Advances in processes and materials are extending replication technology into the submicrometer world and enabling new commercial applications in diffractive optics and micro-optics. The ability to mold very high resolution binary and continuous-relief microstructures in a cost effective, mass production process will have a major impact on the manufacture of micro-optical elements. Numerous micro-optics products manufactured by replication technology are already commonplace, many more will follow.
The replication of optical microstructures and nanostructures from a mold into a polymer or other formable material is a well-established technique used to manufacture a number of products which are very evident in our lives. Examples include diffractive wrapping foil, holograms on credit cards, compact discs, and molded polymer lenses for optics in consumer products (see Fig. 1). In the optical laboratory, high performance replicated diffraction gratings, with profile and dimensional tolerances in the nanometer regime, are evidence of the degree of precision with which replicated structures can today be produced. Replication technology is continuously evolving. Corresponding improvements in the fidelity and cost of replicated components are continuously being registered.

It is no wonder then that in the future, this technique is destined to find increased usage in optical modules and optical systems.

**Replication technologies**

Three basic types of replication technology are used today:

- **Hot embossing**, in which a mold typically made out of nickel (the shim) is used to emboss sheets or rolls of polymer foil. Practitioners of modern roll-to-roll embossing are also capable of hot embossing metalized foil to directly produce reflective optical microstructures. Typical commercial applications include diffractive foil for packaging and display purposes and security holograms for credit cards and bank notes.

**Figure 1.** Replicated micro-optics in everyday life. (Left) Hot embossing: diffractive foil; (center) Injection molding: CDs; (right) UV embossing: microlenses.
Injection molding, in which an optical microstructure is produced from a nickel or steel mold (the tool or insert) by injection of molten polymer under pressure. The best known example is the compact disc (CD) and its successor, the digital versatile disc (DVD). Microlens and diffractive optical elements (DOEs) can also be produced by injection molding, as can complete optical microsystems with multiple components.

UV embossing, the curing of liquid monomer or polymer by ultraviolet (UV) light, is used for replicating high quality micro-optics and diffractive optics. The mold, which can be made of nickel, often consists of transparent fused silica or a polymer material. Commercial applications include the production of microlenses and DOEs for optical modules in consumer products and optical communications systems.

Key advantages
Replication technology has three major advantages. The first is the ability to reproduce very high resolution microstructure features. Even with common polymers such as polymethyl methacrylate (PMMA) and polycarbonate, it is easy to hot emboss grating structures with submicrometer linewidths; nanometer-sized structures can be readily replicated in the laboratory. The roll-to-roll hot embossing of holograms and DOEs has long utilized this high resolution capability, producing submicrometer features in kilometer foil lengths. Today, further reduction in feature size—to sub-100 nm structures—is possible by use of improved hot embossing equipment, materials and technology. Figure 2 shows an example of hot embossed foil for a new generation of security features based on subwavelength diffractive optical structures. Similar resolution can be achieved with UV embossing and, to a certain degree, with injection molding. In practice, the lateral feature resolution achievable is limited by the structure
A general guideline is that, independent of feature size, a height-to-width ratio of 1:1 is readily achievable and 10:1 is "challenging." More difficult to optimize the replication process, the basic point remains: the technology is inherently capable of reproducing highly complex combinations of very different microstructures.

The third advantage associated with replication technology is the ability to achieve low cost mass production of replicas from a mold. Although the fabrication of a mold with micrometer- or nanometer-sized structures can be very expensive, the replication process still results in low cost per replica and hence commercial viability.

From design to replicas
The process chain that leads to replicated micro-optical elements is shown in Fig. 3. It begins with the fabrication of an original surface microstructure which corresponds to the optical design. A large palette of microfabrication technologies is available to accomplish this step: examples include holographic origination, "conventional" high resolution semiconductor lithography and etching, e-beam lithography and direct patterning technologies such as diamond turning and laser writing.

The origination can be in any suitable material, for example in photoresist, fused silica, silicon or metal. Fabrication of the molding tool is the next step. If the original microstructure area is smaller than the desired final mold, the area can be copied and repeated by use of a recombination technology that is typically based on a multiple embossing...
approach. The final tool can be electro-formed nickel or a mold in metal or polymer. Mass production is then carried out by one of the technologies outlined above.

High quality replicated micro-optical elements are now offered by a number of companies. Figure 4 shows double-sided optical modules produced by UV embossing onto a glass substrate. Such replicated components have very high optical performance and satisfy the stringent environmental testing and lifetime requirements of the telecom industry. They can be fabricated by a wafer-scale process which combines the high alignment and positioning accuracy of photolithography with the low fabrication costs of replicated micro-optics.

Sol-gel materials
A recent development in replicated micro-optics is the use of sol-gel materials which can be cured by UV exposure into hard, glasslike layers. Figure 5 shows research and development being carried out at CSEM using materials developed within the European Union “DONDO-DEM” project by the Fraunhofer Institute for Silicate Research (ISC) in Würzburg, Germany. These ORMOCER* materials are inorganic-organic hybrid polymers, developed especially for optical applications, that can be processed by both UV embossing and lithography to enable components to be replicated onto glass or device substrates with areas left free of material for dicing or bonding. Figure 6 shows examples of microstructures fabricated by means of this technology.

Individual lenslets can be replicated onto vertical cavity surface emitting laser (VCSEL) devices on a wafer, in this case to focus light from the VCSEL into a fiber. A very interesting application is the replication of mechanical microstructures with diffractive or refractive optical microstructure, for example for the positioning of additional components or for packaging alignment. Figure 6(c) shows replicated mechanical features for positioning additional lenslets over a micro-optical layer.

The same technology is being used to investigate micro-optical electromechanical systems (MOEMS) fabricated in sol-gel materials. Figure 7 shows the fabrication process and an example taken

* ORMOCER is a registered trademark of the Fraunhofer-Gesellschaft in Germany.
from the development work now being carried out at CSEM. The refractive lenslets and the MEMS cantilever structure are fabricated in the same replication step by UV embossing. The aim is to determine the technical and commercial feasibility of fabricating MEMS and optical MEMS components using materials other than silicon as part of a cost effective process in which both very high resolution nanostructures and continuous-relief optical microstructures can be fabricated.

**Outlook**

The outlook for replicated micro-optics is bright. The ability to fabricate very high resolution and continuous-relief microstructures fits well with the future requirements of diffractive and refractive micro-optics. Combined with the potential for low cost mass production, such advantages put replication technology firmly on the micro-optics road-map.

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**Further reading**


