Replication of micro- and nano-scale features in polymers is of interest in a number of fields—microfluidics, illumination optics, diffractive optics, and many others. In optics, replication occurs at several points in the manufacturing process. Molds are typically made by replication of masters, since diamond machined or lithographically produced masters are not usually suitable for use directly as molds. Mold replication is usually through either nickel electroforming or silicone casting. Optics are replicated in quantity from those nickel or silicone molds by several methods, including compression molding, injection molding, and casting.

Our group has fabricated many optics with microscale and nanoscale features, using each of these methods. Applications of these optics have included diffusers, tailored illumination, collection of light for measuring instruments, and many others.

Moldmaking

Molds for microscale polymer optics are generally produced in a multistep process, because the available processes for mastering generally produce a soft, brittle or otherwise easily damaged surface unsuitable for molding in production volumes. Many molds are produced via diamond machining. One typical example of a diamond machined microscale mold is a mold for a Fresnel lens. These are made on a diamond lathe, either with an additional axis for articulation of the angle of the tool or by aspheric contouring of each individual groove. Typical grooves are as small as perhaps 10µm width, with maximum depth for those grooves of perhaps 15-20µm. A photomicrograph of Fresnel lens grooves (though not the smallest possible grooves) is shown in Figure 1. Because of the small grooves, and the necessity of using a very narrow and sharply pointed tool to make them, the diamond turned masters are usually made either from PMMA, from copper, or from brass. None of these materials is suitable for use as a production mold, though brass can be electroless nickel plated to prevent surface degradation and used directly in small production runs.

Another typical diamond machined microstructure is shown in Figure 2. This is an array of linear prismatic grooves, in this case 45-45-90 triangles. Linear structures such as this one can be made by diamond flycutting, where a spinning tool scoops small bits out of a slowly moving workpiece, or by planing, where a tool is pushed at relatively high speed through the workpiece. The choice of method depends on the structure one wishes to cut, on the workpiece material, and on other factors including the stiffness, speed and acceleration capabilities of the available machines. These linear structures are also generally made in PMMA (acrylic), copper, or brass, necessitating another step to a production mold. Structures that do not require a small-radius tool, such as lenticular arrays, can sometimes be made directly in materials suitable for production molds, such as electroless nickel on steel or copper-nickel alloys.
Other masters are made using various combinations of resist exposure and etching, from binary and grayscale optical lithography to electron beam writing to direct laser writing in resist. Still others are made via focused ion beam milling directly on a substrate. These techniques generally produce only flat masters, in contrast to the diamond machining techniques that can produce masters on a substrate of nearly any shape. However, they can make shapes that are not possible using diamond machining, notably those with high spatial frequencies such as holograms. The direct-writing methods are very flexible, but are generally slow, since they were originally designed for writing of only small areas to be incorporated into step and repeat processes used in the semiconductor industry.

These methods again produce masters that are unsuitable for direct use as production molds, even apart from any desire to keep an archival copy in case of accidental damage to a production mold.
This leads us to the common thread among the various mastering methods—they all generally require nickel electroforming to produce a mold suitable for replication of large numbers of polymer optical elements.

Electroforming is a well-established technique for replication of conductive substrates. Electroforming can replicate structures with dimensions well under one micrometer, with claimed minimum feature sizes down to perhaps 4 nanometers. The electroforming process can be used to deposit many different metals, from nickel to copper to gold, but nickel is generally chosen for moldmaking due to its relatively high hardness and toughness. Since a conductive substrate is required, many of the masters produced using techniques mentioned above must be metallized before they can be electroformed. Metallizing of complex substrates is an art all its own; particularly if the structures on the substrate have a high ratio of depth to width, vacuum metallizing is required (and difficult).

Once a conductive substrate is obtained, the first generation nickel electroform is often designated as an archival copy since the soft original is often damaged during separation from the first generation electroform. As many production molds as one wishes can be made from the initial copy, broadly speaking. A schematic of the electroforming process is shown in Figure 3.

![Figure 3: Electroforming of nickel mold from a PMMA (or other nonconductive) master](image)

The other method sometimes used for making production molds, though typically only for casting processes, is replication in silicone. It is possible to cast a thin layer of silicone against the master and get replication comparable to that possible in nickel electroforming, or in some cases even better. The silicon mold can then be held on a glass substrate or wrapped around a casting roller for use in production. The silicone mold is quite delicate, but the cost of making another copy if it is damaged is usually not large.

**Replication in polymeric materials**

Broadly speaking, there are three main methods for replication of microstructures made using the above manufacturing techniques into polymer optical elements. They are compression molding, in-
jection molding, and casting. Another method, hot embossing, is essentially a lower-resolution form of compression molding.

Compression molding can be defined as a process involving placing a solid substrate between mold halves, heating the substrate to soften it, applying pressure to replicate the mold surfaces, then cooling the substrate under pressure. Because there is very little material flow during the compression molding process, there is little or no molded-in stress in optics produced by this method, and thus little or no stress birefringence. Because the mold halves are held apart only by the substrate, the substrate can be compressed as much as necessary during cooling and shrinkage, leading to extraordinarily high-fidelity reproduction of the mold surfaces. However, this same feature means that the thickness of the final product is not very well controlled. A typical compression molding press and mold halves are shown in Figure 4. The compression molded product, again due to the open mold, has ill-defined edges and must be cut to its final size; compression molded optical products are also limited to flat or nearly flat shapes. Compression molding has a long cycle time, but can be economical when many parts can be molded at once, and is especially economical if the parts can be separated by die-cutting rather than CNC milling.

![Figure 4. Compression molding press and mold halves](image)

Injection molding can be defined as a process where a material is melted, then squeezed into a cavity that is the inverse of the desired product shape. Pressure is applied to the molten material during the initial phase of cooling in order to minimize the shape change during shrinkage, but the time during which pressure can be applied is limited by material freezing in the melt delivery system (runner and gate). Material flow leads to high molded-in stress, and thus to high birefringence in materials subject to stress birefringence. Injection molded parts can be practically any desired shape, and thickness control can be excellent since the cavity is closed (except for air vents). However, this characteristic of injection molds also means that the fidelity of surface reproduction is generally lower in injection molding than in compression molding. Injection molding has a relatively short cycle time, so especially if multiple-cavity molds are used it can be a very economical production process. The molds are complex even for simple optical microstructures, and so usually have a considerably higher cost than compression molds for the same product. A typical injection molding press and
mold are shown in Figure 5. Note the barrel on the right for melting the polymer material and injecting it into the cavity, and the clamp on the left for maintaining pressure on the mold halves during injection.

![Injection molding machine, showing barrel, clamp, and mold](image)

Figure 5: Injection molding machine, showing barrel, clamp, and mold

Casting is a process wherein either a monomer or a polymer dissolved in some suitable solvent is placed against a mold. In the monomer case the monomer is then polymerized by heat, ultraviolet light, or some other trigger; in the polymer case the solvent is driven off by heat or vacuum. In either case the polymer replica of the mold is then removed from the mold, and often undergoes further processing. Casting can be either a continuous process as in the manufacture of optical films for LCD panels or security or branding holograms, or a piecewise process as in nanoimprinting or the casting of eyeglass lens blanks from CR-39. Continuous-process cast optical elements generally require at least edge trimming, and if they must be made into small pieces also die-cutting. Piecewise process cast optical elements often require significant further processing; for instance, the very large shrinkage of CR-39 requires grinding and polishing of the cast lens blanks to obtain the desired optical figure, and the blanks are also edged to size after casting. Casting can produce optics with low or no stress, and can reproduce mold surfaces with exceptional fidelity. If a sufficiently large volume of parts is required, continuous casting can be an economical production process. The required equipment is large and expensive, the tooling for a particular pattern is expensive, and the changeover between different patterns is lengthy and difficult. A (very) schematic view of a continuous casting process is shown in Figure 6.
Figure 6: Schematic of continuous casting process

Examples of molds and polymer optics produced by the various methods discussed will be shown.

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