The role of lasers in solar cell manufacture

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Abstract

Purpose – The aim of this paper is to provide a review of the present-day and anticipated future uses of lasers in the production of solar cells.

Design/methodology/approach – Following a brief introduction to photovoltaics (PV), this paper first describes the two main types of solar cell, crystalline silicon and thin film and then discusses the use of lasers in their manufacture. Finally, future developments are considered.

Findings – The paper shows that lasers are used in the manufacture of both crystalline silicon and thin film PV. Applications are many and varied, e.g. edge isolation, hole drilling, border deletion and selective doping but few are yet adopted universally across the industry. Significant future prospects exist for laser-based processes, as solar cell manufacturers seek to improve conversion efficiency and reduce production costs.

Originality/value – The paper shows that lasers play a vital role in solar cell manufacture and many additional applications will arise as photovoltaic technology is further developed.

Keywords Lasers, Solar power, Silicon, Semiconductors, Thin films, Research

Paper type Technical paper

Introduction

Photovoltaics (PV) is the generation of electrical power from sunlight and is the most rapidly growing field of "green" energy. Indeed, it is the fastest growing of all energy technologies, and PV production has been increasing by an average of more than 20 per cent each year since 2002. At the end of 2009, cumulative global PV installations surpassed 21 GW and annual installations reached to 7.3 GW in 2009, up from 6.08 GW in the previous year.

Despite this, PV technology is far from mature and R&D continues at a pace, with the aim of achieving improved conversion efficiency and reducing manufacturing and material costs. The "holy grail" for the PV technologist is to develop devices with sufficiently low costs and high enough conversion efficiencies to be competitive with traditional generation methods. Developments include new PV materials, improved cell structures and configurations and enhanced manufacturing processes, all areas where lasers are playing a role. This paper discusses the present-day and potential future uses of lasers in PV manufacture.

Solar cell technologies

There are two main PV technologies: crystalline silicon (c-Si) and thin film (TF). The former presently dominates the market which a share of over 85 per cent but TF technologies are emerging that are potentially cheaper and simpler to manufacture and have recently experienced very rapid growth.

Historically, c-Si has been used as the light-absorbing semiconductor, even though it is relatively inefficient and requires a considerable thickness of material, typically several hundred microns. Nevertheless, it yields stable cells with good conversion efficiencies and uses established process technology developed by the microelectronics industry. Two types of c-Si are used: monocrystalline, produced by slicing wafers from a high-purity, single-crystal boule, and multicrystalline, which is produced by sawing a cast block of silicon first into bars and then into wafers. The trend is toward multicrystalline technology. For both types of c-Si, a semiconductor homojunction is formed by diffusing phosphorus (the *n*-type dopant) into the top surface of a boron-doped (*p*-type) silicon wafer (Figure 1). Screen-printed contact fingers are applied to the front and rear of the cell, with the front contact pattern designed to allow maximum light exposure of the material with minimum resistive losses in the cell. Each c-Si cell generates about 0.5 V, so cells are usually connected (soldered) in series to produce a module with an output to charge a 12 V battery. The cells are hermetically sealed under toughened, high-transmission glass to produce highly reliable, weather-resistant modules (Figure 2).

Thin film technology uses stronger light absorbers and the layers only need to be about 1 μm thick, so material costs are significantly reduced. The most common materials are amorphous silicon (a-Si) or the polycrystalline compounds cadmium telluride (CdTe), copper indium diselenide (CIS) and copper indium gallium diselenide (CIGS). All are amenable to large-area deposition and hence high volume manufacturing. The TF semiconductor layers are deposited onto either coated glass or a stainless steel sheet (Figure 3). The semiconductor junctions are formed in different ways, either as a p-i-n device in a-Si or as a heterojunction for CdTe and CIS/CIGS. A transparent conducting oxide (TCO) layer (e.g. tin oxide) forms the front electrical contact of the cell and a metal layer forms the rear contact. Amorphous silicon is the most well developed of the TF technologies and has an

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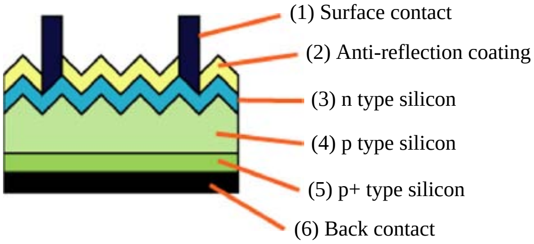
Assembly Automation
31/1 (2011) 6–11

[DOI 10.1108/01445151111104119]

Figure 1 Schematic of a c-Si solar cell



Source: Wikipedia

Figure 2 Silicon solar cell

Source: Wikipedia

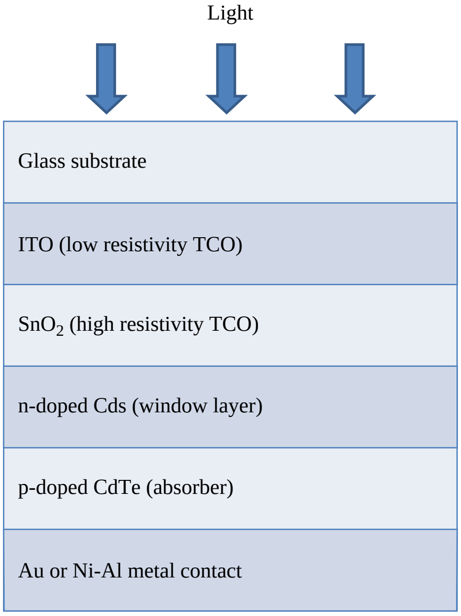
interesting avenue of further development through the use of "microcrystalline" silicon, which seeks to combine the high efficiencies of c-Si technology with the simpler and cheaper large area deposition technology of a-Si.

The role of lasers

Lasers play an important and growing role in the manufacture of both c-Si and TF solar cells. In some instances, lasers represent the only means of conducting a particular process, but in others, they are replacing more traditional methods. While c-Si presently represents the main market for laser systems in PV production, TF technologies also use them but for different functions and in different stages of production. Some applications are now routine and widely used, but because both technologies are evolving rapidly, many uses are still either experimental or employed only on specific PV designs or by particular cell manufacturers. Nevertheless, many of the world's leading laser and PV processing equipment manufacturers have developed dedicated systems for this industry.

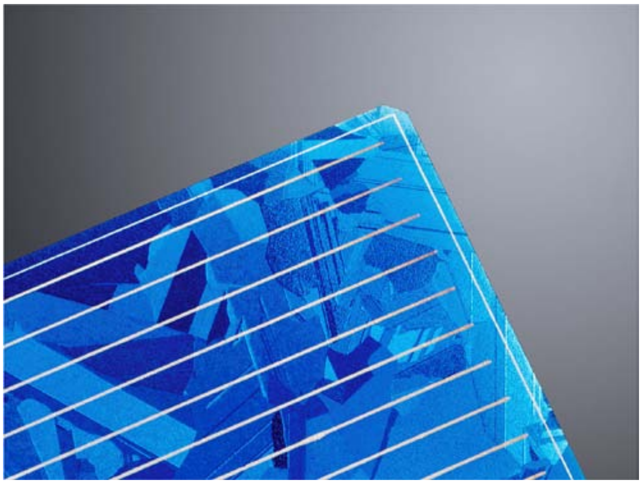
An established c-Si laser application is edge isolation. After manufacture of the active layer of the cell, a continuous edge creates a potential short circuit between the active and the back sides. To overcome this, green (532 nm) or UV (355 nm) nanosecond pulses from a Nd:YAG or Nd:Vanadate laser are used to scribe narrow grooves which are typically 30-50 μm wide and 5-10 μm deep between the finger grid and the cell edges (Figure 4). Scribing speeds are generally between 400 and 800 mm/second. The use of lasers minimises sidewall and surface damage and bulk micro-cracks are negligible. Several laser manufacturers produce edge isolation systems with the ability to process up to 3,000 wafers per hour. A variant on the laser edge isolation process is the water jet-guided laser, which has recently been commercialised by Synova. Utilising the difference in the refractive indices of air and water, the

Figure 3 Schematic of a CdTe thin film solar cell



Notes: TCO, transparent conductive oxide;
ITO, indium tin oxide
Source: Wikipedia

Figure 4 Laser edge isolation on a polycrystalline silicon solar cell



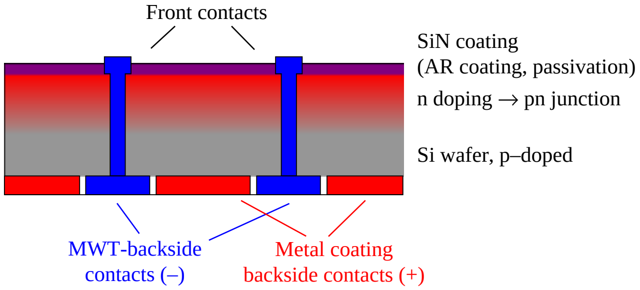
Source: TRUMPF Laser- und Systemtechnik GmbH

Laser MicroJet product creates a laser beam that is completely reflected at the air-water interface and contained within the water jet as a parallel beam, similar in principle to an optical fibre. Conventionally focused laser beams have a working distance limited to just a few millimeters due to beam divergence, and as a result, they may generate a heat-affected zone in the material, causing damage. Contamination can also be an issue as the molten material is not always fully expelled. Synova argues that its technology overcomes these problems.

In the continuing quest for even incremental improvements to efficiency, some c-Si PV manufacturers are adopting what are termed "wrap-through" designs. These are back contact technologies and there are two variants: emitter wrap through (EWT) and metallisation wrap through (MWT). Conductive pathways (vias) are laser drilled through c-Si substrates to allow contacts to be located at the rear of the cells. In the MWT design, 25-50 holes with diameters ranging from 300 to 500 μm are drilled into each cell and filled with a conductive material (Figure 5). By locating the metallisation on the back of the cell, shading on the front is reduced, leading to an improvement in efficiency of ~0.5 per cent. In the EWT cell, laser drilling is used to make an array of holes in the silicon substrate (Figure 6). These are doped with phosphorus during the emitter diffusion, thereby "wrapping" the emitter from the front surface to the rear. A fairly high density of holes (~1 for every 1-2 mm^2) is required because of the limited conductivity of the emitter diffusion on the front surface. In a typical cell, approximately 10-15,000 holes with diameters of 60-70 μm are drilled. Q-switched disc lasers are frequently used for this application and can achieve throughputs of up to 5,000 holes/second. Another laser-based approach to achieving improved efficiency in c-Si cells is the so-called "selective doping" process. This involves the use of a laser to melt a region of the bulk silicon where the contact fingers are later deposited. A phosphorous coating diffuses into the melt region causing a decrease in sheet resistance, typically from around 120-150 to 20 Ω/square. This reduction in ohmic losses at the contacts has been shown to yield an increase in cell efficiency of up to 2 per cent. Many types of laser have been employed in experimental selective doping systems, i.e. IR, visible (green) and UV but none have yet proven wholly suitable for use in full-scale production systems. Q-switched solid-state lasers appear to offer strong prospects.

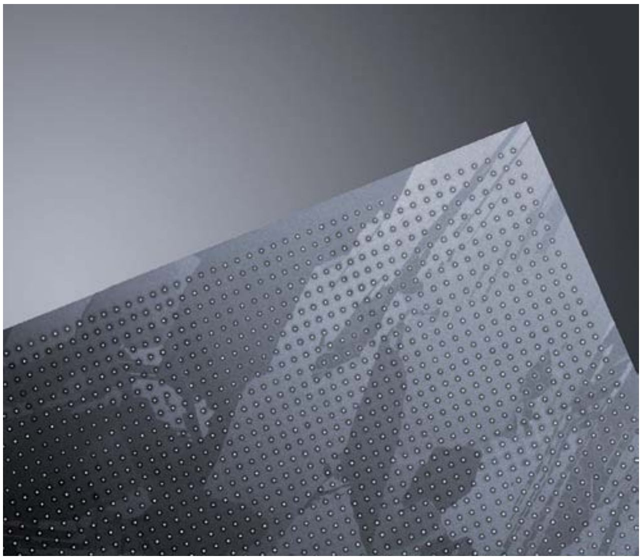
A key TF laser application is edge or border deletion, which is effectively the TF equivalent of c-Si edge isolation. Following the scribing and deposition processes, the last stage before encapsulation and framing is the removal of the coatings around the edge of the panel. This is required for two reasons: to isolate the active photovoltaic regions electrically from the metal frame and to allow the environmental sealing process to bond directly to the glass. Typically, the width of the deleted border is 10-15 mm (Figure 7), so in order to meet high volume manufacturing requirements with large area panels, removal (ablation) rates in the order of 30-50 cm^2/second are required. These are achieved with diode-pumped, solid-state nanosecond lasers, pulsed at 6-10 kHz and operating at 1,064 nm. The most common interconnect scheme in TF cells uses three laser scribes per cell along the length of the panel. These are often termed P1, P2 and P3 (for pattern 1, 2 and 3). The P1 scribe cuts the TCO coating on the glass into stripes. The P2 scribe cuts the absorber layer (e.g. a-Si, CdTe or

Figure 5 The MWT design



Source: Jenoptik Laser GmbH

Figure 6 Laser-drilled silicon wafer



Source: TRUMPF Laser- und Systemtechnik GmbH

Figure 7 Thin film solar cell showing edge deletion conducted with the TRUMPF TruMicro 7050 laser

Source: TRUMPF Laser- und Systemtechnik GmbH

CIGS) into parallel stripes, stopping at the TCO and the P3 scribe breaks the back conductor into cells, also stopping at the TCO. This process divides the panel into a series of cells, each ~ 1 cm wide. A typical TF solar panel is ~ 1 m wide, thus providing around 100 series-connected cells. The scribes can be as narrow as 50 μm, but some allowance is required for small angular errors that prevent the lines from being perfectly parallel. As a result, the scribe structure can occupy 300-500 μm, i.e. $\sim$3-5 per cent of the active area. A typical scribing process uses a pulsed vanadate laser, operating at 1,064 nm for the P1 scribe and 532 nm for the P2 and P3 scribes.

An example of where lasers are poised to replace an older, lower technology technique is glass cutting in TF cell production. Flat glass substrates are most often cut by scribing and subsequent mechanical breaking, but this can cause splinterings and the development of micro-cracks which reduces significantly the bending strength of the glass. These problems frequently necessitate post-cutting processes such as edge grinding and polishing but can be overcome by the use of diode-pumped, continuous-wave YAG or pulsed CO_2 lasers. Laser-cut glass exhibits a bending strength of around two to three times that of glass cut by traditional methods and the technique is used widely during the production of flat panel displays (FPDs). A laser glass cutting machine is shown in Figure 8.

Future developments

Several of the applications considered above are topics of the three-year, EU-funded Solasys ("Next Generation Solar Cell and Module Laser Processing Systems") project, which started in 2008 and involves ten organisations from six European countries. These are:

- *Research institutes*. IMEC (Belgium), Fraunhofer-ILT, the project coordinator (Germany) and CNRS-LP3 (France).
- *Laser and components manufacturers*. Laserline GmbH, Trumpf Laser GmbH and Scanlab AG (Germany).
- *Machine integration specialist*. Manz Automation GmbH (Germany).
- *Solar cell and module manufacturers*. BP Solar (Spain), Solland Solar (Netherlands) and Energy Solution (Bulgaria).

Figure 8 Laser glass cutting machine

Source: Grenzebach Maschinenbau GmbH

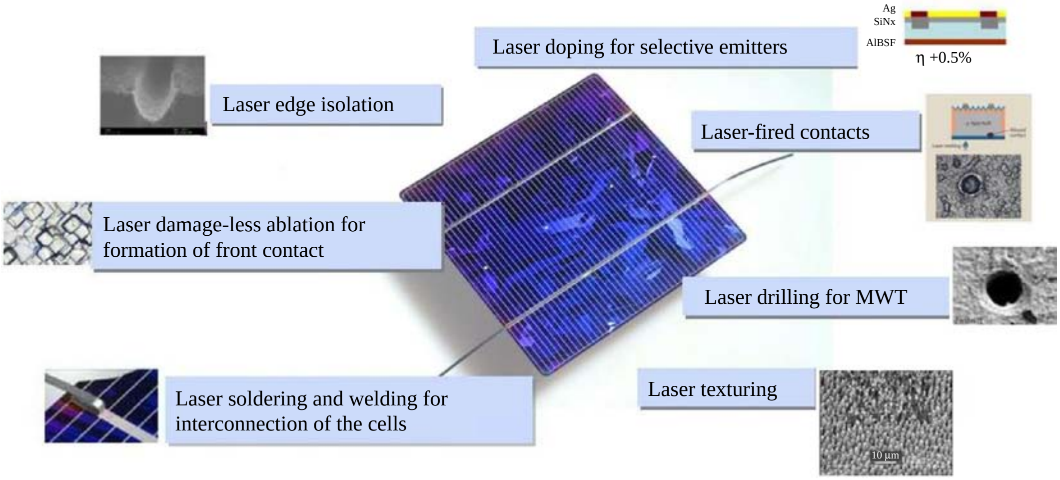
With an EU contribution of €3.5 million, Solasys (Figure 9) aims to improve current laser-based processes and integrate new methods into industrial production. The specific techniques being studied are high-speed laser micro-drilling for new cell concepts (EWT and MWT); laser surface texturisation; damage-free laser ablation of dielectric coatings on solar cell emitters for contact formation; laser selective emitter doping; high-throughput laser junction isolation and laser micro-soldering for module interconnection.

The ablation of dielectric coatings is an application offering future prospects for ultra-short pulse lasers. The dielectric silicon nitride (SiN) passivation layer reduces reflectivity, allowing a larger fraction of the sunlight to enter the cell and also reduces the effect of crystal lattice defects at the surface of the wafer. The disadvantage of front passivation is the need for a high temperature step to drive the screen-printed metallisation paste through the SiN to form the electrical contact to the emitter. To avoid this step, or at least to reduce the temperature, laser ablation can be used to open the passivation layer before the metallisation step. Several types of laser generating ultra-short pulses have been investigated, including picosecond UV and femtosecond (fs) IR types. Good results have been achieved by German laser manufacturer Jenoptik who used a commercial diode-pumped, solid-state IR fs laser (the JenLas D2.fs; Figure 10) which generated a maximum pulse energy of 40 μJ with a repetition rate of 100 kHz at a wavelength of 1,025 nm.

An emerging use which, like laser glass cutting, takes its cues from the FPD industry, is the laser crystallisation of a-Si. This technique is a key element of another EU project, the two-year "high-Ef", which aims to develop TF-PV devices with improved sensitivity through the use of laser crystallisation and epitaxial thickening. The consortium comprises eight organisations from three member states (France, Germany and Hungary) and one associated country (Switzerland). The process is based on a combination of melt-mediated crystallisation of an a-Si seed layer (<500 nm thick) and thickening the layer to $>2\,\mu$m by a solid-phase epitaxy (SPE) process. Melting the a-Si layer and solidifying large grains ($\sim 100\,\mu$m) will be achieved by scanning the beam of a laser diode array. Epitaxial thickening of the large grained seed layer (including a p-n junction) is achieved by the deposition of doped a-Si on top of the seed layer and a subsequent SPE process by way of a furnace anneal. A low-cost laser system with a power density of 7 kW/cm^2 will be developed using highly efficient laser diodes, combined to form a line focus that will allow the crystallisation of an entire PV module (i.e. 1.4×1 m on a production line or 30×39 cm for research), with a single scan.

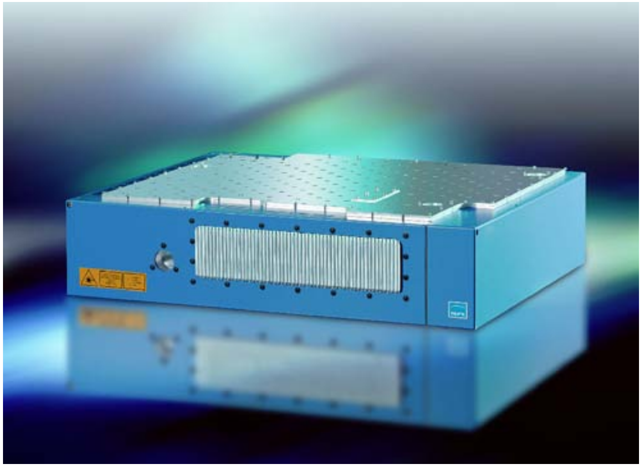
February 2009 saw the start of a collaborative project dubbed KOMET which is funded by the German Federal Ministry of Economics and Technology. The aim is to develop a "compact solid-state laser for efficient material ablation with radially polarised light" which will be used to enhance laser cutting and drilling in PV production. Participants in the project include the research institutes Laser-Laboratorium Göttingen, the Fraunhofer Institute for Laser Technology and the University of Erlangen-Nürnberg, together with seven industrial partners. By 2012, they are planning to develop

Figure 9 The EU-funded Solasys project



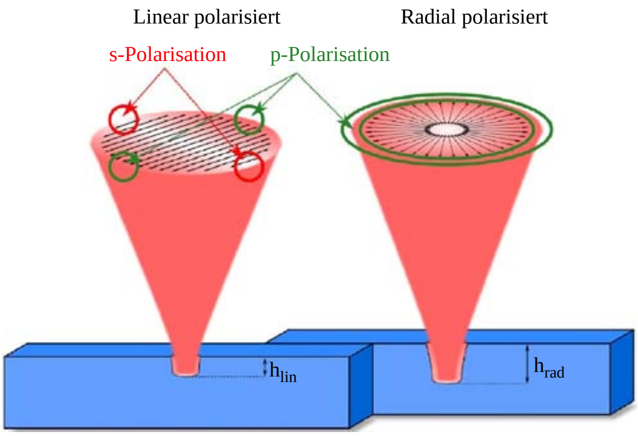
Source: Wikipedia

Figure 10 The "JenLas D2.fs" femtosecond laser



Source: Jenoptik Laser GmbH

Figure 11 The use of radially polarised laser light is being studied by the German KOMET project



Source: Fraunhofer-Institut für Lasertechnik

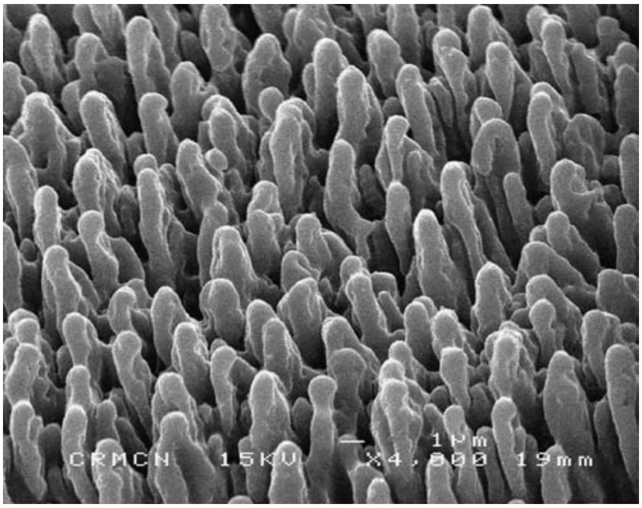
a modular, solid-state laser for precision cutting and drilling that features significantly improved beam quality and an increase in cutting efficiency of up to 50 per cent. A radially polarised laser beam exhibits up to 30 per cent better absorption than a circularly polarised beam (Figure 11), thereby reducing coupling losses. Under optimum conditions, the focusing point of the beam is up to 60 per cent smaller than that of a conventional laser, which allows the usable surface area of the material being processed to be maximised. At a wavelength of 1,064 nm, the laser will be designed with an output power of a few hundred milliwatts (master oscillator) or up to 30 W (power amplifier).

New PV materials are attracting great interest, particularly wide band-gap III-V and II-VI compound semiconductors with energy gaps of 2.0-6.5 eV. These figures far exceed the band-gap of silicon, which is 1 eV. This property allows the materials to absorb a wider region of the electromagnetic spectrum than silicon, resulting in a higher conversion efficiency. Materials can be in the form of crystalline substrates, thin films, multi-quantum well structures, quantum dots or other nanostructures. Many are not fully compatible with existing silicon processes but lasers may well emerge as the key processing technology. AppliCote Associates LLC, together with the University of Central Florida's college of optics and photonics and Lee Laser, Inc., is developing laser technology to inject impurity atoms into lattice sites of wide band-gap materials to adjust their semiconducting properties without melting or recrystallising the substrate. Wide-area solid-state doping of the entire wafer and substrate surface is an advance over thermal diffusion which is limited by the high diffusion temperatures of these materials and also over ion implantation which induces lattice defects. While these materials may eventually yield high-efficiency devices, costs are likely to be high and there has been much recent interest in far less costly organic PV materials. Organic photovoltaic (OPV) technology has the potential to yield cells which are flexible and light and benefit from low manufacturing costs arising from high-speed roll-to-roll coating and/or printing processes. Mitsubishi Corporation, the National Institute of Advanced Industrial Science and Technology and Tokki Corporation have recently developed a highly integrated OPV module which uses fullerene (C_{60}) as the *n*-type semiconductor (acceptor) and copper phthalocyanine as the *p*-type donor. The materials are deposited on a glass substrate and laser scribing is used to divide the coating into separate cells which eliminates the need for deposition mask patterning. Another material attracting great interest from the PV community is black silicon. This has a microstructured surface (Figure 12) which absorbs far more light, over a wider wavelength range (into the IR), than conventional silicon and could eliminate the need for, and be more effective than, the SiN anti-reflective coatings now used on c-Si cells. The surface structure is created by irradiating silicon with a fs laser beam in an atmosphere of sulphur hexafluoride and other dopants. In 2010, laser specialist coherent announced a joint development agreement with SiOnyx for solar cell manufacturing using black silicon process technology.

Conclusions

The PV industry is in a highly buoyant phase and is characterised by rapidly growing production levels and technological innovation. Lasers already play a central role during the production of c-Si and TF solar cells but will become ever more important as manufacturers seek to improve performance and reduce costs.

Figure 12 Scanning electron micrograph of black silicon surface



Source: Wikipedia

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