Nanoimprint Lithography

The technology makes its mark on CMOS image sensors and in the nano-world

CMOS image sensors represent a multi-billion-dollar market, with continued growth expected due to increasing demand for a multitude of consumer and industrial applications. To continue to drive down manufacturing costs while enabling increased device performance, manufacturers are looking to innovative production methods, such as nanoimprint lithography (NIL). In addition to lower cost, NIL offers high repeatability and accuracy, all of which are particularly critical for ensuring optimal production of micro lenses, which are an integral part of the CMOS image sensor. Beyond CMOS image sensors, NIL offers the potential to enable a number of other device applications, from high-brightness light emitting diodes (HB-LEDs) to micro-fluidics.

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Introduction

Following more than a decade of greater than 20% compound annual growth and a brief decline in 2009, the image sensor market is expected to return to modest single-digit growth in the coming years, according to market research firm Strategies Unlimited (Mountain View, Calif.) [1]. Despite the lower projected growth rates, image sensors will continue to represent a multi-billion-dollar industry that affords lucrative opportunities for manufacturers that can effectively compete in this market. This is due to the wide-ranging and continuously expanding applications for image sensors, including cell phones and wafer-level cameras, optical mouse devices, notebook webcams, digital cameras, video camcorders and surveillance systems.

Image sensors fall into two main camps: CMOS (complementary metal oxide semiconductor) and CCD (charge coupled device). Each type has traditional strengths and weaknesses. For example, CCD image sensors have historically been known to provide superior image quality, while CMOS image sensors have offered the potential for greater integration (i.e., more functions on a silicon chip), reduced power consumption, single-voltage power supply and smaller system size [2]. Recent developments have enabled significant improvements in CMOS image sensor quality, and today CMOS image sensors now dominate the overall image sensor market.

An integral component in the CMOS image sensor module is the micro lens. Micro lenses focus incoming light onto a photodiode, or pixel, which converts the light into electrical signals. Transistors built into the CMOS image sensor then convert the signals into an image. Up to 5 or more lenses can be stacked (Figure 1) on top of a CMOS image sensor depending upon the application. Only a small portion of the pixel is designed to absorb the light while the remaining area is dedicated to support the transistors [3]. Thus, the micro lens must focus the light onto the smaller photosensitive area with high accuracy—making the quality of the lens a critical factor in determining the overall performance of the CMOS image sensor.

For the wafer-level camera market in particular, where cost margins are extremely tight, CMOS image sensor manufacturers need a low-cost method for producing micro lenses. One approach that has gained significant traction due to its relatively low cost, high repeatability and high accuracy is nanoimprint lithography (NIL).

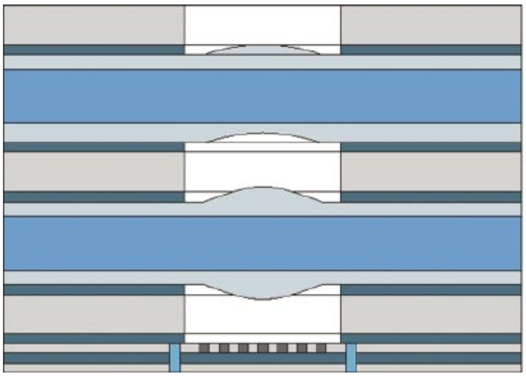

FIGURE 1: **Cross section of wafer-level camera module consisting of a CMOS image sensor, double-side lens wafers and spacer wafers.**

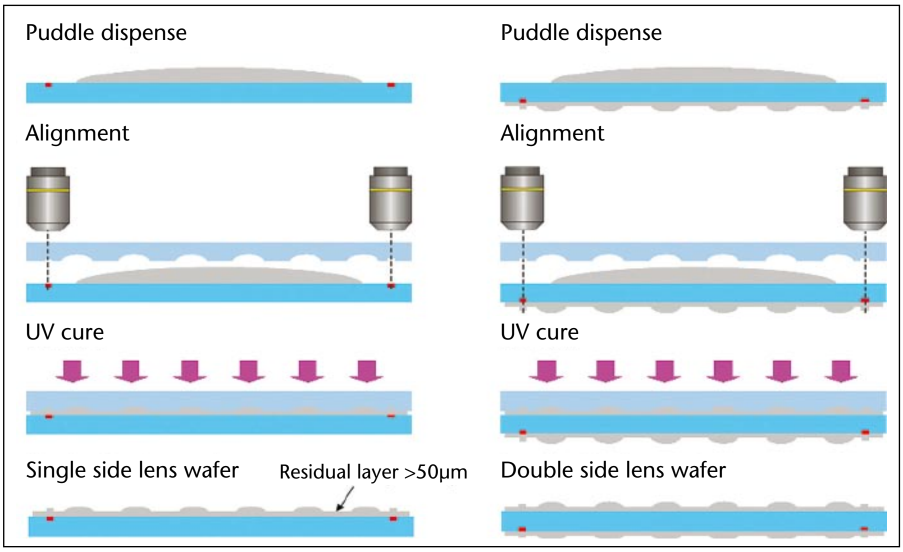

FIGURE 2: **UV-NIL processes for manufacturing single and double side micro lens wafers used in wafer level camera modules.**

Nanoimprint Lithography: How it Works

The concept of NIL has been around for several decades, but only within the past decade has the technology progressed to the point where it has moved beyond research and into implementation for both early-stage and volume production for wafer-level optic applications. Compared with optical lithography, NIL is a far simpler process. Optical lithography requires high-power excimer lasers and complex stacks of precision-ground lens elements to project nanometer-scale patterns onto the surface of semiconductor wafers. These excimer lasers and complex optics can result in equipment costs around tens of millions of dollars. In comparison, NIL uses a stamp process to print features directly onto surfaces, which means that the size of the printed feature is only limited by what can be etched into the stamp or template. As a result, NIL can print features far smaller than today's most advanced optical lithography systems — 10 nm or less — without the need for complex optical equipment or finely tailored photoresists. There are two primary forms of NIL: hot embossing and ultraviolet (UV)-based nanoimprint lithography (UV-NIL). In hot embossing, a thin polymer material is spin-coated onto a substrate. After the substrate and polymer coating undergo a pre-bake process and are heated up to a specified temperature, a template with pre-defined patterns representing device circuit features is applied to the polymer coating on the substrate. Then, the template and substrate assembly is cooled down, after which the template is removed (known as "de-embossing"). The polymer coating on the substrate is "imprinted" with a reverse pattern from the template. With UV-NIL, a substrate is coated with a photo-curable resist. A transparent template is then applied to the resist at room temperature and is exposed with UV illumination. When the template is removed from the resist, it leaves the reverse pattern from the template imprinted onto the substrate [4]. UV-NIL is a room-temperature process, which typically enables higher precision alignment and increased pattern placement accuracy.

Today, the most established method of manufacturing wafer-level optics is sequential double-side micro lens molding onto glass wafer substrates utilizing puddle dispense and UV-NIL. As shown in Figure 2, a pre-polymer material is dispensed as a single puddle onto the center of the wafer. The template is then aligned to special marks that are patterned onto the wafer during first-side lens replication or to molded polymeric marks during second-side lens replication. During the subsequent imprint process, the puddle is squeezed between the template and the wafer, which causes the material to fill into all of the lens cavities in the template. After the material is cured with a UV lamp and the template is lifted from the surface of the wafer, a thin residual layer with the reverse impression from the template remains on the wafer's surface.

Both the total thickness variation of the residual layer and the degree of alignment between the template and substrate are key parameters that affect the performance of the wafer-level optic module. Also key to micro-lens performance is pattern fidelity—how well the template pattern is faithfully replicated onto the substrate. High-pattern fidelity can be achieved by controlling the amount of space between the template and substrate during the imprint process, if the polymer material is not prone to shrinkage. Otherwise, high-pattern fidelity can be achieved by controlling the amount of force applied to the template during the imprint process. UV-NIL can also utilize "soft" templates to compensate for thickness variations on the substrate, which makes it possible to imprint over larger surface areas with a high degree of uniformity. This, in turn, enables the use of NIL for high-throughput and high-resolution applications, such as the production of micro-optics used in wafer-level camera modules (Figure 3).

In high-volume micro-lens manufacturing, the introduction of defects to the manufacturing process is a top concern. Since UV-NIL is a contact process, it is pos-

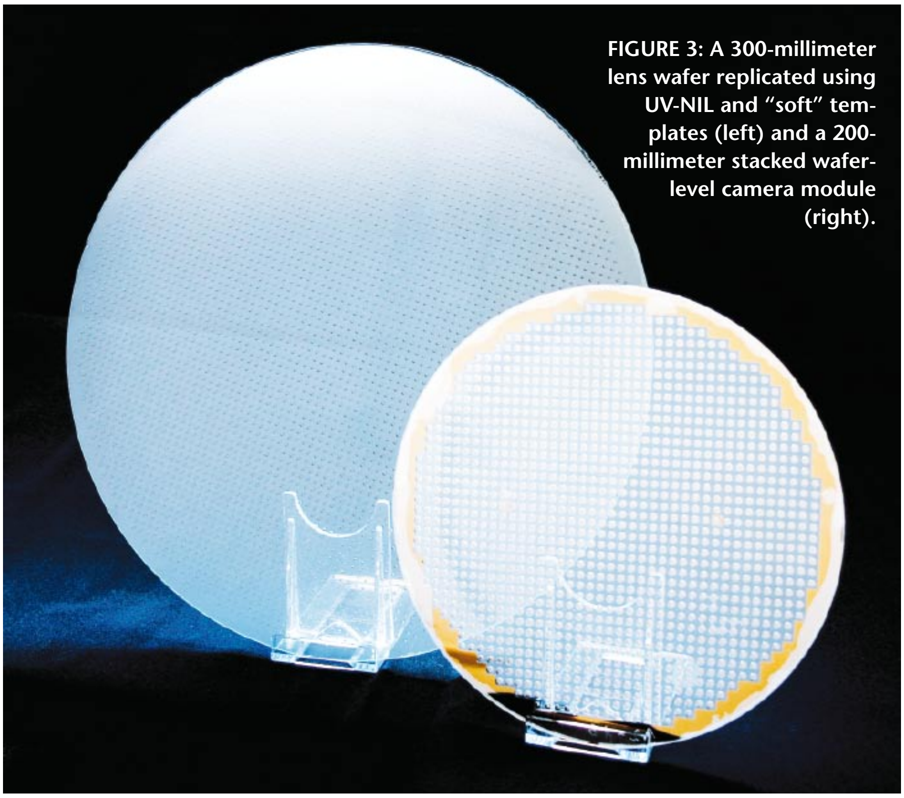

FIGURE 3: A 300-millimeter lens wafer replicated using UV-NIL and "soft" templates (left) and a 200-millimeter stacked wafer-level camera module (right).

THE COMPANY

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EV Group (EVG) is a world leader in wafer-processing solutions for semiconductor, MEMS and nanotechnology applications. Through its flexible manufacturing model, EVG develops reliable, high-quality, low-cost-of-ownership systems that are easily integrated into customers' fab lines. Key products include wafer bonding, lithography/nanoimprint lithography (NIL), metrology, photoresist coating, cleaning and inspection equipment.

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sible for residual material to remain on the template after it lifts off from the substrate, causing particle defects to be introduced in subsequent processes. To ensure smooth separation between the template and the substrate, as well as minimize defects, the material combination of the template and cured polymer must feature low adhesion force. By adjusting the surface energy of the template, the release properties can be tuned in such a way that enables repetitive imprinting without introducing defects.

Nanoimprint Lithography: Emerging Applications

Beyond the CMOS image sensor market, NIL's ability to provide low-cost and highly repeatable patterning of nano-scale features offers potential benefits to numerous other applications. For example, UV-NIL can be used to pattern photonic crystal structures on the surface of high-brightness light-emitting diodes (HB-LEDs) in order to increase light efficiency and brightness (Figure 4). UV-NIL provides the optimal balance between high resolution, high repeatability and low cost.

Another promising emerging application for NIL is the fabrication of next-generation high-density-storage hard disk drives (HDDs). In the HDD industry, manufacturers have historically been shrinking the size of the magnetic bits used to store data in the drives in order to increase drive density—a trend similar to that of semiconductor manufacturers (but at a much more aggressive rate) as they increase the density and complexity of semiconductor devices. Over the years, HDD manufacturers have developed new recording methods to support the production of smaller bits, which in turn increases storage density. With perpendicular recording (the current recording method) expected to reach its physical limits at areal densities of about one terabit (TB) per square inch, new production methods are being sought after.

Due to its high scalability, NIL is being considered by several leading HDD manufacturers to extend their product roadmaps by enabling two possible recording methods: discrete track recording (DTR) and bit patterned media (BPM). DTR increases recording density by forming a „groove" between the tracks on the PMR medium (Figure 5). The groove reduces signal interference between adjacent data tracks, allowing the pitch of the tracks to be shortened [5]. In bit patterned media, each magnetic bit is physically patterned onto the disk. In both DTR and BPM, the features that might be produced by NIL will be much smaller than those found in today's most advanced semiconductor devices.

The emerging fields of microfluidics and biosensors can also benefit from the advantages of NIL. Disposable, polymer-based point-of-care diagnostic and bio-sensing devices require a low-cost manufacturing

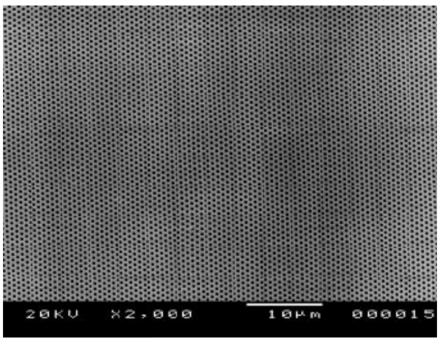

FIGURE 4: **SEM image of 350-nm photonic crystal holes, structure depth 600 nm utilizing UV-NIL.**

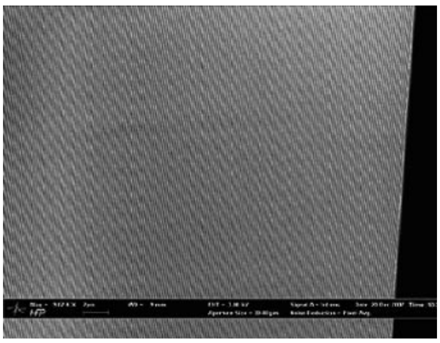

FIGURE 5: **SEM measurement of 50-nm half pitch imprinted data track features utilizing soft stamp imprint lithography.**

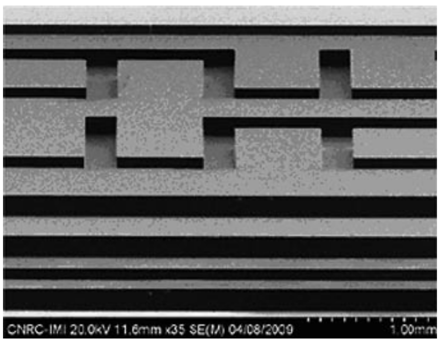

FIGURE 6: **SEM image of 200-micron wide hot embossed micro fluid channels utilizing working stamp substrate top area.**

method. Hot embossing provides better performance over UV-NIL if polymer materials need to be imprinted directly, and can be used to address a variety of these types of applications—from polymer-based lab-on-a-chip systems, where imprinting is performed on thick polymers substrates, to bio-sensing or data recording applications, where the fabrication of extremely minute (sub-100-nanometer) features require imprinting into spin-on polymers (Figure 6). Some micro-fluidic devices require an additional process step that involves bonding a flat polymer substrate to the structured or "printed" polymer substrate following hot embossing. The added bonding process is essential for sealing micro-fluidic channels within the device after the hot embossing process [6].

NIL is also being considered as a potential solution for the manufacturing of leading-edge semiconductor devices. The International Technology Roadmap for Semiconductors (ITRS), which is established by leading experts in the semiconductor industry as a guide for directing research and development efforts, has identified the entry point for NIL technology in semiconductor fabrication at the 22-nanometer node (the point at which the half-pitch, or one-half the distance between identical features in an array, for a memory cell is shrunk to about 22 nanometers), which several leading memory manufacturers are expected to reach in the 2011-2012 timeframe. However, recent technology developments to extend existing optical lithography processes for semiconductor fabrication may delay the introduction of NIL to the 16-nanometer or smaller nodes, which will occur in later years. NIL still requires significant development, especially in the areas of overlay alignment accuracy and low defect density, before it can meet the extremely stringent manufacturing standards required for leading-edge semiconductor fabrication.

Conclusion

NIL offers myriad benefits for micro- and nano-scale device manufacturers, including low cost, resolution scalability and pattern repeatability. NIL is particularly well-suited for producing micro-lens optics used in CMOS image sensors for wafer-level cameras and other applications. At the same time, NIL offers potential in supporting the production of HB-LEDs, next-generation HDD storage products and future semiconductor devices.

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