Designing for MEMS Reliability

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Introduction

Microelectromechanical systems (MEMS) devices are being manufactured in the hundreds of millions and are widely deployed for pressure sensor, accelerometer, display, and printing applications.[1] This suggests customer confidence in the long-term reliability of MEMS (also known as microsystems or micromachines) under diverse stringent conditions. However, reliability-physics aspects of these early MEMS applications may have been viewed as a market differentiator, resulting in limited public dissemination of MEMS-specific physical-failure models and appropriate design solutions for long-term reliability.

This article provides a review of MEMS reliability-physics issues and MEMS-specific test methodologies, failure modes, and solutions. The examples emphasize electrostatically actuated MEMS and materials choices deriving from silicon or silicon-compatible fabrication techniques leveraged from the microelectronics industry. Solutions to reliability issues can be based on design, materials, or operational choices. Reliability concepts are potentially applicable over many MEMS device types, despite differences in materials choice, fabrication technique, or microelectromechanical design.

Designing for Reliability

To ensure built-in reliability, MEMS reliability research has a fourfold mission:

1. To obtain a fundamental understanding of chip-level, MEMS-specific failure mechanisms;
2. To facilitate the design, packaging, manufacturability, and testing of commercially interesting MEMS research and development concepts;
3. To preview compliance and qualification testing of MEMS devices; and
4. To ensure the long-term reliability of MEMS products in the field.

Commercial applications of MEMS that mandate rapid introduction into the marketplace can benefit from such a built-in reliability paradigm. Specifically, an interdependent relationship and tight feedback loop between all contributors to device, subsystem, and system design, fabrication, manufacturing and testing, reliability physics, and packaging can greatly accelerate time-to-market of emerging MEMS products (see Figure 1).

Classic reliability-physics methodology, as applicable to MEMS, begins with an initial test plan designed to reveal failure modes or failure mechanisms through the application of a series of, for example, thermal, electrical, mechanical, and optical environmental applied conditions. A fundamental understanding of each observed failure mode or mechanism is then sought. Experiments are designed to identify and isolate each mechanism, and to determine its fundamental physical characteristics, root cause, and statistical distribution.

Accelerating factors for each mechanism are then identified to permit more rapid (i.e., time-efficient) experimentation. "Overstressing" strategies for accelerating the failure of the devices relative to nominal operating conditions depend on device design, materials choices, and intended operating conditions.[2] The most straightforward accelerated test design results in a single failure mode whose characteristics represent nominal operating and environmental conditions, thus facilitating extrapolation and prediction of lifetimes.

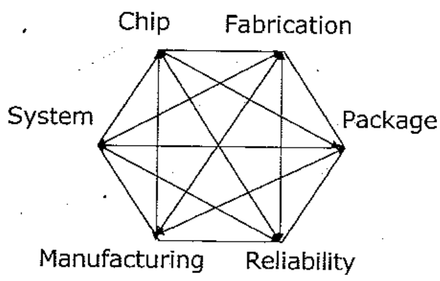

Figure 1. Graphic representation of built-in reliability paradigm based on interdependent microelectromechanical systems (MEMS) product-development activities.

The most widely known and conceptually simple graphic representation of reliability concepts is known as the bathtub curve (Figure 2).[3,4] The relative contributions of "infant mortality," external events, and wear-out phenomena are modeled as independent and additive to obtain the characteristic bathtub-shaped curve of hazard rate versus time.

Infant mortality in MEMS devices is visualized as an initially high, rapidly diminishing hazard rate. It is assumed to derive primarily from nonuniformity and unpredictable or unobserved discrepancies in manufacture. Infant mortality may result from missing or poorly formed structural elements, wiring, or electrodes; surface or bulk contamination; scratches; bridging; particulate; stringers; incomplete hermetic seals; and similar fabrication- or packaging-induced phenomena. Infant mortality can be greatly reduced by burn-in or screening techniques at the MEMS manufacturer, before the devices reach the consumer.

After the initially high rate of infant-mortality failures has diminished, a relatively small, time-independent failure-rate characteristic persists. It is attributed to random unexpected external events (e.g., lightning strikes, earthquakes) that are supposed to have an equal probability of affecting both "strong" and "weak" devices.

Wear-out is conceptualized as a sudden rapid increase in the failure rate after a period of useful product life. Wear-out of MEMS might result from creep (e.g., in metals and polymers); fatigue; formation and propagation of microcracks; interdiffusion (e.g., in metals and semiconductor junctions); compromised barrier layers (e.g., metallization); plasma-induced surface damage; outgassing, moisture uptake or creeping of epoxy die attach materials; dielectric breakdown; corrosion; and many other mechanisms. The wear-out mechanisms characteristic of a given MEMS product are specific to the chosen materials system, fabrication techniques, design, packaging, and operating conditions.

Wear-out mechanisms are presumed to be present in, and to eventually cause the failure of, every device. However, built-in reliability that prevents failure due to wear-out during the intended service life is both possible and normative. This provides the motivation for reliability-physics investigations that iteratively identify the "weak links" (or the most dominant infant-mortality or wear-out mechanisms) in a given technology, device, or product sce-

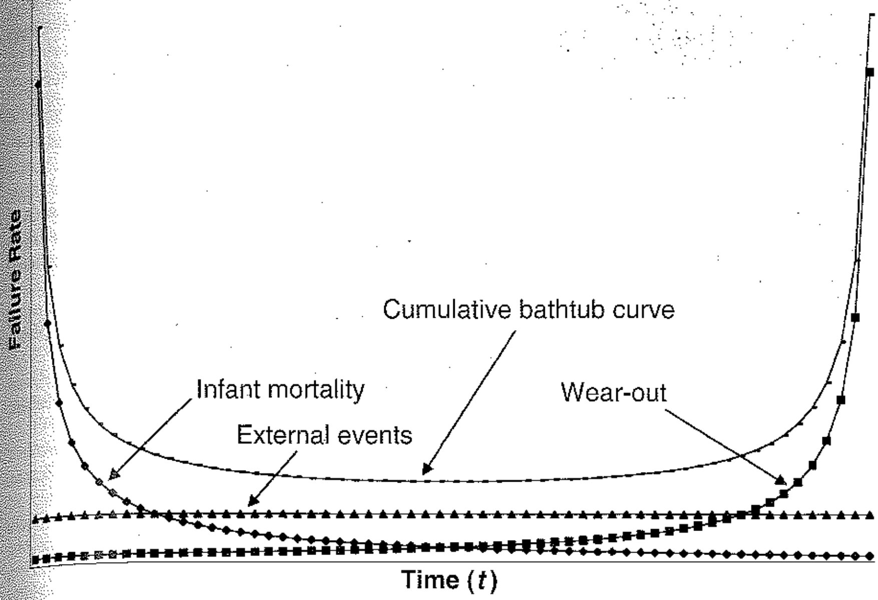

Figure 2. Graphic representation of reliability concept known as the bathtub curve, showing hazard rate versus time. The relative contributions of infant mortality, external events, and wear-out are modeled as independent and additive.

nario, then redesign the technology or product based on the understanding gained.

Exponential, lognormal, and Weibull distributions are variously used to predict lifetimes based on experimental results.[3,4] Failures in 10^9 hours, known as FITs or FIT rates, are used as a metric for comparing test populations. For example, 1 FIT is equivalent to 1 failure in 10^6 devices in 1000 h, or 1 failure in 10^5 devices in 10,000 h. The advantageous statistics of high-volume manufacturing are readily apparent when estimating FITs. As an alternative to large-volume statistical reliability studies, deterministic and predictive methods of MEMS reliability investigation based on failure-mechanism modeling have been demonstrated.[5,6]

MEMS Reliability Test Methodology

For silicon-compatible MEMS electrostatic devices, lessons learned for a broad spectrum of microelectronics devices suggest an initial MEMS reliability evaluation strategy founded on MIL-HDBK-217.[7] This includes protocols for the characterization of materials, processing, packaging, and device design attributes of potential MEMS products under conditions of mechanical, thermal, electrical, and environmental overstress. Mechanical MEMS-specific testing under dynamic, static, or transient operational modes complements the standard methodologies.

Custom environmental chambers enable noninvasive optical (and electrical) monitoring of MEMS devices undergoing electrical, mechanical, or thermal cycling, or static tests in a variety of environments including air, vacuum, humid, and inert ambients.[8,9] Innovations in the use of noninvasive (nontactile) optical techniques permit *in situ* characterization of MEMS mechanical performance under both nominal conditions and accelerated testing experiments. Scanning laser doppler vibrometry is used to quantify dynamic attributes of periodically actuated MEMS devices, such as out-of-plane deflections, resonant mode integrity, mode coupling, and deformation.[10–12] In strobed interferometry, an interferometric video microscope with strobed illumination synchronized to a MEMS device's motion is used to quantify out-of-plane and in-plane, periodic, step, frequency, static, and transient deflections.[13–15] Other noninvasive optical techniques for evaluating MEMS dynamics and system properties include light microscopy, static interferometry,[16] machine vision, and high-speed strobed-image capture.[8,17]

Standard microelectronics techniques and environmental chambers can be used for noninvasive reliability testing through electrical monitoring of resistive, capacitive, or electrostatic failure mechanisms of a MEMS device. Scanning and transmission electron microscopy, scanning probe microscopy (particularly atomic force microscopy),[18] focused ion-beam, and standard surface science techniques have also proven valuable in investigating MEMS failure modes.[19]

MEMS Failure Mechanisms, Root Causes, and Solutions

MEMS-specific reliability issues have recently been extensively reviewed.[20,21] Additional overviews, as well as detailed experimental results, have been presented at symposia devoted to MEMS reliability and related packaging issues.[22–31] A wide variety of failure mechanisms have been published for diverse MEMS device designs, materials systems, and field-deployment conditions. We present here a nonexhaustive survey representing important highlights of MEMS reliability based on MEMS materials issues, failure mechanisms, root causes, and solutions.

Initial instinctive perceptions of MEMS devices often include concerns over fragility and mechanical strength. However, the excellent mechanical properties of silicon[32] and related dielectrics (silicon dioxide, silicon nitride) provide a robust materials system in which to build MEMS devices. Appropriate geometric choices resulting in high-stiffness *(k)* and low-mass *(m)* MEMS devices further ensure a mechanically robust MEMS device, since the resonant frequency, and thus vibration or shock sensitivity, of a device are proportional to the ratio k/m. Vibration and shock measurements confirm the excellent mechanical properties of well-designed silicon MEMS devices.[33,34] MEMS fabrication techniques, device design parameters, operational modes,[8] and operating environments (and hence packaging) can be simultaneously optimized to afford the lowest possible initial materials defect density, stresses, and stress gradients. This can reduce the incidence of time-dependent phenomena such as crack initiation and propagation, fatigue-related fracture, or mass transfer through glide and diffusion mechanisms resulting in creep.[24]

Experimental test structures to study the nature of crack initiation and propagation in polycrystalline silicon reveal the significant effect of moisture in reducing the mechanical integrity of MEMS devices by stress-corrosion cracking.[35] MEMS devices themselves are increasingly used for mechanical "testing" of silicon and polysilicon materials properties.[36–39]

Fabrication procedures, design protocols, and modeling have been developed to engineer and control residual-stress gradients in thin films used to build MEMS.[40,41] This enables selective use of both stressed and unstressed thin films. "Stressy," or curling, MEMS devices can be used to do mechanical work, as in self-assembly during the release process,[42] or in conjunction with electrostatic or other actuation forces. Unstressed, "flat" MEMS structures more accurately reflect the "as-drawn" MEMS design, ensuring higher fabrication yields, and are extremely important for optical MEMS applications. Stresses due to coefficient of thermal expansion (CTE) mismatch in multimaterial MEMS devices must similarly be engineered.

Mechanical failure mechanisms in MEMS devices can be separated into bulk, thin-film, and surface effects. Bulk and thin-film effects include residual-stress gradients, thermal mismatch in multicomponent MEMS, and time-dependent responses to high stress levels resulting in creep, crack initiation at defects, and static or dynamic fatigue. While fatigue-induced crack growth has been observed for both polycrystalline and single-crystal silicon test structures, robust MEMS designs with excellent mechanical properties have been realized. Extensive fabrication, design, and testing of diverse MEMS devices confirms that devices whose fabrication, design, and operational attributes including environment (and thus packaging) have been optimized rarely exhibit bulk mechanical failure by fatigue or fracture.[25]

Mechanical failure mechanisms due to contacting, sliding, or rubbing MEMS device surfaces have been widely reported. Stiction (static friction, or adhesion)[43] must be avoided during both fabrication and operation. Wet chemical sacrificial-layer etches are typical of the "release" process in MEMS fabrication. To avoid stiction during release, fabrication techniques, including supercritical CO_2 drying,[44] sublimation, and self-assembled monolayer films, have been employed to prevent capillary forces from drawing compliant MEMS structures into contact with one another during the drying step. Design techniques to prevent both "release" and "in-use" stiction include the use of very stiff structures, flexure or bending structures without bearings, and "dimples" or other surface modifications that reduce the contact area between two MEMS surfaces.[29] Packaging techniques, including gettering,[31,45] that limit outgassing and moisture (or other contaminant gas) ingress can also be helpful in reducing in-use stiction. Finally, operational choices in conjunction with MEMS actuator and flexure design can reduce the incidence of surfaces contacting due to vibration, shock, or electrical overvoltage. Friction and wear of silicon MEMS surfaces can be reduced through the use of low levels of humidity,[9,46] anti-stiction coatings,[46] and selective tungsten coatings.[47]

Surface effects play a role as well in the electrical reliability of MEMS. Unpassivated surfaces exposed during the release step in MEMS fabrication may not be optimized. Surface leakage currents or associated anodic oxidation[48] may result in MEMS reliability issues such as shorting, open circuits, and capacitance changes. Surface charge trapping or generation[49] can result in short- or long-term mechanical drift of electrostatically actuated MEMS devices. Surface roughness or asperities may enhance the probability of electrical-field concentration, arcing, and related surface electrical breakdown.

Bulk or thin-film electrical-reliability issues of MEMS devices include radiation-induced dielectric degradation;[20] electric-field-induced dielectric breakdown; electrostatic discharge (ESD) and associated conductor melt, conductor fusion, or stiction;[50] electromigration (less significant for electrostatic than for electromagnetic actuation); and bulk or thin-film charge trapping and generation.

MEMS failure mechanisms based on thermal sensitivity may include CTE mismatch and associated delamination, curvature, deformation, or residual-stress relaxation; optical-wavelength absorption[51,52] and associated degradation of reflecting surfaces through grain growth, deformation, or melting; and time-dependent deformation due to creep or fatigue.

Summary

Microelectromechanical systems concepts have already been widely deployed across diverse market sectors, with varying stringent reliability requirements. As MEMS concepts continue to exhibit enormous potential in emerging market applications, rapid commercialization can be facilitated by a design-for-reliability or built-in-reliability mindset.

An effective MEMS reliability research program must identify and characterize chip-level, MEMS-specific, reliability-physics phenomena; extract and implement experiments based on accelerating factors; estimate lifetimes; and most important, iterate this process in tight concert with other areas of MEMS component, package, subsystem, and system development.

This article has presented examples of MEMS infant mortality and long-term wear-out reliability phenomena that can be addressed through a combination of materials choices, manufacturing practice, MEMS mechanical design, fabrication, packaging, and device-performance protocols.

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