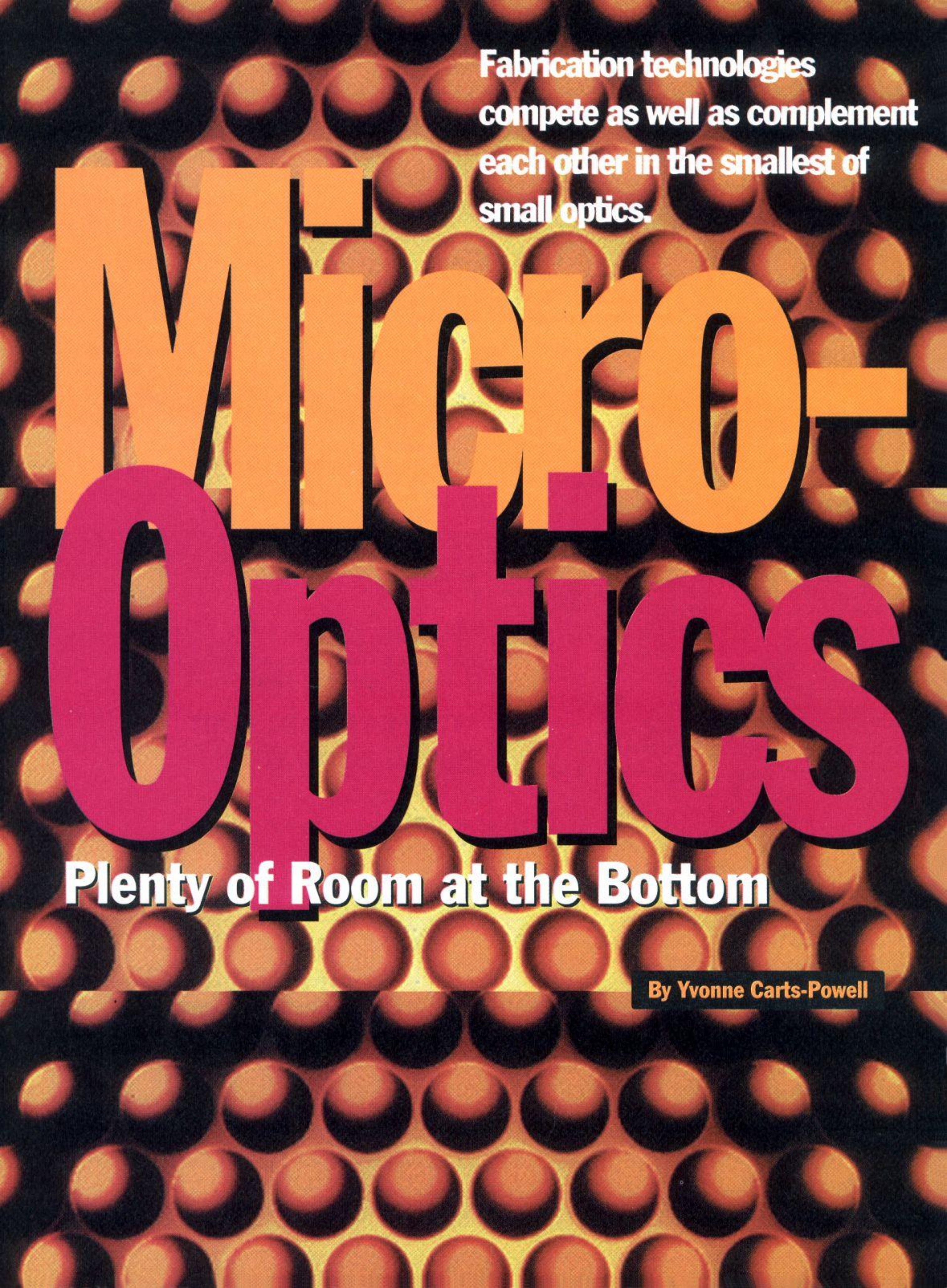


Micro-Optics

Plenty of Room at the Bottom

Fabrication technologies compete as well as complement each other in the smallest of small optics.

By Yvonne Carts-Powell

The world is getting smaller—and faster—every day. Electronics are continuing to shrink and telecommunications systems are using ribbons of fibers to carry more data in parallel. The optical elements for these applications are shrinking as well. With market forces driving research, cost is a deciding factor in the technique used to make micro-optics. In addition, the cost per element is intimately tied to the number of elements that a market requires. "The volume you do," says Harvey Pollicove, director of the Center for Optics Manufacturing (Rochester, NY), "makes a heck of a lot of difference in how you make it."

The largest application of micro-optics has been in optical data storage. In addition to objective lenses for compact disc players and DVD systems, optics also are used as encoders for tracking the position of heads in other storage media (see sidebar on page 20). Other major applications include endoscopes and a blossoming market in components for telecommunications and data communications.

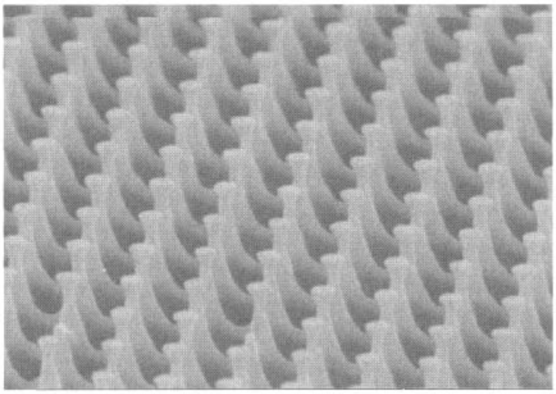
The dividing line between micro- and mini-optics is fuzzy, but for the purpose of this article, we will assume such optics measure 5 mm or less in diameter. Such optics can be made of plastics, glasses, silica, or semiconducting materials. Although traditional glass optics are made by grinding, glass micro-optics are typically made using molds or photolithographic techniques.

Breaking away from the circle

The grinding and polishing methods traditionally used to manufacture macroscopic glass lenses are most easily used to make planar and spherical surfaces. Optical designers have accepted spherical aberrations for hundreds of years, simply because aspheric lenses have been much more difficult to make accurately than spherical lenses.

However, with micro-optics, grinding and polishing is difficult. The Center for Optics Manufacturing has developed and sold several Opticam SX50 machines, which automate the grinding of optics with diameters ranging from 3 to 12 mm, up to 50 mm. Other methods, however, which do not rely on grinding and polishing also are being used, and for some of these methods, the penalties for making non-spherical lenses shrink or disappear. Aspheric and anamorphic lenses can be tailored to specific applications. In many cases, refractive, diffractive, and hybrid lenses can be made using the same method. Arrays of lenses also can be made using several of these technologies.

If the application has a narrow bandwidth, users may be able to choose between a diffractive or refractive optical element to solve the lensing problem. Photolithographic methods for making diffractive lenses are more advanced than applying similar methods for refractive lenses, and elements tend to work without precise or active alignment (see Figure 1). On the other hand, diffractives have focal lengths strongly dependent on the wavelength, and pass on less light than refractives.



U. Neuchatel

Figure 1. A photolithographically made crossed grating, which diffracts light in two axes.

Plastics

Plastic lenses made by injection molding or embossing are attractive for high-volume micro-optics because the plastic itself is cheap and the processing methods are well developed. Because the cost of making the molds is the major expense, the cost per element decreases as volume increases. Paul D. Ludington at Eastman Kodak Co. (Rochester, NY) explains the molding process briefly: "We start with a hopper of plastic pellets, warm to liquid, inject the liquid into a mold." The two sides of the mold are pressed together, the mold (and contents) are cooled until the plastic is solid, then the sides of the mold come apart, freeing the plastic element.

In general, says sales manager John Rauseo of MEMS Optical (Huntsville, AL), plastic optics, including lenses and diffractive optics, can offer faster delivery of large volumes, and greater design freedom than glass optics. Volume makes a difference in the cost: "If I want a single 10-mm-diameter optic, total costs including tooling will almost always be cheaper in glass," explains Rauseo, but; "if I want a thousand 10-mm-diameter optics, total costs including tooling will almost always be cheaper in plastic."

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Wafer-scale Optical Integration Shrinks System to 100th Size

Micro-optics using photolithographic methods which allow wafer-scale integration of optics and electronics are being made by Digital Optics. Integrated micro-optical systems allow parallel integration of hundreds or thousands of components at a time.

Chief technical officer Mike Feldman says, "We got into wafer-based optics from data storage." The company was asked to redesign an optical system for tracking the location of a floppy drive head. Using the new method, the company shrank the volume of the system by three orders of magnitude, from an assembly measuring about 1 in. x 1 in. x 1.5 in. "Instead of using discrete components," says Feldman, "we bonded the optical components together at the wafer level, and we bonded bare laser die (instead of packaged lasers) directly to the optics with assistance from structures we fabricated on the optics at the wafer level."

One of the most critical steps in integrating optical systems is aligning the components. As component sizes shrink, the tolerances tend to shrink as well. The precise alignment techniques designed for microelectronics manufacturing come in handy here. The company manufactures optical elements on both sides of a wafer. Components on one side can be aligned to those on the other to about 2 µm, and, entire wafers can be bonded together with a precision of 3 µm. At the same time the optical components are being formed, metallic features, including solder pads, traces, and alignment marks, can be made on the substrate. Pick-and-place systems can then be die-bonded to the substrate.

The head was designed on a fused silica substrate. The head, explains Feldman, "included four refractive and one diffractive optical element, a turning mirror, a laser diode, photodiodes, and a signal detector." The refractive lenses and the diffractive lens were produced on separate wafers, then the wafers were bonded together and epoxied at the edge of each optical die. The wafers were metallized, providing mounts for the laser, detector dies, and the turning mirror.

Most plastic lenses are made from acrylic (also known as PMMA and Plexiglas) or polycarbonate (the same material used to make compact discs). Rauseo says other plastics used for more specialized applications include ABS (acrylonitrile butadiene styrene), styrene (the same base material used to make plastic forks but with modifications), nylon, and epoxy.

One area into which plastics may be reaching is endoscopy. Surgeons use endoscopes as an enabling technology for minimally invasive surgery to see inside the body. At the moment, the optics are made of glass, because the expensive scopes must be sterilized at high temperatures that would melt plastics. Integrated Endoscopy (Irvine, CA), however, is developing an endoscope—expected to be on the market next year—that combines glass and plastic lenses. The goal is to reduce the cost by a factor of 10—down from several thousands of dollars each to a few hundred dollars each—and allow these endoscopes to be disposable. With an estimated 7,400,000 minimally invasive surgeries performed endoscopically in the U.S. in 1999, the savings would be significant.

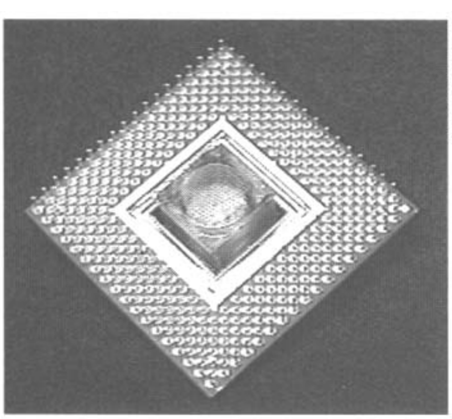
MEMS Optical

Figure 2. An array of tiny mirrors is made using photolithographic processing, including deposition of metal coatings.

In addition to melting at high temperatures, plastics have other limitations. Plastics are neither as hard as glass, nor do they offer as wide a transmission range. The surface quality and shape are often not as good as what is available from glasses. The refractive index is strongly dependent on operating temperature, which limits the thermal range of an application using plastics. Plastics tend to absorb water, which changes the shape of the surface—and thus the optical properties of the lens. Finally, the narrow choices of available plastics limit the designer's choices of refractive index and dispersion compared to the hundreds of optical glasses available.

Molded glass

Glass molding, on the other hand, has the potential to be used with dozens of glasses. With glass, the process begins with a pre-form in the shape of a disk, ball, or gob, that contains a controlled volume. The pre-form is warmed in the mold until soft, then it is pressed. Mounting flanges can be built in and the center thickness can be held to a tight tolerance, explains Ludington. The lens may need centering and coating, but not polishing. Because the mold can be reused many times, molding is the cost-effective way to make aspheres. He adds, "the cost of making aspheres by hand [by using grinding and polishing] is prohibitive."

By tailoring the glass and the lens shape to the application, the number of lenses can be reduced, which also leads to cost savings in assembly. Kodak's customers are now quite interested in anamorphic lenses (lenses that focus light differently along different lines in image plane), especially for collimating light from diode lasers. The company currently sells a plastic anamorphic lens for this application.

Kodak has been molding glass in larger lenses for the past 25 years, and is working to develop molded microlenses with diameters of less than 3 mm. Kodak's experience with molding larger lenses in a variety of glasses, and with large sags of more than 100 µm, as well as its ability to control aspheric profiles, is helping the company develop micro-optics. "We can currently fabricate glass aspheric lenses with diameters down to approximately 1 mm," says Ludington, and sub-millimeter prototypes are expected to be ready for evaluation by the end of this year. Ludington adds, "We are working at lens concepts that range from 100 µm to 2 mm in diameter."

Sol-gels

A third molding option is unlike either plastic injection or typical glass molding. Sol-gel optics are made from silica precursors in a solution. This technology is licensed to Geltech (Orlando, FL), a company that also bought Corning's glass molding business.

The process involves mixing the sol, then casting the solution into molds. The silica particles link together into a 3-D network, gelling in the shape of the mold. During the next step (aging) the glass network continues to build, providing enough strength for the material to withstand the stresses of drying, during which the non-silica byproducts of the reaction are eliminated. These last steps involve heating the material to more than 600°C (all the previous steps are performed near room temperature) to densify the material, reducing the pores. The final product, called Gelsil, is transparent from the UV into the mid-IR. Gelsil can be made into refractive, diffractive, or hybrid lenses.

Leveraging semiconductor fabrication

Photolithography, the staple of micro-electronics manufacturing, also can be adapted to make micro-optics. With this method comes the potential of making hundreds of micro-optical elements in parallel on a single wafer. In the 1980s, Gary Swanson and Wilfrid Velddkamp at MIT's Lincoln Laboratories developed a process for making diffractive optics using photolithography. Now the method is commercially used to make multiple-level diffractive, quantized refractive, and hybrid optics on silicon or fused silica substrates.

Photoresist on a wafer is patterned using photolithography, and then the pattern is etched into the substrate. In this one step, a two-level surface is formed. If the process is repeated n times, then the number of levels possible equals 2^n. The different surface levels can be used to manipulate the phase of light, creating diffractive optics. Alternatively, the surface levels can approximate a curved lens surface, resulting in quantized refractive lenses. Semiconductor manufacturing methods also can be used to deposit metallic or anti-reflection coatings onto the optics (see Figure 2). Several companies, including MEMS Optical and Digital Optics Corp. (Charlotte, NC), have the equipment necessary to make binary optics.

Photolithography also can be used to create smoothly curved surfaces using a reflow process, in which the photoresist is deposited, patterned, and then remelted, explains Michael Feldman, chief technical officer of Digital Optics. The process retains the advantages of photolithography, allowing large arrays of lenses to be made (see Figure 3). Hans Peter Herzig of IMT (University of Neuchatel, Switzerland) explains, "An array of photoresist cylinders is obtained by photolithography. The height of the cylinders varies from a few microns up to about 100 µm." When the resist cylinders are heated to 150—200°C, they melt, and surface tension results in a smoothly curved surface. This method can be used to make lenses with spherical, elliptical, and cylindrical shapes and surface roughnesses of a few nanometers. "The method works well," says Herzig, "for diameters below a few millimeters and high numerical apertures of more than 0.1."

The photoresist pattern then can be transferred into quartz by reactive ion etching. The lens profile can be modified during etching to achieve aspheric surfaces or low-numerical-aperture lenses. Herzig adds, "for high quality lenses you need to invest a lot of time in order to optimize the process." One disadvantage is that the lenses are not butted together—some unused space between the lenses results in a low fill factor. Other methods, such as photothermal glass processing (which uses thermal processing of a photosensitive glass to create optical surfaces) can yield higher fill factors.

Another development in photolithographic methods for manufacturing micro-optics is the use of gray-scale masks. Herzig's group is investigating ways of making micro-prisms in quartz with depths of 10-60 µm. (For more about gray-scale photolithography, see the sidebar on page 22.)

Wafer-scale optics for fiber arrays

Digital Optics is developing commercial equipment especially for fiber applications in telecomm/datacom systems. In the past, fibers were usually discrete devices, handled one by one. Now, says Feldman, "the demand is

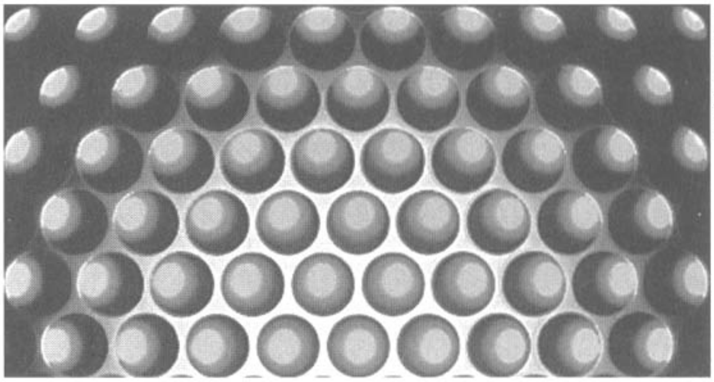
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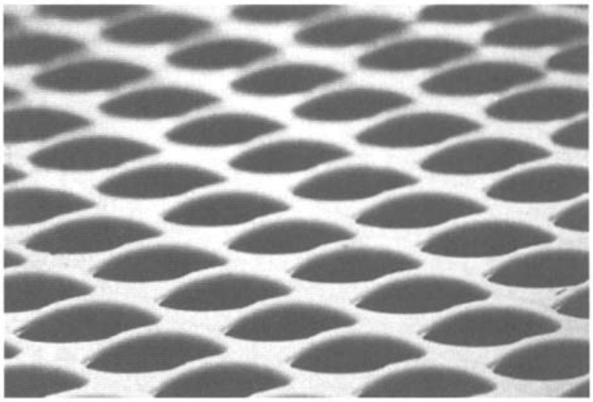
Figure 3. A microlens array is formed by lithographic patterning of a photoresist, followed by melting of the resist. Surface tension forms the smoothly curved refractive lens.


MEMS Optical

An array of silicon microlenses.

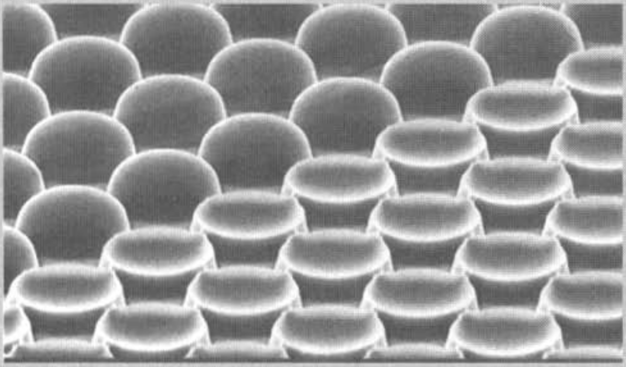
Gray-scale Photolithography

Binary and gray-scale lithography methods allow users to make whole wafers-full of lenses at once. But both diffractive and refractive methods involves tradeoffs.

Binary fabrication is a digital process in which multiple binary masks are used in succession to pattern photoresist. Each photoresist pattern is either clear or opaque, and the pattern is etched into a substrate at specific depths to create a digital approximation of the desired diffractive pattern, or a quantized refractive surface shape.

With grayscale fabrication, a single grey-level mask is used to pattern the photoresist. Instead of the mask being either transparent or opaque to the photoresist-curing radiation, certain portions can transmit some percentage of the light. Feldman explains, "This pattern is then transferred into the substrate by etching both the photoresist and the substrate with a fixed ratio."

"The advantage of the digital technique," says Feldman, "is that it is an extremely precise, highly repeatable, mature manufacturing process." The method takes advantage of typical semiconductor manufacturing equipment.



MEMS Optical

There are very few companies in the world that can make negative microlensarrays. MEMS has a gray-scale technology that allows the production of the highest theoretical diffraction efficiencies.

Back to analog

Gray-scale techniques have the potential to lower the cost of fabrication and/or increase the diffraction efficiency. Money can be saved by requiring only one masking and etching step. The use of a single mask can also reduce errors introduced by aligning multiple masks. This technique can produce any shape structure, as opposed to the stair-step structures of binary methods.

On the other hand, gray-scale techniques introduce errors due to process variation. The photoresist is highly nonlinear, and accurately representing the desired profile in the substrate can be difficult. Feldman explains, "Small variations in process conditions can lead to severe changes in the profile, due to the analog nature of the manufacturing process." This method also has difficulty creating sharp steps in the profile, which can result in lower efficiencies. Feldman concludes, "Whether gray-scale or digital methods yield higher efficiency will depend on the precise optic to be manufactured and on the required tolerances."

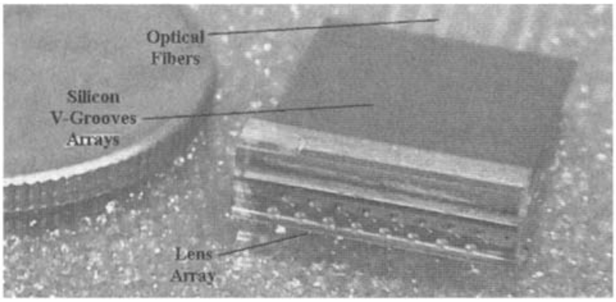
Making refractives

Both binary and gray-scale techniques can be used to make refractive elements on a wafer scale, as well as a third option, reflowed photoresist (see main article, section "Leveraging semiconductor fabrication"). Gray-scale techniques can be used to make refractive lenses, but the process variability makes processing difficult. Feldman adds, "a small percentage change in the thickness of resist or etched part can lead to a substantial wavefront error." On the other hand, the gray-scale system allows any shape surface structure to be produced as opposed to a stair steps of binary processing. For example, gray-scale processing was used to create an array of both positive and negative lenses.

A method that falls between the digital approach of binary masks and the analog approach of gray-scale masks is the reflow method, in which the resist is patterned by a binary mask, then the resist is melted to form a curved shape. The shape is then transferred into the substrate through dry etching. Feldman says, "Although reflow methods involve analog processing steps, reflow methods tend to be a fairly mature process, especially for small sag heights. Process variability leads to a variation in wavefront error and in focal length, but is significantly less than with gray-scale techniques."

just getting started" for devices that will handle arrays of fibers. The company has designed a product in which the ends of a linear array of fibers are placed in V-grooves, and collimated with an array of lenses (see Figure 4). Users can put a variety of components between one array and another, including switches, isolators, and wavelength-division-multiplexing components. The arrays can be spaced from 1 mm to a few centimeters apart.

As these methods are developed further, the fabrication technique will probably depend on the types of lenses required, allowing designers to take advantage of each method's strengths. The various fabrication methods described above each have their strengths and weaknesses, and no single method fits all needs. For a single microlens, the cheapest fabrication method may be grinding and polishing, whereas for tens of thousands of elements, plastic molding or embossing may be the technique of choice. Between these two extremes, the choice of methods will largely depend on the designer.



Digital Optics Corp.

Figure 4. A tiny assembly of V-grooves and integrated micro-optics allows users to collimate an array of fibers in telecommunications and data communications systems.

Although a great deal of optical fabrication has been raised to a science, there is still plenty of room for art in the fabrication of these tiny optics.

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