325.6	1921.0	1730.9 ^b	1678.4 ^b	292.8 ^b	222.2 ^b	214.4	95.0 ^b	93.8 ^b	27.5 ^b	14.1 ^b	14.1 ^b
37 Rb	15199.7	2065.1	1863.9	1804.4	326.7 ^b	248.7 ^b	239.1 ^b	113.0 ^b	112 ^b	30.5 ^b	16.3 ^b	15.3 ^b
38 Sr	16104.6	2216.3	2006.8	1939.6	358.7 ^c	280.3 ^c	270.0 ^c	136.0 ^c	134.2 ^c	38.9 ^c	20.3 ^c	20.3 ^c
39 Y	17038.4	2372.5	2155.5	2080.0	392.0 ^b	310.6 ^b	298.8 ^b	157.7 ^c	155.8 ^c	43.8 ^b	24.4 ^b	23.1 ^b
40 Zr	17997.6	2531.6	2306.7	2222.3	430.3 ^c	343.5 ^c	329.8 ^c	181.1 ^c	178.8 ^c	50.6 ^c	28.5 ^c	27.7 ^c
41 Nb	18985.6	2697.7	2464.7	2370.5	466.6 ^c	376.1 ^c	360.6 ^c	205.0 ^c	202.3 ^c	56.4 ^c	32.6 ^c	30.8 ^c
42 Mo	19999.5	2865.5	2625.1	2520.2	506.3 ^c	411.6 ^c	394.0 ^c	231.1 ^c	227.9 ^c	63.2 ^c	37.6 ^c	35.5 ^c
43 Tc	21044.0	3042.5	2793.2	2676.9	544 ^b	445 ^b	425 ^b	257 ^b	253 ^b	68 ^b	39 ^b	39 ^b
44 Ru	22117.2	3224.0	2966.9	2837.9	586.2 ^c	483.5 ^c	461.4 ^c	284.2 ^c	280.0 ^c	75.0 ^c	46.5 ^c	43.2 ^c
45 Rh	23219.9	3411.9	3146.1	3003.8	628.1 ^c	521.3 ^c	496.5 ^c	311.9 ^c	307.2 ^c	81.4 ^b	50.5 ^c	47.3 ^c
46 Pd	24350.3	3604.3	3330.3	3173.3	671.6 ^c	559.9 ^c	532.3 ^c	340.5 ^c	335.2 ^c	87.6 ^b	55.7 ^c	50.9 ^c
47 Ag	25514.0	3805.8	3523.7	3351.1	719.0 ^c	603.8 ^c	573.0 ^c	374.0 ^c	368.0 ^c	97.0 ^c	63.7 ^c	58.3 ^c

Table A.3 (continued)

Element	K 1s	L ₁ 2s	L ₂ 2p _{1/2}	L ₃ 2p _{3/2}	M ₁ 3s	M ₂ 3p _{1/2}	M ₃ 3p _{3/2}	M ₄ 3d _{3/2}	M ₅ 3d _{5/2}	N ₁ 4s	N ₂ 4p _{1/2}	N ₃ 4p _{3/2}
48 Cd	26711.2	4018.0	3727.0	3537.5	772.0 ^c	652.6 ^c	618.4 ^c	411.9 ^c	405.2 ^c	109.8 ^c	63.9 ^c	63.9 ^c
49 In	27939.9	4237.5	3938.0	3730.1	827.2 ^c	703.2 ^c	665.3 ^c	451.4 ^c	443.9 ^c	122.7 ^c	73.5 ^c	73.5 ^c
50 Sn	29200.1	4464.7	4156.1	3928.8	884.7 ^c	756.5 ^c	714.6 ^c	493.2 ^c	484.9 ^c	137.1 ^c	83.6 ^c	83.6 ^c
51 Sb	30491.2	4698.3	4380.4	4132.2	946 ^c	812.7 ^c	766.4 ^c	537.5 ^c	528.2 ^c	153.2 ^c	95.6 ^c	95.6 ^c
52 Te	31813.8	4939.2	4612.0	4341.4	1006 ^c	870.8 ^c	820.8 ^c	583.4 ^c	573.0 ^c	169.4 ^c	103.3 ^c	103.3 ^c
53 I	33169.4	5188.1	4852.1	4557.1	1072 ^b	931 ^b	875 ^b	631 ^b	620 ^b	186 ^b	123 ^b	123 ^b
54 Xe	34561.4	5452.8	5103.7	4782.2	1148.7 ^b	1002.1 ^b	940.6 ^b	689.0 ^b	676.4 ^b	213.2 ^b	146.7	145.5 ^b
55 Cs	35984.6	5714.3	5359.4	5011.9	1211 ^b	1071 ^b	1003 ^b	740.5 ^b	726.6 ^b	232.3 ^b	172.4 ^b	161.3 ^b
56 Ba	37440.6	5988.8	5623.6	5247.0	1293 ^b	1137 ^b	1063 ^b	795.7 ^b	780.5 ^b	253.5 ^c	192	178.6 ^c
57 La	38924.6	6266.3	5890.6	5482.7	1362 ^b	1209 ^b	1128 ^b	853 ^b	836 ^b	247.7 ^b	205.8	196.0 ^b
58 Ce	40443.0	6548.8	6164.2	5723.4	1436 ^b	1274 ^b	1187 ^b	902.4 ^b	883.8 ^b	291.0 ^b	223.2	206.5 ^b
59 Pr	41990.6	6834.8	6440.4	5964.3	1511.0	1337.4	1242.2	948.3 ^b	928.8 ^b	304.5	236.3	217.6
60 Nd	43568.9	7126.0	6721.5	6207.9	1575.3	1402.8	1297.4	1003.3 ^b	980.4 ^b	319.2 ^b	243.3	224.6
61 Pm	45184.0	7427.9	7012.8	6459.3	–	1471.4	1356.9	1051.5	1026.9	–	242	242
62 Sm	46834.2	7736.8	7311.8	6716.2	1722.8	1540.7	1419.8	1110.9 ^b	1083.4 ^b	347.2 ^b	265.6	247.4
63 Eu	48519.0	8052.0	7617.1	6976.9	1800.0	1613.9	1480.6	1158.6 ^b	1127.5 ^b	360	284	257
64 Gd	50239.1	8375.6	7930.3	7242.8	1880.8	1688.3	1544.0	1221.9 ^b	1189.6 ^b	378.6 ^b	286	270.9
65 Tb	51995.7	8708.0	8251.6	7514.0	1967.5	1767.7	1611.3	1276.9 ^b	1241.1 ^b	396.0 ^b	322.4 ^b	284.1 ^b
66 Dy	53788.5	9045.8	8580.6	7790.1	2046.8	1841.8	1675.6	1332.5	1292.6 ^b	414.2 ^b	333.5 ^b	293.2 ^b
67 Ho	55617.7	9394.2	8917.8	8071.1	2128.3	1922.8	1741.2	1391.5	1351.4	432.4 ^b	343.5	308.2 ^b
68 Er	57485.5	9751.3	9264.3	8357.9	2206.5	2005.8	1811.8	1453.3	1409.3	449.8 ^b	366.2	320.2 ^b
69 Tm	59398.6	10115.7	9616.9	8648.0	2306.8	2089.8	1884.5	1514.6	1467.7	470.9 ^b	385.9 ^b	332.6 ^b
70 Yb	61332.3	10486.4	9978.2	8943.6	2398.1	2173.0	1949.8	1576.3	1527.8	480.5 ^b	388.7 ^b	339.7 ^b

Table A.3 (continued)

Element	K 1s	L ₁ 2s	L ₂ 2p _{1/2}	L ₃ 2p _{3/2}	M ₁ 3s	M ₂ 3p _{1/2}	M ₃ 3p _{3/2}	M ₄ 3d _{3/2}	M ₅ 3d _{5/2}	N ₁ 4s	N ₂ 4p _{1/2}	N ₃ 4p _{3/2}
71 Lu	63313.8	10870.4	10348.6	9244.1	2491.2	2263.5	2023.6	1639.4	1588.5	506.8 ^b	412.4 ^b	359.2 ^b
72 Hf	65350.8	11270.7	10739.4	9560.7	2600.9	2365.4	2107.6	1716.4	1661.7	538 ^b	438.2 ^c	380.7 ^c
73 Ta	67416.4	11681.5	11136.1	9881.1	2708.0	2468.7	2194.0	1793.2	1735.1	563.4 ^c	463.4 ^c	400.9 ^c
74 W	69525.0	12099.8	11544.0	10206.8	2819.6	2574.9	2281.0	1871.6	1809.2	594.1 ^c	490.4 ^c	423.6 ^c
75 Re	71676.4	12526.7	11958.7	10535.3	2931.7	2681.6	2367.3	1948.9	1882.9	625.4	518.7 ^c	446.8 ^c
76 Os	73870.8	12968.0	12385.0	10870.9	3048.5	2792.2	2457.2	2030.8	1960.1	658.2 ^c	549.1 ^c	470.7 ^c
77 Ir	76111.0	13418.5	12824.1	11215.2	3173.7	2908.7	2550.7	2116.1	2040.4	691.1 ^c	577.8 ^c	495.8 ^c
78 Pt	78394.8	13879.9	13272.6	11563.7	3296.0	3026.5	2645.4	2201.9	2121.6	725.4 ^c	609.1 ^c	519.4 ^c
79 Au	80724.9	14352.8	13733.6	11918.7	3424.9	3147.8	2743.0	2291.1	2205.7	762.1 ^c	642.7 ^c	546.3 ^c
80 Hg	83102.3	14839.3	14208.7	12283.9	3561.6	3278.5	2847.1	2384.9	2294.9	802.2 ^c	680.2 ^c	576.6 ^c
81 Tl	85530.4	15346.7	14697.9	12657.5	3704.1	3415.7	2956.6	2485.1	2389.3	846.2 ^c	720.5 ^c	609.5 ^c
82 Pb	88004.5	15860.8	15200.0	13035.2	3850.7	3554.2	3066.4	2585.6	2484.0	891.8 ^c	761.9 ^c	643.5 ^c
83 Bi	90525.9	16387.5	15711.1	13418.6	3999.1	3696.3	3176.9	2687.6	2579.6	939 ^c	805.2 ^c	678.8 ^c
84 Po	93105.0	16939.3	16244.3	13813.8	4149.4	3854.1	3301.9	2798.0	2683.0	995 ^b	851 ^b	705 ^b
85 At	95729.9	17493	16784.7	14213.5	4317	4008	3426	2908.7	2786.7	1042 ^b	886 ^b	740 ^b
86 Rn	98404	18049	17337.1	14619.4	4482	4159	3538	3021.5	2892.4	1097 ^b	929 ^b	768 ^b
87 Fr	101137	18639	17906.5	15031.2	4652	4327	3663	3136.2	2999.9	1153 ^b	980 ^b	810 ^b
88 Ra	103921.9	19236.7	18484.3	15444.4	4822.0	4489.5	3791.8	3248.4	3104.9	1208 ^b	1057.6 ^b	879.1 ^b
89 Ac	106755.3	19840	19083.2	15871.0	5002	4656	3909	3370.2	3219.0	1269 ^b	1080 ^b	890 ^b
90 Th	109650.9	20472.1	19693.2	16300.3	5182.3	4830.4	4046.1	3490.8	3332.0	1330 ^b	1168 ^b	966.4 ^c
91 Pa	112601.4	21104.6	20313.7	16733.1	5366.9	5000.9	4173.8	3611.2	3441.8	1387 ^b	1224 ^b	1007 ^b
92 U	115606.1	21757.4	20947.6	17166.3	5548.0	5182.2	4303.4	3727.6	3551.7	1439 ^b	1271 ^b	1043.0 ^c

Table A.3 (continued)

Element	N ₄ d _{3/2}	N ₅ d _{5/2}	N ₆ f _{5/2}	N ₇ f _{7/2}	O ₁ s	O ₂ p _{1/2}	O ₃ p _{3/2}	O ₄ d _{3/2}	O ₅ d _{5/2}
48 Cd	11.7 ^c	10.7 ^c	—	—	—	—	—	—	—
49 In	17.7 ^c	16.9 ^c	—	—	—	—	—	—	—
50 Sn	24.9 ^c	23.9 ^c	—	—	—	—	—	—	—
51 Sb	33.3 ^c	32.1 ^c	—	—	—	—	—	—	—
52 Te	41.9 ^c	40.4 ^c	—	—	—	—	—	—	—
53 I	50 ^b	50 ^b	—	—	—	—	—	—	—
54 Xe	69.5 ^b	67.5 ^b	—	—	23.3 ^b	13.4 ^b	12.1 ^b	—	—
55 Cs	79.8 ^b	77.5 ^b	—	—	22.7	14.2 ^b	12.1 ^b	—	—
56 Ba	92.6 ^c	89.9 ^c	—	—	30.3 ^c	17.0 ^c	14.8	—	—
57 La	105.3 ^b	102.5 ^b	—	—	34.3 ^b	19.3 ^b	16.8 ^b	—	—
58 Ce	109 ^b	—	—	—	37.8	19.8 ^b	17.0 ^b	—	—
59 Pr	115.1 ^b	115.1 ^b	—	—	37.4	22.3	22.3	—	—
60 Nd	120.5 ^b	120.5 ^b	—	—	37.5	21.1	21.1	—	—
61 Pm	120	120	—	—	—	—	—	—	—
62 Sm	129	129	—	—	37.4	21.3	21.3	—	—
63 Eu	133	127.7 ^b	—	—	31.8	22.0	22.0	—	—
64 Gd	140.5	142.6 ^b	—	—	43.5 ^b	20	20	—	—
65 Tb	150.5 ^b	150.5 ^b	—	—	45.6 ^b	28.7 ^b	22.6 ^b	—	—
66 Dy	153.6 ^b	153.6 ^b	—	—	49.9 ^b	29.5	23.1	—	—
67 Ho	160 ^b	160 ^b	—	—	49.3 ^b	30.8 ^b	24.1 ^b	—	—
68 Er	167.6 ^b	167.6 ^b	—	—	50.6 ^b	31.4 ^b	24.7 ^b	—	—
69 Tm	175.5 ^b	175.5 ^b	—	—	54.7 ^b	31.8 ^b	25.0 ^b	—	—
70 Yb	191.2 ^b	182.4 ^b	—	—	52.0 ^b	30.3 ^b	24.1 ^b	—	—

Table A.3 (continued)

Element	N ₄ d _{3/2}	N ₅ d _{5/2}	N ₆ f _{5/2}	N ₇ f _{7/2}	O ₁ s	O ₂ p _{1/2}	O ₃ p _{3/2}	O ₄ d _{3/2}	O ₅ d _{5/2}
71 Lu	206.1 ^b	196.3 ^c	8.9 ^b	7.5 ^b	57.3 ^b	33.6 ^b	26.7 ^b		
72 Hf	220.0 ^c	211.5 ^c	15.9 ^c	14.2 ^c	64.2 ^c	38 ^b	29.9 ^b		
73 Ta	237.9 ^c	226.4 ^c	23.5 ^c	21.6 ^c	69.7 ^c	42.2 ^b	32.7 ^b		
74 W	255.9 ^c	243.5 ^c	33.6 ^b	31.4 ^c	75.6 ^c	45.3 ^b	36.8 ^b		
75 Re	273.9 ^c	260.5 ^c	42.9 ^b	40.5 ^c	83 ^c	45.6 ^b	34.6 ^b		
76 Os	293.1 ^c	278.5 ^c	53.4 ^c	50.7 ^c	84 ^c	58 ^b	44.5 ^c		
77 Ir	311.9 ^c	296.3 ^c	63.8 ^c	60.8 ^c	95.2 ^b	63.0 ^b	48.0 ^c		
78 Pt	331.6 ^c	314.6 ^c	74.5 ^c	71.2 ^c	101 ^c	65.3 ^b	51.7 ^c		
79 Au	353.2 ^c	335.1 ^c	87.6 ^c	83.9 ^c	107.2 ^b	74.2 ^c	57.2 ^c		
80 Hg	378.2 ^c	358.8 ^c	104.0 ^c	99.9 ^c	127 ^c	83.1 ^c	64.5 ^c	9.6 ^c	7.8 ^c
81 Tl	405.7 ^c	385.0 ^c	122.2 ^c	117.8 ^c	136 ^b	94.6 ^c	73.5 ^c	14.7 ^c	12.5 ^c
82 Pb	434.3 ^c	412.2 ^c	141.7 ^c	136.9 ^c	147 ^b	106.4 ^c	83.3 ^c	20.7 ^c	18.1 ^c
83 Bi	464.0 ^c	440.1 ^c	162.3 ^c	157.0 ^c	159.3 ^b	119.0 ^c	92.6 ^c	26.9 ^c	23.8 ^c
84 Po	500 ^b	473 ^b	184 ^b	184 ^b	177 ^b	132 ^b	104 ^b	31 ^b	31 ^b
85 At	533 ^b	507 ^b	210 ^b	210 ^b	195 ^b	148 ^b	115 ^b	40 ^b	40 ^b
86 Rn	567 ^b	541 ^b	238 ^b	238 ^b	214 ^b	164 ^b	127 ^b	48 ^b	48 ^b
87 Fr	603 ^b	577 ^b	268 ^b	268 ^b	234 ^b	182 ^b	140 ^b	58 ^b	58 ^b
88 Ra	635.9 ^b	602.7 ^b	299 ^b	299 ^b	254 ^b	200 ^b	153 ^b	68 ^b	68 ^b
89 Ac	675 ^b	639 ^b	319 ^b	319 ^b	272 ^b	215 ^b	167 ^b	80 ^b	80 ^b
90 Th	712.1 ^c	675.2 ^c	342.4 ^c	333.1	290 ^b	229 ^b	182 ^b	92.5 ^c	85.4 ^c
91 Pa	743 ^b	708 ^b	371 ^b	360 ^b	310 ^b	232 ^b	232 ^b	94 ^b	94 ^b
92 U	778.3 ^c	736.2 ^c	388.2 ^b	377.4 ^c	321 ^b	257 ^b	192 ^b	102.8 ^c	94.2 ^c

^bFrom M. Cardona and L. Lay, Eds., *Photoemission in Solids I: General Principles*, Springer-Verlag, Berlin (1978).
^cFrom J. C. Fuggle and N. Mårtensson, "Core-level binding energies in metals," *J. Electron. Spectrosc. Relat. Phenom.* **21**, 275 (1980).

Table A.4 Photon energies in electron volts of principal K- and L-shell emission lines.⁶

Element	K α_1	K α_2	K b_1	L α_1	L α_2	L b_1	L b_2	L g_1
3 Li	54.3							
4 Be	108.5							
5 B	183.3							
6 C	277							
7 N	392.4							
8 O	524.9							
9 F	676.8							
10 Ne	848.6	848.6						
11 Na	1,040.98	1,040.98	1,071.1					
12 Mg	1,253.60	1,253.60	1,302.2					
13 Al	1,486.70	1,486.27	1,557.45					
14 Si	1,739.98	1,739.38	1,835.94					
15 P	2,013.7	2,012.7	2,139.1					
16 S	2,307.84	2,306.64	2,464.04					
17 Cl	2,622.39	2,620.78	2,815.6					
18 Ar	2,957.70	2,955.63	3,190.5					
19 K	3,313.8	3,311.1	3,589.6					
20 Ca	3,691.68	3,688.09	4,012.7	341.3	341.3	344.9		
21 Sc	4,090.6	4,086.1	4,460.5	395.4	395.4	399.6		
22 Ti	4,510.84	4,504.86	4,931.81	452.2	452.2	458.4		
23 V	4,952.20	4,944.64	5,427.29	511.3	511.3	519.2		
24 Cr	5,414.72	5,405.509	5,946.71	572.8	572.8	582.8		
25 Mn	5,898.75	5,887.65	6,490.45	637.4	637.4	648.8		
26 Fe	6,403.84	6,390.84	7,057.98	705.0	705.0	718.5		
27 Co	6,930.32	6,915.30	7,649.43	776.2	776.2	791.4		
28 Ni	7,478.15	7,460.89	8,264.66	851.5	851.5	868.8		
29 Cu	8,047.78	8,027.83	8,905.29	929.7	929.7	949.8		
30 Zn	8,638.86	8,615.78	9,572.0	1,011.7	1,011.7	1,034.7		

Table A.4 (continued)

Element	Ka ₁	Ka ₂	Kb ₁	La ₁	La ₂	Lb ₁	Lb ₂	Lg ₁
31 Ga	9,251.74	9,224.82	10,264.2	1,097.92	1,097.92	1,124.8		
32 Ge	9,886.42	9,855.32	10,982.1	1,188.00	1,188.00	1,218.5		
33 As	10,543.72	10,507.99	11,726.2	1,282.0	1,282.0	1,317.0		
34 Se	11,222.4	11,181.4	12,495.9	1,379.10	1,379.10	1,419.23		
35 Br	11,924.2	11,877.6	13,291.4	1,480.43	1,480.43	1,525.90		
36 Kr	12,649	12,598	14,112	1,586.0	1,586.0	1,636.6		
37 Rb	13,395.3	13,335.8	14,961.3	1,694.13	1,692.56	1,752.17		
38 Sr	14,165	14,097.9	15,835.7	1,806.56	1,804.74	1,871.72		
39 Y	14,958.4	14,882.9	16,737.8	1,922.56	1,920.47	1,995.84		
40 Zr	15,775.1	15,690.9	17,667.8	2,042.36	2,039.9	2,124.4	2,219.4	2,302.7
41 Nb	16,615.1	16,521.0	18,622.5	2,165.89	2,163.0	2,257.4	2,367.0	2,461.8
42 Mo	17,479.34	17,374.3	19,608.3	2,293.16	2,289.85	2,394.81	2,518.3	2,623.5
43 Tc	18,367.1	18,250.8	20,619	2,424.0	–	2,536.8	–	–
44 Ru	19,279.2	19,150.4	21,656.8	2,558.55	2,554.31	2,683.23	2,836.0	2,964.5
45 Rh	20,216.1	20,073.7	22,723.6	2,696.74	2,692.05	2,834.41	3,001.3	3,143.8
46 Pd	21,177.1	21,020.1	23,818.7	2,838.61	2,833.29	2,990.22	3,171.79	3,328.7
47 Ag	22,162.92	21,990.3	24,942.4	2,984.31	2,978.21	3,150.94	3,347.81	3,519.59
48 Cd	23,173.6	22,984.1	26,095.5	3,133.73	3,126.91	3,316.57	3,528.12	3,716.86
49 In	24,209.7	24,002.0	27,275.9	3,286.94	3,279.29	3,487.21	3,713.81	3,920.81
50 Sn	25,271.3	25,044.0	28,486.0	3,443.98	3,435.42	3,662.80	3,904.86	4,131.12

Table A.4 (continued)

Element	K α_1	K α_2	K β_1	L α_1	L α_2	L β_1	L β_2	L β_3
51 Sb	26,359.1	26,110.8	29,725.6	3,604.72	3,595.32	3,843.57	4,100.78	4,347.79
52 Te	27,472.3	27,201.7	30,995.7	3,769.33	3,758.8	4,029.58	4,301.7	4,570.9
53 I	28,612.0	28,317.2	32,294.7	3,937.65	3,926.04	4,220.72	4,507.5	4,800.9
54 Xe	29,779	29,458	33,624	4,109.9	–	–	–	–
55 Cs	30,972.8	30,625.1	34,986.9	4,286.5	4,272.2	4,619.8	4,935.9	5,280.4
56 Ba	32,193.6	31,817.1	36,378.2	4,466.26	4,450.90	4,827.53	5,156.5	5,531.1
57 La	33,441.8	33,034.1	37,801.0	4,650.97	4,634.23	5,042.1	5,383.5	5,788.5
58 Ce	34,719.7	34,278.9	39,257.3	4,840.2	4,823.0	5,262.2	5,613.4	6,052
59 Pr	36,026.3	35,550.2	40,748.2	5,033.7	5,013.5	5,488.9	5,850	6,322.1
60 Nd	37,361.0	36,847.4	42,271.3	5,230.4	5,207.7	5,721.6	6,089.4	6,602.1
61 Pm	38,724.7	38,171.2	43,826	5,432.5	5,407.8	5,961	6,339	6,892
62 Sm	40,118.1	39,522.4	45,413	5,636.1	5,609.0	6,205.1	6,586	7,178
63 Eu	41,542.2	40,901.9	47,037.9	5,845.7	5,816.6	6,456.4	6,843.2	7,480.3
64 Gd	42,996.2	42,308.9	48,697	6,057.2	6,025.0	6,713.2	7,102.8	7,785.8
65 Tb	44,481.6	43,744.1	50,382	6,272.8	6,238.0	6,978	7,366.7	8,102
66 Dy	45,998.4	45,207.8	52,119	6,495.2	6,457.7	7,247.7	7,635.7	8,418.8
67 Ho	47,546.7	46,699.7	53,877	6,719.8	6,679.5	7,525.3	7,911	8,747
68 Er	49,127.7	48,221.1	55,681	6,948.7	6,905.0	7,810.9	8,189.0	9,089
69 Tm	50,741.6	49,772.6	57,517	7,179.9	7,133.1	8,101	8,468	9,426
70 Yb	52,388.9	51,354.0	59,370	7,415.6	7,367.3	8,401.8	8,758.8	9,780.1
71 Lu	54,069.8	52,965.0	61,283	7,655.5	7,604.9	8,709.0	9,048.9	10,143.4
72 Hf	55,790.2	54,611.4	63,234	7,899.0	7,844.6	9,022.7	9,347.3	10,515.8
73 Ta	57,532	56,277	65,223	8,146.1	8,087.9	9,343.1	9,651.8	10,895.2
74 W	59,318.24	57,981.7	67,244	8,397.6	8,335.2	9,672.35	9,961.5	11,285.9
75 Re	61,140.3	59,717.9	69,310	8,652.5	8,586.2	10,010.0	10,275.2	11,685.4

Table A.4 (continued)

Element	K α_1	K α_2	K β_1	L α_1	L α_2	L β_1	L β_2	L γ_1
76 Os	63,000.5	61,486.7	71,413	8,911.7	8,841.0	10,355.3	10,598.5	12,095.3
77 Ir	64,895.6	63,286.7	73,560.8	9,175.1	9,099.5	10,708.3	10,920.3	12,512.6
78 Pt	66,832	65,112	75,748	9,442.3	9,361.8	11,070.7	11,250.5	12,942.0
79 Au	68,803.7	66,989.5	77,984	9,713.3	9,628.0	11,442.3	11,584.7	13,381.7
80 Hg	70,819	68,895	80,253	9,988.8	9,897.6	11,822.6	11,924.1	13,830.1
81 Tl	72,871.5	70,831.9	82,576	10,268.5	10,172.8	12,213.3	12,271.5	14,291.5
82 Pb	74,969.4	72,804.2	84,936	10,551.5	10,449.5	12,613.7	12,622.6	14,764.4
83 Bi	77,107.9	74,814.8	87,343	10,838.8	10,730.91	13,023.5	12,979.9	15,247.7
84 Po	79,290	76,862	89,800	11,130.8	11,015.8	13,447	13,340.4	15,744
85 At	81,520	78,950	92,300	11,426.8	11,304.8	13,876	—	16,251
86 Rn	83,780	81,070	94,870	11,727.0	11,597.9	14,316	—	16,770
87 Fr	86,100	83,230	97,470	12,031.3	11,895.0	14,770	14,450	17,303
88 Ra	88,470	85,430	100,130	12,339.7	12,196.2	15,235.8	14,841.4	17,849
89 Ac	90,884	87,670	102,850	12,652.0	12,500.8	15,713	—	18,408
90 Th	93,350	89,953	105,609	12,968.7	12,809.6	16,202.2	15,623.7	18,982.5
91 Pa	95,868	92,287	108,427	13,290.7	13,122.2	16,702	16,024	19,568
92 U	98,439	94,665	111,300	13,614.7	13,438.8	17,220.0	16,428.3	20,167.1
93 Np	—	—	—	13,944.1	13,759.7	17,750.2	16,840.0	20,784.8
94 Pu	—	—	—	14,278.6	14,084.2	18,293.7	17,255.3	21,417.3
95 Am	—	—	—	14,617.2	14,411.9	18,852.0	17,676.5	22,065.2

References

1. D. Attwood, *Soft X-Rays and Extreme Ultraviolet Radiation, Principles and Applications*, Cambridge Univ. Press, Cambridge, UK (2000).
2. E. Gullikson, <http://www.cxro.lbl.gov>.
3. E. R. Cohen and B. N. Taylor, "The fundamental physical constants," *Phys. Today*, p. BG9 (August 1995).
4. <http://physics.nist.gov/constants>. 2006 update to original source: P. J. Mohr and B. N. Taylor, "CODATA recommended values of the fundamental physical constants: 2002," *Rev. Mod. Phys.* **77**(1), 1–107 (2005).
5. A compilation by G. P. Williams of Brookhaven National Laboratory, "Electron binding energies," in *X-Ray Data Booklet*, Lawrence Berkeley National Laboratory Pub-490 Rev. 2 (2001), based largely on values given by J. A. Bearden and A. F. Barr, "Reevaluation of x-ray atomic energy levels," *Rev. Mod. Phys.* **39**, 125 (1967); corrected in 1998 by E. Gullikson (LBNL, unpublished). For further updates, consult the Web site <http://www.cxro.lbl.gov>. The energies are given in electron volts relative to the vacuum level for the rare gases and for H₂, N₂, O₂, F₂, and Cl₂; relative to the Fermi level for the metals; and relative to the top of the valence bands for semiconductors.
6. Photon energies in electron volts of some characteristic emission lines of the elements of atomic number $3 \leq Z \leq 95$, as compiled by J. B. Kortright, "Characteristic x-ray energies," in *X-Ray Data Booklet*, Lawrence Berkeley National Laboratory Pub-490 Rev. 2 (1999). Values are largely based on those given by J. A. Bearden, "X-ray wavelengths," *Rev. Mod. Phys.* **39**, 78 (1967), which should be consulted for a more complete listing. Updates may also be noted on the Web site <http://xdb.lbl.gov>.



Eric M. Gullikson received his BA in physics from the University of Hawaii in 1977 and a PhD in physics from the University of California, San Diego in 1984. After a post-doc at AT&T Bell Labs he joined the Center for X-Ray Optics at Lawrence Berkeley National Laboratory in 1987. He has worked on the development of high-accuracy reflectometry and scattering measurement techniques for EUV and soft x-ray radiation. He is author or coauthor of over 200 publications.



David Attwood received his PhD in Applied Physics from New York University in 1972. He has been a Professor in Residence at UC Berkeley since 1989. He was co-founder of the Applied Science and Technology PhD program and serves on its Executive Committee. He has been faculty advisor for the undergraduate Engineering Physics program for 15 years. His research interests center on the use of short wavelength electromagnetic radiation, soft x-rays, and extreme ultraviolet

radiation in the 1–50 nm range. Applications of particular interest include element specific soft x-ray microscopy and EUV lithography. He and his students are also active in the use of novel Fourier optics, image contrast techniques, and the development and use of coherent sources at these short wavelengths. At the contiguous Lawrence Berkeley National Laboratory, he is the founding Director of the Center for X-Ray Optics (CXRO) and was the first (1985–1988) Scientific Director of the Advanced Light Source (ALS). He is a Fellow Member of the American Physical Society and the Optical Society of America. He is author of *Soft X-Rays and Extreme Ultraviolet Radiation: Principles and Applications* (Cambridge University Press, 2000). His lectures are regularly broadcast live over the Internet and electronically archived, such as at <http://www.coe.berkeley.edu/AST/sxreuv> and <http://www.coe.berkeley.edu/AST/srms>.

Index

#

10×-II Schwarzschild, 14
193 nm, 588, 606, 616, 629, 634
248 nm, 606, 613, 616

A

aberration, 205, 207, 213
 correction, 24
absolute ion flux, 295
absorber defect inspection, 357
 repair, 357
absorber layer, 349
absorber stack etch, 355
absorption
 data, 643
 edge of Si, 4
absorption coefficient, 36
 definitions, 391
 of EUV photoresists, 391
absorption cross-sections of the elements,
 392
acid diffusion, 395, 426
actinic inspection, 342
Advanced Light Source (ALS), 140, 177,
 213, 241, 408
Advanced Micro Devices (AMD), 60
Advanced Technology Program (ATP), 41
aerial image, 208, 470, 471, 475
 monitors, 217
 sensor, 507
Airy pattern, 163
alpha class lithography tool, 87
alternating phase shift mask (APSM), 371,
 372, 603
American Institute of Physics (AIP), 242
amorphous, 239
amortize, 627, 635
amplitude defect, 343
annealing temperatures, 315
annular illumination, 522
antireflective coating (ARC), 328, 350, 401
apodization, 136, 171, 194
appearing dose (Da), 565
application specific integrated circuit
 (ASIC), 597, 600, 603, 627, 635, 638
asphere fabrication, 27
aspheric

 departure, 24, 137, 143, 467
 mirror, 15, 31, 154
 surfaces, 2, 18

Association for Super-Advanced Electronics
 Technologies (ASET), 19, 70, 420
atomic force microscopy (AFM), 16, 340,
 528
atomic hydrogen, 230
atomic layer deposition (ALD), 180
attenuated phase shift mask, 366
at-wavelength inspection, 34, 35
Auger electron spectroscopy (AES), 246, 303
autofocus, 467
automated material handling systems
 (AMHS), 607, 608
automated process control (APC), 628

B

backside conductive coating, 349, 353
bandwidth (BW), 213
barrier layers, 310
beamline, 115, 213, 217, 221, 241, 422, 613
Be K edge, 188
Bennett relation, 110
beta class, 220
bilayer period, 287
bilayers, 290
binary chrome on glass (BIN COG), 603,
 618
binary collision approximation (BCA), 271
boron-containing resists, 425
Bossung curve, 352, 472, 487, 520
bottom antireflective coating (BARC), 589
Bragg
 equation, 336
 reflectors, 135
 wavelength, 21
bright-field signal, 342
Brookhaven National Laboratory (BNL), 37,
 397
buffer layer, 349
 etch, 360

C

calibrated debris diagnostic tool, 292
calixarenes, 421
Canon, 66

- capping layer, 231, 302
 - carbon
 - contamination, 35
 - deposition, 229
 - catoptric projection system, 136
 - cell projection (CP), 626
 - Center for Plasma Material Interactions (CPMI), 292
 - Center for X-Ray Optics (CXRO), 297
 - database, 193, 297, 388, 643
 - centroid wavelength, 335
 - changes in joint requirements for EUV sources, 105
 - charge-coupled device (CCD), 209, 215, 344
 - charge exchange, 295
 - charging, 359
 - chemically amplified photoresist (CAR), 404, 433, 604
 - chemical-mechanical polishing (CMP), 395, 403, 507
 - chemical vapor deposition (CVD), 189
 - chromatic vignetting, 23
 - chuck nonflatness, 504
 - cleaning
 - cycles, 280
 - in-situ, 120, 228, 232
 - optics contamination, 249
 - clear aperture (CA), 165
 - clear defect, 357
 - clearing dose
 - (Dc), 565
 - (Eo), 386, 428
 - coefficients of thermal expansion (CTE), 173, 329
 - coherent flux, 213
 - collector
 - lifetime, 39, 281
 - mirror, 265, 287
 - reflectivity, 117
 - competitive technologies, 78
 - component degradation calculations, 108
 - computer-controlled surfacing (CCOS), 27
 - computer-generated holographic (CGH)
 - nulls, 28, 153, 155
 - condenser
 - mirrors, 38
 - optics, 179
 - confocal microscopy, 344
 - consumables, 589, 613, 616
 - contact size variation, 548
 - contamination, 232, 290
 - contrast transfer function (CTF), 530
 - conversion efficiency (CE), 37, 287
 - of EUV sources, 112
 - for Xe, Li, and Sn, 112
 - cooperative research and development
 - agreement (CRADA), 12, 58, 66, 76, 82
 - coordinate measuring machine (CMM), 174
 - cost of ownership (CoO), 585
 - cracking of residual hydrocarbons, 33
 - critical dimension (CD) control, 31, 37, 108, 148, 355, 497, 551, 610, 611, 618, 627, 630, 633
 - critical-illumination optics, 12
 - CrON, 618
 - cross-grating, 214
 - cross-sectional TEM, 335
- D**
- damped least squares (DLS), 136
 - dark-field microscopy, 342
 - DC-magnetron, 171
 - debris, 290
 - measurement, 292
 - mitigation, 37, 39, 279, 296
 - suppression, 269
 - debris mitigation tool (DMT), 305
 - defect, 589, 590, 594, 603, 611, 617, 626, 629, 630, 633, 634, 640
 - density reduction, 340
 - in ultrathin resist films, 397
 - printability, 528
 - Defense Advanced Research Projects Agency (DARPA), 65
 - dense plasma focus (DPF), 114
 - Department of Commerce (DOC), 65
 - Department of Defense (DOD), 65
 - Department of Energy (DOE), 12, 18, 56, 58
 - deposition, 270, 286
 - depth of focus (DOF), 21, 408, 517, 525, 629
 - design of experiment (DOE), 411
 - die size, 597, 598, 600, 603, 639
 - diffraction-limited, 213
 - imaging, 7
 - diffusion barriers, 286
 - digital signal processor (DSP), 596
 - Dill B- and C-parameters, 388
 - dimethylaminopentamethyldisilane (DMAPMDS), 395
 - dioptric projection lens, 151
 - direct cover with absorber pattern, 347
 - discharge-produced plasma (DPP), 109, 286, 453, 472, 629
 - dose
 - sensor, 507
 - to clear (E_0), 559, 624
 - d spacing, 333
 - dual pod concept, 508
 - dummification, 568
 - DUV contrast, 328
 - dynamic random access memory (DRAM), 596, 597, 600, 603, 627, 639

E

- e-beam
 - repair technology, 359
 - writing, 355
- electric-field foil trap, 299
- electrode
 - lifetime, 125
 - materials, 292
- electron beam, 209
 - repair, 346
- electron-beam projection lithography (EPL), 66, 588
- electron binding energies, 653
- electrostatic chuck, 349, 461, 482, 503
- embedded phase shift masks (ePSM), 368, 570
- energy sector analyzer (ESA), 292
- engineered MLs, 89
- engineering test stand (ETS), 72, 147, 517–519
 - camera, 178
- environmentally stable chemically amplified photoresists (ESCAP), 404, 407
- erosion, 270, 290
 - rate, 271, 297
- etch
 - rates, 302
 - selectivity, 356
- etch stop layer (ESL), 367
- etched binary mask, 364
- étendue, 150
 - mismatch, 118
 - of source output, 104
- E10 RAM, 624
- EUV
 - absorbance, 393
 - attenuation, 368
 - blank requirements, 327
 - collection and illumination system, 455
 - critical issues, 105
 - illumination, 473
 - imaging objective, 453
 - imaging tool, 344, 450
 - interferometry, 31, 221
 - microscope, 475
 - microstepper, 138, 453
 - objective, 475
 - optics, 453
 - PAG, 426
 - radiation monitoring, 463
 - reflectometry, 336
 - reticle aerial image, 485
 - source, 103, 453, 472
 - performance, 112
 - power measurements, 115
 - requirements, 106
 - technology limits, 116
 - EUVL, 1–3, 7, 16, 104
 - optical design considerations, 135
 - printing, 90
 - EUV LLC, 2, 59
 - business model, 60
 - funding, 76
 - organizational structure, 63
 - program goals, 61
 - EUV mask
 - fabrication process, 327
 - technology, 326
 - EUV-reflective ML coating, 327
 - EUV-2D resist, 393, 524
 - exact constraint design, 177
 - exposure
 - dose control, 469
 - mechanisms, 426
 - sensitivity curves, 390
 - tool cell, 589, 606, 611, 622, 635
 - laser, 613
 - throughput, 589
 - wavelength, 21
 - exposure-defocus (E-D) process window, 170
 - exposure latitude (EL), 519, 629
 - extended DUV resists, 90
 - extension of DUV, 78
 - Extreme Ultraviolet Imaging Telescope (EIT), 228
 - Extreme Ultraviolet Lithography System Development Association (EUVA), 19
 - Extreme UV Alpha Tools Integration Consortium (EXTATIC), 19
 - Extreme UV Concept Lithography Development System (EUCLIDES), 19
- F**
 - Faraday cup, 292
 - far field (FF), 210, 264
 - fast-ion mitigation, 296
 - fast ions, 295
 - field image alignment (FIA) sensor, 507
 - field size, 501, 596, 598, 607, 613, 627
 - figure
 - aberrations, 207
 - error, 207
 - film quantum yield, 434
 - finite element analysis (FEA), 266, 459
 - flare, 15, 169, 551
 - calculation, 551, 557
 - mitigation, 568
 - flare variation compensation (FVC), 566
 - flatness requirement, 340
 - Flying Circus (FC) project, 115
 - focus budget, 509
 - focus exposure latitude, 630
 - focus exposure matrix (FEM), 519
 - focused ion beam (FIB), 345

foil trap, 126, 298
 Foucault, 208, 210
 Fourier transform infrared spectroscopy (FTIR), 247
 Free electron lasers (FEL), 221
 front-opening unified pod (FOUP), 628
 full-width half maximum (FWHM), 524
 Fundamenteel Onderzoek der Materie Institute (FOM), 19

G

gas
 curtain mitigation, 299
 flow, 298
 jet, 38
 transmission, 117
 gas-assisted etching (GAE), 357
 geometrical collector efficiency, 117
 glass-transition temperature (T_g), 395
 good wafer level exposure (GWLE), 109, 587, 588, 595, 604, 636, 637
 graphical user interface (GUI), 96, 464
 grating, 212
 grazing angle collector, 261
 grazing-incidence (GI), 106, 263

H

half pitch (HP), 42, 261
 Hartmann
 test, 208
 wavefront sensor, 215
 heat stability, 316
 Henke Tables, 36
 hexamethyldisilazane (HMDS), 399
 high-power laser status, 123
 high-purity fused silica (HPFS), 618
 high-resolution imaging, 488
 high-spatial-frequency errors, 170
 high spatial frequency roughness (HSFR), 16, 330
 high volume manufacturing (HVM), 104
 Himeji Institute of Technology (HIT), 19, 41
 horizontal/vertical (HV) effects, 533
 hydrogen silsesquioxane (HSQ), 422

I

IBM, 60
 I-line, 599, 601, 602, 606, 610, 613, 615, 616
 Illinois ion energy reduction technique (INERT), 298
 illumination optics, 12, 494
 design, 494
 illumination uniformity, 468
 image
 flare, 30
 placement, 617, 627, 629
 image log slope (ILS), 406, 567
 image placement error (IPE), 149, 331

imaging layer (IL), 395, 399
 implantation, 286
 implementation delays, 77
 inductively coupled plasma, 302
 Infineon, 60
 in-plane distortion (IPD), 354, 504
 in-situ
 cleaning, 301
 metrology, 246
 instantaneous clear aperture (ICA), 165
 integrated energy stability, 104
 integrated product scheduling (IPS), 628
 Intel, 60
 intellectual property (IP), 59
 disclosures, 76
 portfolio, 76
 interdiffusion
 layers, 312
 of MLs, 497
 interface stabilization, 312
 interferogram, 206
 interferometer, 207, 208
 interferometry, 206, 219–222
 intermediate focus (IF), 104, 106, 262, 316, 463, 495
 International SEMATECH, 65
 International SEMATECH Manufacturing Initiate (ISMI), 600
 International Technology Roadmap for Semiconductors (ITRS), 42, 58, 127, 489
 inverse bremsstrahlung absorption (IBA), 111
 inverse Cassegrain, 23
 ion
 energy, 293
 gun, 292
 polishing, 339
 spectra, 293
 ion beam figuring (IBF), 331
 ion-beam projection lithography (IPL), 66, 588
 ion beam sputter deposition (IBSD), 34, 333
 ion-enhanced etching, 301

J

Japan Society for Precision Engineering (JSPE), 42, 50
 joint development agreement (JDA), 66, 450
 joint development program (JDP), 59
 joint requirements, 107
 for EUV sources, 104

K

kinetic energy, 111, 296
 kirk test, 559
 knife-edge, 208, 210

k_1 , 516, 603, 619, 630, 631
KRS photoresists, 413

L

lactonization polarity switch, 419
laser
 ablation, 357
 excimer, 9, 111, 115, 451, 494, 589, 605, 610, 624
 plasma source, 9
 power, 123
 source, 604, 607, 612, 613, 624, 629, 633, 636
laser-produced plasma (LPP), 111, 285, 629
laser shock wave cleaning (LSC), 361, 363
Lawrence Berkeley National Laboratory (LBNL), 213, 216
Lawrence Livermore National Laboratory (LLNL), 219
layer mixing, 286
layered synthetic microstructure (LSM), 3
Li DPP, 123
lifetime, 290
light element gas, 299
light scattering and surface roughness, 553
line edge roughness (LER), 42, 428, 539, 543
 versus E_{size} , 399
line edge roughness transfer function (LTR), 539
line width roughness (LWR), 437
liquid-droplet targets, 39
lithium salt of ethylenediamine (LiEDA), 36
local oxidation of silicon (LOCOS), 16
logic, 596, 597, 604, 607, 627
Los Alamos National Laboratory (LANL), 45
low-angle x-ray diffraction, 336
low defect depositon (LDD), 67
low departure aspheric reflectors, 15
low-frequency (figure) errors, 165
low-pressure chemical vapor deposition (LPCVD), 16
low-temperature oxide (LTO), 16, 17
low thermal expansion material (LTEM), 32, 327

M

magnetic
 confinement, 296
 field, 297
magnetohydrodynamics (MHD), 111
magnetorheological finishing (MRF), 175, 331
magnetron sputtering, 286, 334
Marechal criterion, 31, 164, 168
mask, 325, 587
 cleaning, 361
 format, 326

 handling, 353
 patterning, 355
 roughness, 543, 549
 substrate, 328, 329
Mask Blank Development Center (MBDC), 90, 341
mask blank fabrication, 332
mask error enhancement factor (MEEF), 574
maskless lithography (ML2), 631
mass-limited target, 39
master oscillator–power amplifier (MOPA), 123
material characterization, 294
maximum solid angle input to illuminator, 104
mean time between failure (MTBF), 108, 619, 622
mean time to repair (MTTR), 619, 622
mean time to test (MTTT), 611
membrane micropore filtration, 625
Metal-oxide semiconductor (MOS) devices, 11
 demonstration, 16
MET-1K resist, 525
microchannel plates (MCP), 293
Microelectronics Development for European Applications+ (MEDEA+), 19
micro-exposure tool (MET), 138, 140, 216, 530
 camera, 178
 projection optics performance summary, 143
Micron, 60
microprocessing unit (MPU), 597, 600, 603, 606, 609
microstepper design parameters, 140
mid-spatial-frequency errors, 169
mid-spatial-frequency roughness (MSFR), 15, 30, 140, 329
minimum feature size (MFS), 634
mirror
 lifetimes, 292
 reflectivity, 120
mitigation
 debris, 37, 106, 116, 237
 thermal, 121
modified alternating phase shift mask, 372
modified Bragg's law, 333
modified illumination, 522, 533
modulation transfer function (MTF), 542
molecular beam epitaxy (MBE), 189, 250
Mo/Si, 228, 618
Motorola, 60
multilayer (ML), 135, 228
 added figure errors, 194
 adders, 340
 characterization, 335

- coatings, 187
- defect compensation, 347
- defect inspection, 342
- defect repair, 345
- deposition, 189, 332
- materials, 188
- resists, 394
- thickness specifications, 193

N

- nano imprint lithography (NIL), 631
- nanostructure, 238
- National Institute for Standards and Technology (NIST), 65
- National Synchrotron Light Source (NSLS), 203
- Nd:YAG, 123
- negative chemically amplified resist, 388
- negative tone resists, 419, 425, 569
- next-generation lithography (NGL), 62, 285, 488
- Nikon, 66
- Nikon Step and Repeat System (NSR), 507
- non-actinic inspection, 342
- nonflatness, 331
- normal-incidence (NI)
 - angle, 106
 - mirrors, 290
 - molybdenum-silicon (Mo/Si) multilayer (ML), 136
 - reflective optics, 3
- normalized image log slope (NILS), 472, 570
- NPNPNP configurations, 154
- n-type metal-oxide semiconductor (NMOS), 16, 17, 606
- null tests, 218
- numerical aperture (NA), 21, 22, 136, 496, 498

O

- off-axis illumination (OAI), 570, 624
- Office of the Director of Defense Research & Engineering (DDR&E), 65
- Offner relay, 154
- Offner ring-field imaging system, 7
- opaque defect, 357
- optical
 - constants, 192, 643
 - design, 269
 - microscope, 471
- optical proximity correction (OPC), 347, 607, 620, 631
- Optical Society of America (OSA), 9, 42
- optical transfer function (OTF), 539
- optics, 219, 230
 - cleaning, 300
 - fabrication, 89
 - lifetime, 232

- out-of-band (OOB) radiation, 118
- out-of-plane distortion, 354, 504
- overhead (OH), 592, 593, 607, 609, 610, 612, 617, 623, 626, 634
- overlay (OL), 611, 624, 628, 633, 634, 637
- overlay budget, 509
- oxidation, 229

P

- partial coherence, 524
- particle, 508
 - flux, 291
- patents, 93
- pattern transfer of UTR into hard masks, 400
- Paul Scherrer Institut (PSI), 418
- peak
 - reflectance, 333
 - reflectivity, 312
 - wavelength, 312
- penetration depth, 6
- Petzval sum, 152, 156
- phase
 - bumps, 163
 - defects, 33, 343, 345
 - errors, 163
- phase-measuring interferometer (PMI), 27
- phase-measuring microscopy (PMM), 176
- phase shift concept, 363
- phase shifter, 368
- phase shifting, 212
- phase-shifting diffraction interferometer (PSDI), 176, 219
- phase-shifting point diffraction interferometer (PS/PDI), 20, 179, 211
- phase-shift mask (PSM), 363, 527
- photo acid generators (PAGs), 391
- photochemical decomposition mechanism of PMMA, 417
- photoelectron emission microscopy (PEEM), 344
- photon energies, 659
- photoresist, 221, 383
- physical constants, 652
- physical vapor deposition (PVD), 189
- Physikalisch-Technische Bundesanstalt (PTB), 32, 241
- pinch effect, 109
- pinhole, 210–213
 - defects, 397
- pits, 340
- planarization layer (PPL), 395
- plasma-assisted cleaning by electrostatics (PACE), 362
- plasma-enhanced chemical vapor deposition (PECVD), 249
- plasma expansion, 286, 292
- plasma sources, 109

PNNPNP configuration, 153
PNPPNP configuration, 150
PN114, 388
point diffraction, 208, 213
point-diffraction interferometry (PDI), 210
point-spread function (PSF), 163, 524, 555
polybutene-1 sulfone (PBS), 36
polycrystalline, 239
polyhydroxystyrene (PHS), 413
polyimide, 181
polymethylmethacrylate (PMMA), 385, 389, 416
 exposure mechanism, 417
polystyrene latex (PSL), 332
post-exposure bake (PEB), 355, 388, 395, 409, 414, 429
power spectral density (PSD), 30, 167, 554
PPNNPN configuration, 152
preventative maintenance (PM), 593
printed CD bias, 351
process window, 520, 524, 551
productivity, 586, 599, 600, 603, 606, 610, 613, 619, 622, 627, 629, 635, 639, 640
profilometer, 303
PRogramme Extreme UV (PREUV), 19, 100
projection optics (PO), 163, 207, 229, 498
projection optics box (POB), 566
projection optics performance summary for the ETS, 148
proximity effect, 355
pulsed foil trap mitigation, 298
pupil, 212

Q

quantum yield, 387, 418
quartz crystal, 298
quartz crystal microbalance (QCM), 126

R

Rayleigh
 constant, 516
 criterion, 31
reactive ion etching (RIE), 301, 386
reflection
 coefficient, 273
 of fast particles, 272
reflection mask (RM), 13, 141, 386
reflective
 masks, 7
 ML coatings, 2
reflectivity, 3, 191, 233, 287, 560
 of MLs, 5, 21, 41
 collector, 117
 degradation, 104, 120, 241, 265, 269, 286, 290, 297, 345
 loss, 290
relative humidity (RH), 416

reliability, availability, and maintainability (RAM), 619
repeller field, 38
repetition frequency, 104, 497
Research Development Center (RDC), 81
residual gas analyzer (RGA), 302, 467
resist
 development, 450
 exposure, 470
 sensitivity, 119
 sidewall profile, 23
resolution (RES), 21, 516
 enhancement, 373, 516, 522
resolution enhancement technique (RET), 620, 624, 630, 640
resolution, LER, sensitivity (RLS), 384, 436
reticle, 105, 107, 109, 138, 163, 335, 459, 461, 475, 589, 601, 605, 607, 617, 620, 624, 626, 628–630, 633, 634, 639
 and wafer stages, 502
 chuck, 503
 focus sensor, 506
 handling system, 508
 imaging, 475
 imaging actinic microscope, 450, 470
 loader, 483
 stages and chuck, 479
reticle imaging microscope (RIM), 470
return on investment (ROI), 489
RF bias, 301
right of first refusal (ROFR), 59, 61
ring-field, 25
ring-opening metathesis polymerization (ROMP), 424
risk management, 68
Ronchi, 208
Ronler Processing 1 (RP1), 559
roughening of surfaces, 15, 18, 30, 32, 265, 286, 290
roughness of interfaces, 339
 specification, 171
Ru(0001), 248
Ru erosion, 275
Ruthenium, 231

S

sagittal plane, 151
Sandia National Laboratories (SNL), 9, 56, 187, 229
scanner, 596, 601, 604, 608–610, 613, 622, 626
 EUVL, 104, 193, 352, 493
scanning electron microscopy (SEM), 34, 359, 386, 399, 417, 421, 447
scanning probe-based mechanical nanomachining, 357
scanning tunneling microscopy (STM), 389
Scheimpflug condition, 141

- schematics of EUV source, 106
- Schwarzschild, 2
 - objective, 139
 - 1/8 reduction optic, 386
- secondary electrons, 236
- secondary-ion mass spectroscopy (SIMS), 247
- secondary ion source, 339
- selectively etch, 301
- self-sputtering, 271
- Semiconductor Equipment and Materials International (SEMI), 89, 491, 588
- Semiconductor Industry Association (SIA), 65, 99, 638
- Semiconductor Research Corporation (SRC), 65, 86, 99
- SEMI E10, 619
- SEMI E35, 592, 639
- SEMI E79, 619
- SEMI P37, 329
- SEMI P38, 326, 353
- SEMI P40, 353, 483, 504
- send-ahead (SAHD), 611
- Shack-Hartmann wavefront sensor (SHWS), 216
- shadowing effect, 351
- shearing, 208, 213
- sidewall angle, 37
- silicide, 338
- silicon-nitride, 209
- silicon oxynitride (SiO_xN), 400
- silicon resists, 422
- Silicon Valley Group Lithography (SVGL), 61
- silicone-based positive photoresist (SPP), 386
- single-layers resist (SLR), 401
- six-mirror EUVL projection systems, 149
- smoothing substrate particles, 339
- Sn contamination, 300
- Sn DPP, 122
- Sn fluence, 278
- Sn halides, 280
- Sn LPP, 125
- Sn surface dose, 275
- Sn-Ru interaction, 271
- snow plough model, 111
- soft bake (SB), 409, 441, 626
- soft x-ray projection lithography (SXPL), 6, 10, 40, 43, 99, 252, 438, 512
- solar and heliospheric observatory (SOHO), 228
- source
 - cleanliness, 104
 - components and their lifetimes, 125
 - EUV, 104
 - requirements, 104, 106, 496
 - size, 113, 118, 119, 496
 - sources of flare, 551
 - spectral purity, 104
 - spectral purity filter (SPF), 106, 118, 122, 458, 464
 - transmission, 116, 117
 - spectral reflectivity of a ML-coated mirror, 108
 - spherical energy sector analyzer (ESA), 292
 - spin-on glass, 181
 - sputtering yield, 291, 309
 - standard mechanical interface (SMF), 333, 451
 - statements of work (SOW), 90
 - statistical process control (SPC), 628
 - stepper, 589, 601, 604, 609, 610, 624, 626, 629, 632–634, 640
 - Strehl ratio, 148, 164, 213
 - stress reduction, 340
 - subaperture polishing, 28
 - Subfield Exposure Station (SES), 518, 522
 - sub-resolution assist features (SRAF), 620
 - substrate
 - defect, 332
 - phase defects, 35
 - super acids, 405
 - Super-Advanced Electronics Technologies (ASET), 19
 - supersonic hydrocleaning (SHC), 361
 - surface
 - chemistry, 246
 - erosion, 286
 - figure, 27
 - finish, 27
 - oxide, 337
 - surface-imaging resist, 36
 - synchrotron, 9, 37, 207, 221
 - system end-of-life transmission, 107
 - systematic errors, 176, 218, 219
- T**
 - tandem stage, 624
 - target accuracy, 207
 - telecentric, 9, 24
 - test elements group (TEG), 496
 - test structure, 403
 - tetramethylammonium hydroxide (TMAH), 422
 - thermal
 - and radiation loads, 305
 - loading of illuminator, 497
 - stability, 286, 312
 - thermo-opto-mechanical design, 267
 - throughput (TPT), 587, 589, 591, 596, 601, 612, 613, 618, 625, 626
 - time
 - of arrival, 293
 - of flight spectra, 293
 - Tinsley, 66

tool

- core, 459, 479
- subsystems, 459
- utilization, 589
- top surface imaging (TSI), 394
- total defects, 340
- total integrated scatter (TIS), 557
- total system wavefront error, 31
- track, 589, 590, 595, 604, 607, 616, 617, 622, 625, 626
- transition region and coronal explorer (TRACE), 228
- transmission electron microscope (TEM), 33, 334
 - characterization, 316
- transmission image sensor (TIS), 217
- transmission mask (TM), 141
- trapped friction, 177
- TRW, 66
- twin scan dual-stage, 624
- two-aspherical-mirror imaging system, 12

U

- ultrahigh vacuum (UHV), 451, 464, 480
- ultra-low-expansion (ULE) light-weighted chucks, 461
- ultra-low-expansion (ULE) (Corning glass), 174, 329
- ultra-pure water (UPW), 361, 617
- Ultratech, 66
- ultrathin resist (UTR), 397
- unexposed film thickness loss (UFTL), 405
- United States Advanced Lithography (USAL), 61
- United States National EUV Lithography Program, 12
- utility requirements, 114
- utilization, 589, 593, 601, 606, 613, 619, 622, 628, 632, 634, 636
- UV cleaning, 361

V

- vacuum
 - conditions, 467
 - system, 464, 483
- vacuum ultraviolet (VUV), 118, 266
- vector-shaped beam (VSB), 626
- Veeco, 66
- visible-light interferometry, 28, 89, 206, 219

visible microscope, 477

Virtual National Laboratory (VNL), 59

W

wafer

- alignment sensor, 507
- and reticle chucks, 461
- and reticle loading, 461
- and reticle stages, 459
- chuck, 505
- focus sensor, 506
- handling system, 508
- size, 601, 607, 622
- throughput budget, 510
- throughput model, 109
- wafers/hour (WPH), 104, 109, 606, 613, 624
- wafers/mask (WPM), 590, 596, 597, 603
- wall plug-to-laser light CE (wall-plug efficiency), 112, 115
- water vapor, 229
- wavefront, 205, 206, 222
- wavefront error (WFE), 145
- Wölter ellipsoid collector shells, 455
- Wölter type, 117
- Wölter-type mirror, 265
- worldwide EUV interest, 86

X

- x-ray diffraction (XRD), 315, 336
- x-ray photoelectron spectroscopy (XPS), 305
- x-ray proximity lithography (XPL), 4, 10
- Xe, 270
- Xe DPP, 121
- Xe LPP, 124

Y

- yield, 587, 589–591, 597, 601, 604, 606, 607, 610, 617, 619, 622, 625–627, 630, 633–635, 637–639
- y-monopole, 538
- yttrium aluminum garnet (YAG), 37, 112, 113, 115, 123, 124, 344, 363, 471, 477

Z

- Zernike, 219
 - expansion, 140
 - terms, 163
- Zerodur, 174, 175
- zone plate, 216, 342
- ZrSiO₄, 618