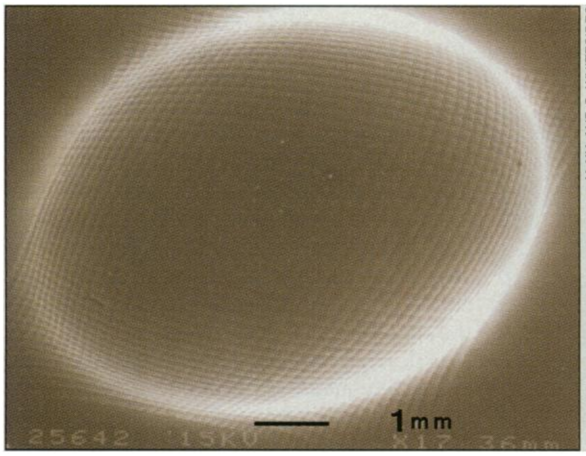
Throwing—or Molding—a Curve Into Nanofabrication

Today's nanotechnology experts are finally beginning to imitate their Iron Age predecessors. The early technologists recognized that replicating everything from swords to statues was far easier if they cast liquids in molds than if they had to carve out these same shapes over and over. Unfortunately, that lesson hasn't been easy to apply to the modern lilliputian worlds of micromachines and optics, where engineers and others use light beams, chemicals, and related tools to carve out tiny features in device after device. Now, however, a team of Harvard University researchers has brought miniaturized molding and casting techniques—and a new flexibility—to the nanoworld.



Y. XIA AND G. WHITESIDES

Bending the mold. Micromolding techniques allow polymer patterns to be placed on curved surfaces such as this lens.

Chemist George Whitesides and his Harvard colleagues report on page 347 that they have developed a new micromolding technique to produce complex patterns known as gratings, just hundreds of nanometers in width, on the surface of both flat and curved optical material. The Harvard team members showed that they could more easily create flat gratings—which are crucial to laser steering devices—by casting plastics in what amounts to a minuscule rubber mold than by using traditional techniques. And because that mold is bendable, they could also make curved gratings, which can be used on lens surfaces and optical fibers to focus and filter light for telecommunications and optical computing applications. Moreover, in a paper published in the 19 June issue of the *Journal of the American Chemical Society* (*JACS*), the researchers reported that a related scheme can create complex microscopic patterns of materials ranging from ceramics and metals to plastics, which could speed procedures for creating tiny gears and motors.

"I think it's very impressive and terribly important work," says Cal Quate, a nanofabrication expert and electrical engineer at Stanford University in Palo Alto, California. In particular, "they can pattern curved surfaces, which is rather unique." Conventional patterning techniques tend to skid on curves, because they depend on tightly focused light to help etch flat surfaces, and that focus changes when surfaces curve. The new patterning schemes are not likely to supersede lithography immediately for all tasks, such as making computer chips, Quate says, but they should make the nanoworld's repertoire a bit bigger.

In creating their micromolds, Whitesides and his colleagues built on a technique they developed 3 years ago known as microcontact printing. First, they use conventional photolithography to etch a pattern in either a hard polymer known as a photoresist or a rigid silicon wafer. This serves as a mold for a liquid polymer called polydimethylsiloxane (PDMS), which is then heated, cured, and peeled off. The PDMS is now a stamp carrying the negative image of the photoresist: Valleys become peaks, and ridges become grooves. These features are then "inked" with organic molecules and stamped on a surface; the organics mask off patterns on the surface so that other materials, such as semiconductors or metals, can be deposited in those patterns (*Science*, 15 December 1995, p. 1760).

In their current *Science* paper, Whitesides and his colleagues—Younan Xia, Enoch Kim, Xiao-Mei Zhao, John Rogers, and Mara Prentiss—give their stamping technique a little twist. The researchers turn the PDMS stamp over and use its face as a master mold for casting polyurethane, another curable liquid polymer. The twist: Unlike the rigid photoresist or silicon master used to create the PDMS, the PDMS mold itself can be bent as easily as a rubber eraser.

By bending this mold, Whitesides and his colleagues showed that they could cast a curved crystalline surface with the regular series of ridges and valleys used in optical gratings—some no wider than 1 micrometer, which approaches the limit of conventional photolithography—or add polymer patterns resembling a fly's eye to the surface of a lens. Placing gratings on the outside of optical fibers, lenses, and other curved surfaces could help telecommunications and optical-computing researchers more easily steer light beams toward different destinations, adds Margaret Stern, a physicist at the Massachusetts Institute of Technology's Lincoln Laboratory.

And the features can get smaller still. "All you have to do is squeeze the mold to change the size of the features," says Whitesides. When they squeezed their PDMS mold from the sides in a small vise and then added polyurethane, Whitesides and his colleagues showed that they could reduce the feature sizes by about half. This polyurethane replica can become a mold for a new PDMS master, which is then compressed and used to create another, smaller, polyurethane replica. In this way, the Harvard group was able to reduce the feature sizes down to 200 nanometers. "I'm pretty confident we can go to the sub-10-nanometer size range," says Whitesides.

Quate and others believe that a related technique developed by Whitesides and his group could be equally useful for the production of tiny gears, motors, and other nanomachine parts. Today such parts are typically crafted out of silicon using photolithography. But in the June *JACS* paper, the team members showed that they can use a technique known as micromolding in capillaries, or MIMIC, to pattern not just polymers, but a wide range of materials including ceramics, metals, and crystalline microparticles.

Like the microcontact printing and micromolding technique, in MIMIC the researchers first use photolithography to create a master PDMS stamp. This stamp is then pressed and held against a surface to be patterned such as glass, so that the grooves in the pattern create a series of tiny channels between the substrate and the bulk of the PDMS stamp. The material to be patterned is then dissolved, and when a small amount is poured at the end of these channels, capillary forces draw it in, further and further, until all the channels are filled. Finally, this material is solidified and the PDMS stamp is peeled off, leaving behind carefully patterned materials with features as small as 1 micrometer.

These new micromolding techniques aren't perfect. They're not great at precisely lining up the patterns on successive layers of material, Whitesides says. So they are still not likely to "stamp out" photolithography for patterning microchips and other multilayer structures. But for optical gratings and other single-layer structures, they do offer ease of use and consequent lower cost, says Stern. And those are not small advantages.

–**Robert F. Service**