LIGA Technologies and Applications

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Introduction

LIGA, an acronym for the German words for lithography, electroplating, and molding, is a technique used to produce microelectromechanical systems (MEMS) made from metals, ceramics, or plastics. The LIGA process utilizes x-ray synchrotron radiation as a lithographic light source. Highly collimated, high-energy x-rays from the synchrotron impinge on a patterned mask in proximity to an x-ray-sensitive photoresist, typically poly(methyl methacrylate) (PMMA). In most cases, the PMMA is attached to a substrate that is used later as an electroplating base. The regions of PMMA irradiated by the x-rays experience bond scission, and these areas are selectively dissolved in a chemical developer. Once the PMMA is developed, the resulting nonconductive mold is filled with metal by electrodeposition from a conductive base. As originally envisioned, after electrodeposition and dissolution of the PMMA, the electroplated structures can be removed from the substrate and used as individual metal microparts, or the metal pattern can be used as a mold insert for replication in a polymer using injection molding or hot embossing.

LIGA parts typically have 1–10-μm minimum lateral feature sizes, and are from hundreds of micrometers to a few millimeters thick. The format used for LIGA processing is generally 3–6-in.-diameter wafers. These processed wafers may contain thousands of microparts or a few larger parts with small, precise features.

The LIGA process was first developed at the Forschungszentrum Karlsruhe (FZK) in the mid-1980s.[1] Since that time, there has been considerable investment in process research, as well as technology maturation for commercial application, at institutions worldwide. A technique similar to LIGA that utilizes UV radiation instead of synchrotron radiation to produce patterns has also been developed and is usually referred to as UV-LIGA.[2] More recently, several other techniques to produce LIGA-like structures without using synchrotron radiation have been developed, including deep reactive ion etching (DRIE)[3] and laser ablation.[4] These techniques use other methods to create a mold in a nonconductive polymer or a semiconducting material, which can then be electroplated and processed in a manner similar to x-ray synchrotron patterned wafers. Likewise, techniques other than polymeric replication have been developed to allow microstructures to be replicated from LIGA masters in other materials.

This article reviews LIGA processing technologies and describes examples of some current applications using LIGA techniques.

LIGA Processing Technologies

LIGA, like other microfabrication technologies, requires a number of serial processes to create a finished product. When a metal micropart is the desired product, the processing steps shown in Figure 1 are followed. When LIGA is used to produce a metal mold insert for replication, the processing steps after plating are modified (and discussed in more detail later).

While optimizing the layout of the mask in LIGA requires considerable process knowledge, generally speaking the tools for CAD drawing, mask layout, and chrome mask fabrication are standard commercial products. Software programs to optimize mask layout are not yet available, but the development of these is under way.[5]

LIGA mask fabrication has not been standardized because the optimum LIGA mask for any particular application depends on the synchrotron beamline being used, as well as the lateral feature size, part height, allowable tolerance, desired throughput, and so on. LIGA masks generally can be categorized as either membrane or substrate masks. Membrane masks utilize a thin, relatively x-ray-transparent membrane supported by a thicker wafer etched away from the active region. An absorber, usually 5 μm thick or less, is patterned onto the membrane. Membrane masks are usually necessary if the beam energy is low, or if especially fine feature sizes are required. Substrate masks utilize a wafer that is completely patterned with absorber. Wafers are 100 μm thick or more and can be made of silicon, beryllium, graphite, or other materials, depending on the synchrotron used and patterns desired. Absorbers are usually 10 μm thick or more. Substrate masks are more robust than membrane masks and contain a larger patterned area, but minimum feature sizes may be larger and exposure times may be longer because the substrate is less transparent than the membrane.[6,7] In both types of masks, the absorber pattern is typically obtained using a commercially available thick photoresist such as SJR5740 and UV i-line (365 nm) lithography in a standard clean room. After the photoresist is developed, gold is electrodeposited to create the x-ray absorber material, and the photoresist is stripped.

Substrate preparation is the step where the PMMA resist, several hundred micrometers or even millimeters thick, is applied to a substrate. Since the substrate will be

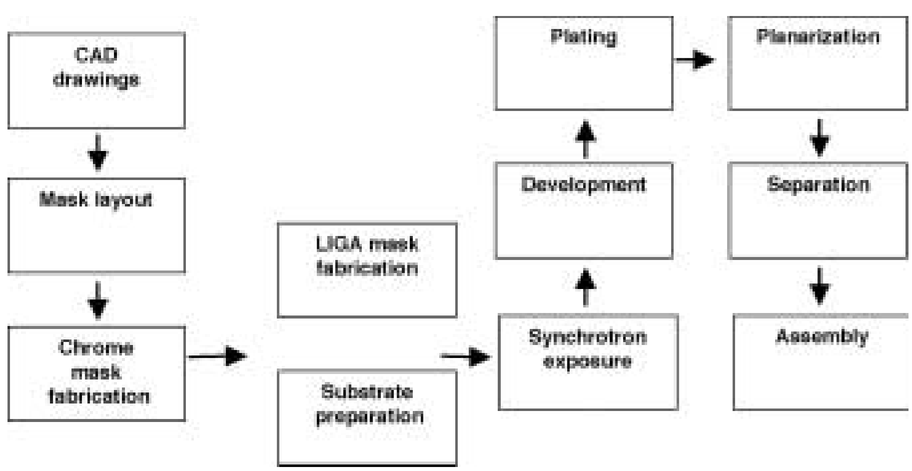

Figure 1. The steps involved in fabricating microparts by means of the LIGA process.

used later as an electroplating base, it must either be conductive or have a conductive layer deposited on a nonconducting base. The PMMA is placed on the metallized substrate by direct polymerization of a resin, by gluing a prefabricated PMMA sheet to the substrate with polymerization glue, or by bonding a prefabricated PMMA sheet to a spin-coated resist layer of a few micrometers' thickness on the substrate.[8] Generally speaking, this step is completed prior to exposure, but sometimes this step is done after exposure or after development. The PMMA must be on the substrate prior to development if the desired pattern contains floating parts.

In order to successfully conduct a LIGA synchrotron exposure, a scanner capable of rastering the mask and resist substrate must be available. Normally, the LIGA scanner is placed at a sufficient distance from the synchrotron to expose a 3- or 4-in. horizontal slice, and rastering is required, as a minimum, in the vertical direction. Added levels of sophistication include rotation and alignment capabilities.*

Suitable developers are available for x-ray-exposed PMMA.[12] Complete, residue-free development is required to successfully electroplate the substrate and the entire thickness of the PMMA mold. Megasonic (1–100 MHz) agitation has been found to assist in the timely development of PMMA in high-aspect-ratio features. The intensity of the megasonic agitation is dependent on the geometry, especially for fragile microstructures. The equipment required for development is, at this point, generally custom-designed and -assembled from commercially available components.

Electroplating the LIGA-produced molds is commonly done using nickel, copper, gold, or nickel iron.[13] Usually, the current density for LIGA electroplating is substantially lower than that for large-scale electroplating used for protective coatings. Uniformity and homogeneity of the electroplating, both through the mold thickness and across the wafer, are important issues that are geometry-dependent. Models to describe and optimize electroplating are not at a predictive stage. Most LIGA research groups rely on experience to choose the appropriate plating conditions and perhaps shields or other means to help achieve the desired homogeneity and uniformity. Like development equipment, electroplating equipment is usually custom-designed and -assembled from commercially available products.[14]

After the electroplating is complete, the wafer must be planarized due to nonuniform plating rates in the mold. The planarization is normally completed using either a lapping or a grinding process, sometimes followed by polishing. Once the metal is planarized, the PMMA is dissolved, and the plated parts are removed from the substrate if metal microparts are desired. An image of an assembled subsystem made from electroplated LIGA microparts is shown in Figure 2.

If the LIGA wafer is to become a mold insert for replication, there are two common methods. One is to follow the exact procedure just described, using a metal base for the electroplating step. Instead of separating the parts from the base, the base becomes the mold insert base. The other method is to overplate the PMMA mold and use the overplated material as the tool base, separating the original substrate from the plated material.

Replication is an active area of research, focused mostly on injection molding and hot embossing in polymer systems.[15,16] Hot embossing is generally used when patterns with aspect ratios of less than 10 within a polymer are the desired end product. A good example of the utility of hot embossing is in the fabrication of chips for micro total analysis systems (μTAS), where flow channels, reservoirs, mixers, and so on can be designed and fabricated directly in a single-layer polymer chip. Injection molding is considered to be more versatile in terms of polymer selection and allows replication of higher aspect ratios.

In addition to the replication of LIGA patterns in polymers, producing ceramic and metal replicates is another area of ongoing research. In the simplest technique, ceramic or metal particles with a binder can be injection-molded into the LIGA-produced mold insert. The primary concerns are sufficient filling of and removal from the mold. Another approach is to fill the polymeric replicate produced by injection molding with micro- or nanoscale ceramic or metal particles and binder by cold pressing. Mold fill density is a concern in this technique, but the polymer replicate can be sacrificed for removal. In either case, if pure metal or ceramic material properties are desired, the binder needs to be removed through a sintering process, and the part shrinks 15–28%, depending on the formulation.[17] The selection of commercially available metal and ceramic micro- and nanoparticles is increasing, which will expand the range of this technique.

LIGA can also be used to make precision tools. One example is the use of a LIGA-produced mold insert as a cutting tool in plunge microelectrodischarge machining.[18] In this case, the metal tool can be used to cut other materials, such as kovar or stainless steel, that cannot be electroplated directly. An example of a LIGA-produced tool is shown in Figure 3.

Whether electroplated or replicated, LIGA structures are usually small parts that need to be assembled into a larger subsystem. The assembly process for small parts is a developing field with no standard commercial technologies available. LIGA parts can be assembled by hand for research purposes, and there is ongoing work in robotic

*Synchrotron exposure requires access to an appropriate beamline. Dedicated LIGA beamlines exist at most synchrotrons in the United States and Europe, as well as in Taiwan, Japan, Korea, and other countries. There are commercially available LIGA scanners as well as many custom scanners that have been utilized. Most synchrotrons allot beam time for research and development efforts through the independent investigator process, and arrangements are available for commercial entities to buy time or buy beamlines.[9–11]

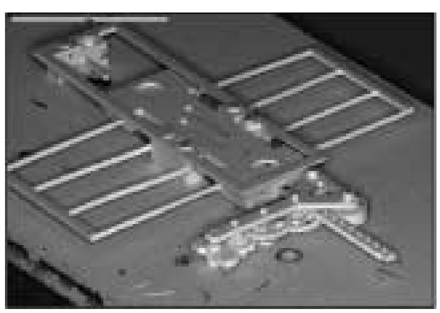

Figure 2. Acceleration sensor assembled from LIGA-produced elements. LIGA materials include electroplated nickel and nickel iron. The struts in the large sensor structure are 6 μm wide. Courtesy of Sandia National Laboratories.

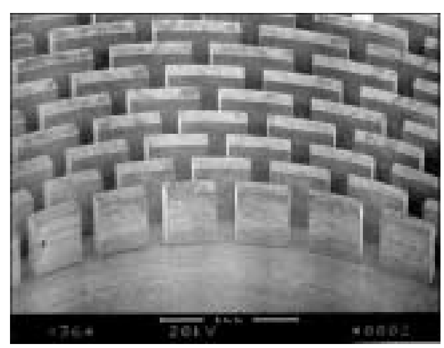

Figure 3. Electroplated nickel precision tool made using the LIGA process. This tool was used with a plunge microelectrodischarge machine to create a precise screen pattern in kovar and stainless steel. Courtesy of Sandia National Laboratories.

manipulation.[19] Another approach is to limit the need for assembly by employing sacrificial layers in LIGA processing. An example of a microturbine using a sacrificial technique is shown in Figure 4. In addition to using sacrificial layers, multilevel LIGA processing has been demonstrated. An image of a multilevel cantilevered structure is shown in Figure 5.

LIGA processing technologies are now sufficiently advanced to produce not only replicates, but also, potentially, sacrificial molds for subsequent materials processing. Over the next decade, techniques that allow traditional materials processing, such as casting, to be extended down to these size scales may develop, along with entirely new approaches to achieving unique materials, materials performance, and geometries.

LIGA Applications

Commercial application of LIGA products is occurring, particularly in Germany. Three German entities have been especially active in introducing LIGA into commercial products: FZK, the Institut für Microtechnik Mainz GmbH (IMM), and STEAG microParts GmbH. STEAG microParts has introduced several products based on a miniaturized polymer spectrometer grating replicated from a LIGA master developed at FZK. The products include a visible spectrometer, a near-infrared spectrometer, and, through a licensing arrangement with U.S. company SpectRx Inc., a bilirubin analyzer.[20] The STEAG microParts spectrometer is shown schematically in Figure 6. In addition, STEAG microParts uses LIGA and LIGA-like techniques in fluidics devices such as ink-jet integrated nozzle plates and biomedical devices.

Both FZK and IMM have developed a number of products for the telecommunications industry. IMM has developed a family of plastic products for telecommunications applications including Starlink, a passive integrated optical component containing six independent identical 4 × 4 couplers, a 1 × 2 switch, a fiber ribbon ferrule, and integrated optical beam splitters. In addition, IMM has produced metal LIGA fiber ribbon alignment parts and micro heat exchangers requiring hot embossing of aluminum and a number of ceramic and plastic molding steps.[21] An image of an IMM mold insert detail for a fiber chip-coupling scheme is shown in Figure 7. An image of an optical bench for a heterodyne receiver made by FZK is shown in Figure 8.

Recently, U.S. company AXSUN Technologies announced the introduction of a product for the telecommunications industry based in part on LIGA technology. In AXSUN's products, LIGA is utilized as a way to make precise metal micromechanical alignment structures. AXSUN licensed LIGA processing know-how from Sandia National Laboratories to realize their prod-

Figure 4. LIGA nickel microturbine fabricated by the sacrificial-layer technique: rotor diameter is 130 μm, height is 150 μm. Courtesy of Forschungszentrum Karlsruhe.

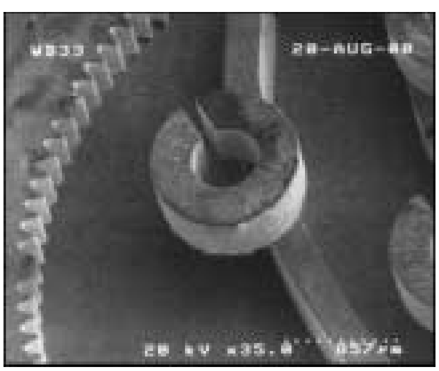

Figure 5. Multilevel LIGA-produced structure showing the ability to produce second-level metal structures cantilevered over the first-level metal structure. Courtesy of Sandia National Laboratories.

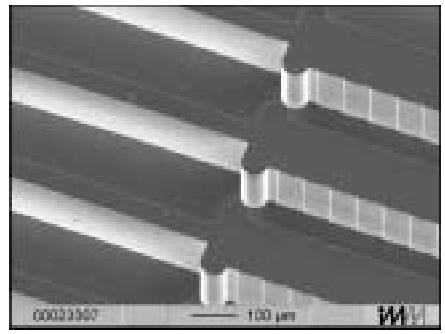

Figure 7. Scanning electron microscopy image of the mold insert detail used for the replication of highly precise fiber chip-coupling schemes allowing passive pigtailing. Courtesy of Institut für Microtechnik Mainz GmbH.

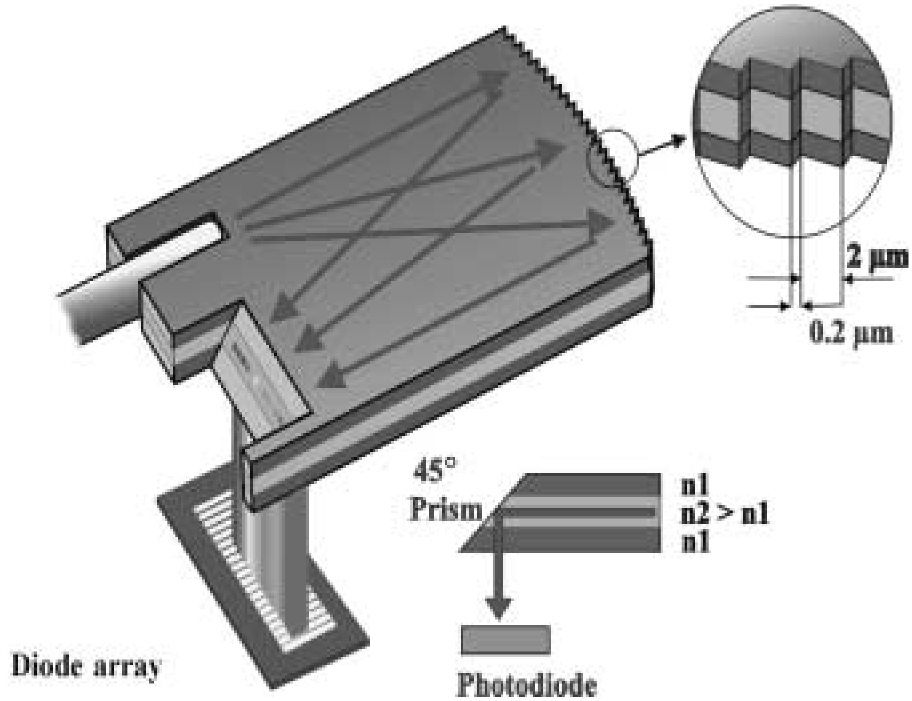

Figure 6. Miniaturized polymer spectrometer grating made using LIGA, where n is the index of refraction. This spectrometer grating is used in three commercial product lines: a visible spectrometer, a near-infrared spectrometer, and a bilirubin sensor. Courtesy of Forschungszentrum Karlsruhe and STEAG microParts.

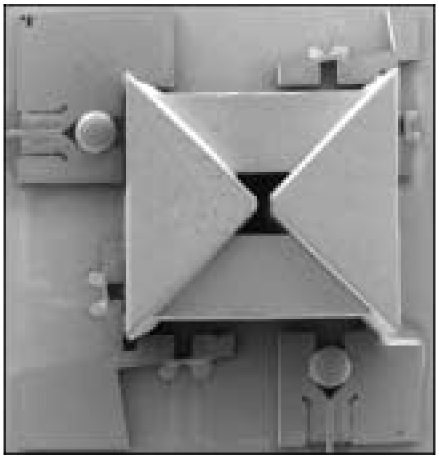

Figure 8. Optical bench for a heterodyne receiver. Fixing structures are used to position ball lenses, fibers, glass prisms, and photodiodes passively with high precision. Courtesy of Forschungszentrum Karlsruhe.

Figure 9. Micromechanical alignment structure in nickel made using the LIGA process. Lateral legs are 40 μm wide. Courtesy of AXSUN Technologies.

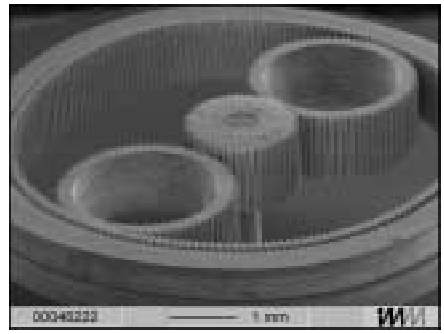

Figure 10. LIGA-produced nickel iron microgear, 8 mm × 1 mm, with flex-spline ring thickness of 40 μm and flexible planet wheels. Courtesy of Institut für Microtechnik Mainz GmbH.

ucts. An AXSUN Technologies LIGA product is shown in Figure 9.[22]

In addition to the commercial products discussed here, LIGA is also advantageous for micromechanical systems such as motors and pumps because the high aspect ratios allow the generation of high torque. LIGA planetary gear systems have been produced by a number of commercial and research entities. An example of a LIGA gear system is shown in Figure 10.

Summary

LIGA produces high-aspect-ratio microstructures by using x-ray synchrotron radiation lithography and subsequent electroplating and replication. Over the past decade, processes to expand the materials suite in LIGA have emerged. Hot embossing and injection molding of polymers, as well as ceramic and metal injection molding and cold pressing of nanoparticles, are extending the range of materials that can be used in LIGA. In addition, processing approaches such as sacrificial layers and multilevel techniques are promising to produce more complicated preassembled structures.

Commercial application of LIGA-produced polymer and metal parts has occurred in both Germany and the United States. These parts are usually deployed in systems with parts machined by means of other methods. As techniques develop to optimize processing, lower costs, and utilize a broader range of materials, more products can be expected to come onto the market.

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