Large-area nanopatterns: improving LEDs, lasers, and photovoltaics

A new robust nanoimprint method has demonstrated improved device performance by economical application of sub-micron patterns over large areas.

Nanopatterns increase light extraction from LEDs, control laser behavior and polarization, and increase the efficiency of photovoltaics. Unfortunately, research and development uses expensive patterning techniques such as electron-beam (e-beam) pattern generators and focused ion beam milling to create such structures. These techniques are not scalable to production volumes, as generating even a single centimeter-square area of nanopatterns can easily take several hours.

To enable the transition to production, nanoimprint lithography (NIL) is seen as a promising technology for cost-effective fabrication of sub-micron and nanopatterns on large areas. However, despite 15 years of research and major developments in materials and techniques, NIL has not yet made the step from academia/research to (mass) production. The main hurdle remains the cost-effective combination of high-throughput, robust, nanometer-resolution patterning on real-world, large-area substrates.

NIL technology is divided into hard and soft imprint lithography depending on the types of stamps used. Rigid stamps offer nanometer resolution and low pattern deformation, but can only pattern a small area (1cm\(^2\)) at a time, and are very sensitive to defects that can damage the expensive stamp. Soft stamps, usually made of silicone rubber, are low-cost and can pattern large areas, but are limited in resolution. We have developed substrate conformal imprint lithography (SCIL), which combines the low cost, flexibility, and robustness of rubber stamps with the resolution and low pattern deformation of rigid stamps. SCIL is based on a sequential imprinting principle, whereby the stamp is deposited gradually on the substrate and is then removed (see Figure 1). The wavelike progression of the contact front minimizes air inclusions even on large areas, and the sequential separation of the stamp and substrate allows for a clean and reliable disconnection that does not damage the patterned structures. SCIL has demonstrated sub-10nm resolution over 150mm-diameter substrates. More important, SCIL enables the transition to mass production as the required value chain is in place, from process development and pilot production at Philips Innovation Services, to commercial SCIL tooling for mass production offered by Suss MicroTec.

A number of interesting applications are enabled by SCIL. For example, solid-state lighting will benefit from using nanostuctures. Photonic crystals (PCs) are used to extract light and to shape the emission profile from LEDs. For optimized light

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extraction and beam shaping, individual LEDs are tested, binned, and assembled to match the PC to the LED emission. The challenge is thus to apply nanopatterns on non-continuous substrates, such as shown in Figure 2(A). We applied the imprint resist by spray coating, and the flexible SCIL allowed patterning of only the top of the individual 1mm² flip-chip LEDs, without making contact in between the chips. Next, we transferred the hole pattern into the gallium nitride semiconductor by dry etching. The inset of Figure 2(A) shows a scanning electron microscopy (SEM) image demonstrating that the patterns continue to the LED edge. The resulting far-field light distribution for 480nm light is shown in Figure 2(B), demonstrating the square-lattice PC air modes.

As higher efficiency cells reduce the cost of photovoltaics, we used two approaches to increase light absorption and therefore improve efficiency. The first approach used plasmonic back reflectors for thin-film amorphous hydrogenated silicon (a-Si:H). A single imprint on a glass substrate replicates regular and random pillar arrays on which the cell was grown. Figure 3(A) shows a sample containing a variety of plasmonic cells, with the SEM cross-section shown in the inset. The plasmonic cell traps light in an only 90nm-thick intrinsic a-Si:H layer and reaches an efficiency of 9.6% under air mass 1.5 illumination (400nm pitch). Second, to reduce the reflectivity of single-crystal silicon wafers we used front-side resonant Mie scatterers. Figure 3(B) shows the difference in reflection between a flat silicon wafer, a standard silicon solar cell, and the Mie scatterers is clearly visible. The inset shows the cylindrical silicon pillars that act as resonators, before 60nm of silicon nitride is deposited. The solar spectrum weighted reflection over 450–900nm is reduced to only 1.3%, compared to 3.4% for a standard textured solar cell. Importantly, this approach is applicable to any high-index material and is compatible with very thin wafer concepts where traditional anti-reflection approaches fail due to the required feature height.

Vertical-cavity surface-emitting lasers, or VCSELs, are a type of low-cost laser manufactured in high volume and used in fiber optic data communications, optical tracking (for example, laser mice, touch-pads), and sensing applications. Due to the planar technology the VCSEL’s polarization direction can flip. To lock the polarization, a grating is applied on one of the laser mirrors. We imprinted gratings on 3 inch gallium arsenide (GaAs) wafers that contain the final laser stack, etched in the semiconductor and processed into VCSELs. By replacing traditional e-beam patterning with SCIL, we improved performance and yield as SCIL enables using a smaller grating pitch, which reduces optical losses and simultaneously lowers cost. Figure 4(A) shows an SEM image of an imprinted grating, next to a growth defect in the GaAs. Figure 4(B) shows that using smaller pitch gratings increases the laser efficiency by 30% (decreased threshold and increased slope). This process has been in production since 2009, and more than 60 million lasers have been produced.

The examples described here show the advantages of using nanostructures over large areas to improve performance and decrease costs. The SCIL technology can cope with non-ideal substrates and allows research and development to work with the same technology that is applicable to production, thereby accelerating transfers toward industry. SCIL is currently having an increasing impact on numerous application areas, and we...
expect that this will be a continuing process, leading to more and more automated production facilities. To promote this, we are currently commercializing the necessary fast-curing inorganic imprint resist and the components for high-resolution silicone stamps. A shift from lab to factory is anticipated in the near future.

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