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L^3: Laser, LIGA and lithography in microstructuring*

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Abstract

Established techniques of laser, LIGA and lithography processes have made the fabrication of three-dimensional structures in micron and submicron order feasible. Presently, most of these technologies employ top-down approach, whereas the futuristic nanotechnology will use the bottom-up approach. These technologies have demonstrated the performance and reliability with high resolution. Combination of these technologies will further enhance the device functionality and increase the device density. This paper highlights some of these features and demonstrates with a few applications.

Keywords: MEMS/NEMS, micromachining, laser, LIGA, lithography, nanotechnology.

1. Introduction

In the emerging field of semiconductors, microelectronics, micro-/nano-electromechanical systems (MEMS/NEMS) and surface-mounting devices, the use of shorter wavelength beam technology as a micromachining/fabrication tool has been increasing. It is often desirable to generate/fabricate complex microstructures in various materials depending upon their applications such as polymeric insulator with patterned structure, microsensors, actuators and micro fluidics control devices, etc. Movable microstructures such as turbines and micromotors have been fabricated using various surface-micromachining techniques [1]. However, as the feature size falls to μm-technology (100–0.1 μm) and nm-technology (100–0.1 nm) [2], the conventional mechanical techniques will be replaced by beam technology. During the last decade, laser, LIGA and lithography processes have been employed to produce such small μm or sub-μm order microstructures and components.

In the laser technology, typically Nd-YAG laser has a dominant role in precision metal processing. Examples of these are stent/stencil/mask processing, precision drilling of cooling holes, microgears or fine patterning applications. However, the short pulse excimer lasers operating in the UV region allow the production of even smaller μm or sub-μm order structures. On the other hand, in medical applications, catheters with miniature wires and reducing features in IC technology are making an increasing use of excimer laser processing. Nanotechnology is replacing the conventional UV light sources due to its inherent advantage of high processing velocity and higher resolution. In contrast to this, X-ray radia-

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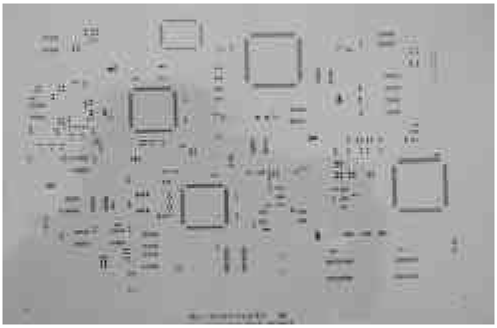

FIG. 1. Metal mask.

tion, in conjunction with LIGA process, has enabled the production of submicron 3D movable structure resulting in fabrication of a microsystem [3]. Keeping in pace with the present technology, the objective of this paper is to demonstrate the comparative use of laser, LIGA and lithography techniques with emphasis on their current applications in polymer, ceramics and metallic micro-/nano-devices.

2. Microprocessing with Nd-YAG/excimer lasers

2.1. *Nd-YAG laser*

In the stent/stencil/metal mask technology, processing with the Nd-YAG laser having higher pulse repetition rate and short pulse width has various advantages over the conventional etching and electroforming techniques. The latter two processes have virtually been replaced by laser technology. Figure 1 illustrates an example of a metal mask generated with Nd-YAG laser technology. Fine structures with slit width of 100 *m*m and resolution of 100 *m*m were achieved [4].

In medicine, coronary artery obstruction is a major problem, which leads to complicated problems of hemorrhage eventually leading to bypass surgery. In order to treat this obstruction, usually a standard angioplasty technique is applied. But its clinical efficacy is limited by acute vessel occlusion and restenosis problems in the first six months. To reduce these deficiencies a new clinical therapy has been introduced with the implantation of metallic cardiovascular stent with adequate radio opacity. Metallic stent is typically a hollow cylindrical tube (d = 2–4 mm; l = 15–20 mm) with a patterned slit structure in two or three segments. It controls the flow of blood in the damaged vessel, thus saving it from rupture. Typically, the percentage of metal-free unit area per total unit area of the stent varies between 76 and 85% values and offers regulatory resistance to the blood flow in the vessel. Figure 2 shows the block diagram and the actual section of such laser-generated metallic (SS316L) stent using pulsed Nd-YAG laser [5]. It consists of three/four segmented parts, connected via bridges with a total length of about 20 mm. By dividing the stent into three/four segments, it provides high flexibility. The metallic body of the stent shows a good X-ray visibility of the device under angioplastic control. Its burr and spattering problem is overcome by soft etching method during post-processing and is further improved against wear and corrosion by ion implantation technique. This produces the microstructural defects and becomes responsible for improved wear and corrosion resistance. Recently, nuclear

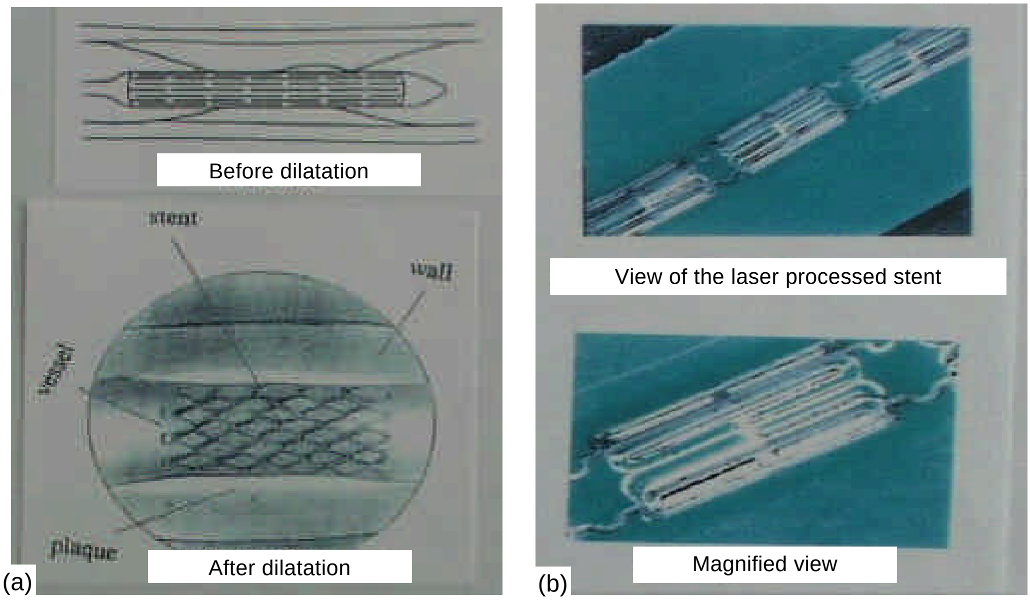

FIG. 2(a). Block diagram of the stent before and after dilatation; (b) A view of the laser-processed stent, close up and magnified view.

irradiation and fluorinated polymer coating as post-processing techniques have been found beneficial to increase life and for biocompatibility of the *in-vitro* stent.

Recently, this laser has also found a new application in microstructuring technology. This technology basically demonstrates the binding of powder particles. It employs the principle of single-component solid-state sintering in which the laser energy is tuned sufficiently enough to induce the temperature in the powder as close as possible to the melting point of the metal particles, without exceeding it, in order to avoid melt, so that binding at the interfacial grain contact area occurs. In this case, the principle of the sintering process with metal powder is based on the particle fusion at temperatures below the melting point. During the sintering process, neck forms between two adjacent powder particles. This reduces the surface area and increases the tendency for powder to aggregate. The driving force for

FIG. 3(a). Build-up of one-component [Ni] MHS microstructure. Line width = 221 *m*m; (b) Microturbine [7] diameter = 14 *m*m.

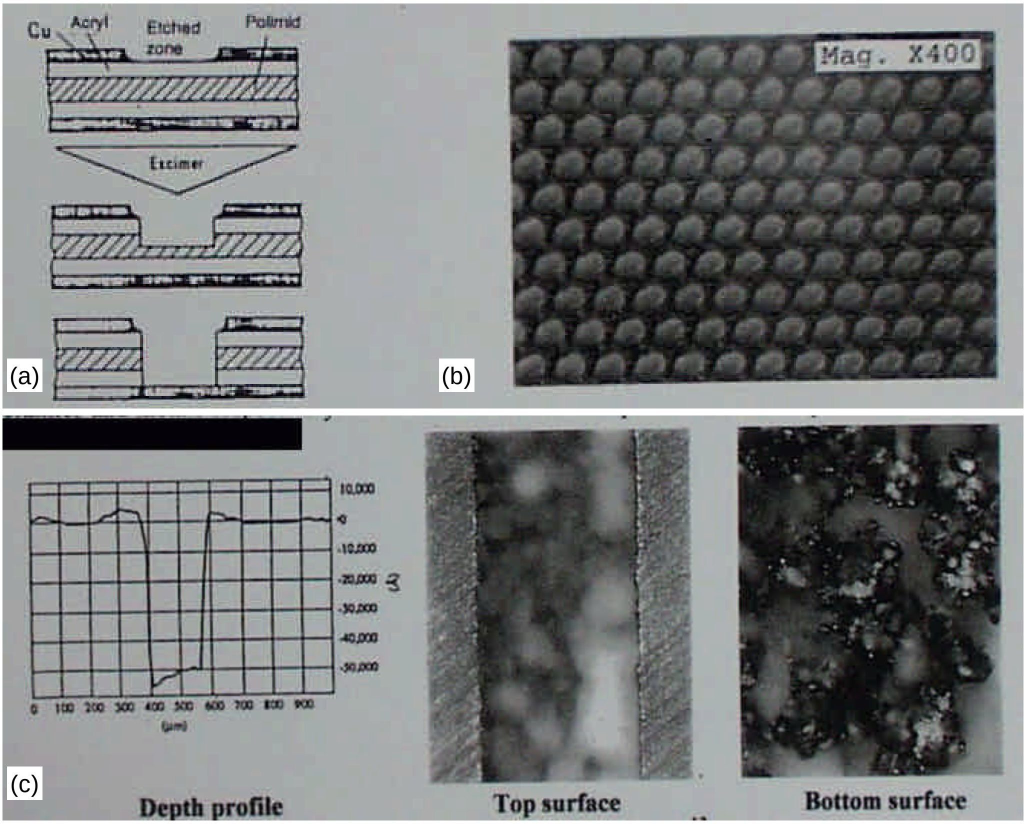

FIG. 4(a). Generation of contact, via hole, (b) patterned hole structure in polyimide, and (c) slotting in silicon nitride.

this is the reduction of the free surface energy of the particle and the densification is proportional to this reduction. Figure 3(a) shows the logo structures for the one-component solid-state sintering, in which Ni powder was preferably used because of its wide application in the electronics industry. The average thickness of the wall structure in this case is about 221 *m*m [6].

Besides this, based on laser photopolymerization process (*l* = 0.381 *m*m), polymer-based 3D microstructure (Fig. 3b) with sub-micron resolution has been fabricated by two-photon micro-streolithography technique [7].

2.2. *Excimer laser*

On the other hand, microprocessing with excimer laser has its unique characteristic applications in the microelectronics industry which cannot be met with the Nd-YAG laser. Examples of such applications are laser generation (Fig. 4a) in MCM via holes or multilevel structures for contact purposes, wire stripping, perforation of plastic film from the substrate, patterning in the flexible printed circuit board and structuring of ceramics for mi-

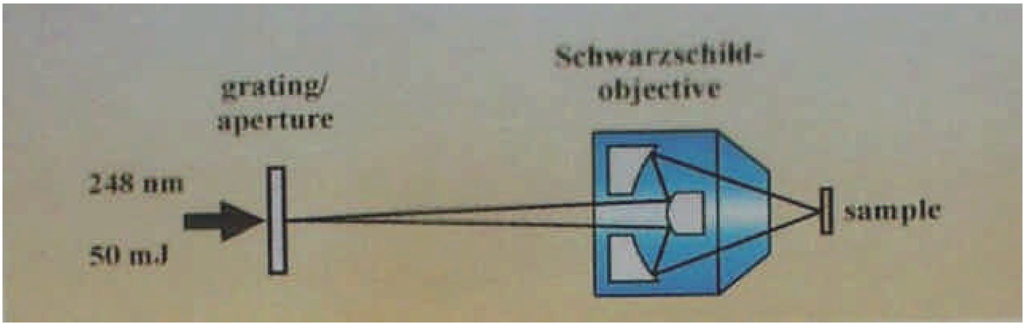

FIG. 5. Material processing with grating mask projection.

cromaterial/medical applications, etc. [8]. The ablation mechanism with the excimer laser which is usually considered a cold ablation process can best be understood by considering the absorption characteristics, binding energy, bandgap energy and the ionization potential of polymers, ceramics and metals. But, as the processing condition changes from ceramics to metal, the material removal process is encountered with increasing thermal effects.

In the microelectronics/multilevel interconnect technology, polyimides are widely used as an insulating material and the excimer laser is often used for selective ablation. Figure 4(b) shows part of such patterns generated in the polyimide. The structure shows a minimum resolution achieved with our technique which are below 10 *m*m. Ceramics can also be patterned very precisely with practically no microcracks. This is demonstrated in Fig. 4(c), where the Si_3N_4 is shown as an example. During the ablation process, the material decomposes and vaporizes because of the missing melting phase and is removed precisely layer by layer with a number of pulses.

On the other hand, excimer laser, coupled with the advanced optical techniques, can be used to produce ultrafine submicron structures [9]. Usually, the excimer laser delivers a nanosecond pulse, but when coupled with the dye laser or 3rd harmonics Ti-sapphire laser, it can deliver even shorter pulses in the pico- or femto-second regime. These short pulses become very effective for generating high-quality patterns, as the thermal diffusion length in this case is minimized. A typical holographic approach of two beam interference has been applied to ablate the interference pattern in polymer, silicon or metals. Keeping in view the poor coherence characteristics of the excimer laser, a typical mask projection technique of grating is appropriate to produce submicron structures. In this case, femto second UV radiation (l = 0.248 *m*m) irradiates the grating mask which is imaged on the processing area by the Schwarzschild-type reflective objective (Fig. 5). When the +1 and –1 orders are recombined, the fringes are the same as the ideal phase mask and spaced by $d/2$, where d is the periodicity of the diffracting element. Figure 6 shows a submicron-order grating created on a silicon wafer [10].

Recently, the femto second pulse laser (l = 0.745 *m*m) has also been used directly for writing gratings, directional couplers as well as microfluidic devices inside the glass [11, 12]. In this case, the internal refractive index of photosensitive glass gets modified when it interacts with the femto second laser beam focused beneath the surface. Besides, a He-

FIG. 6. Submicron periodic structure in Si [10].

Ne/He-Cd laser has also been applied to create submicron grating pattern in photopolymer with a holographic two-beam interference techniques.

3. Three-dimensional microstructuring using LIGA process

LIGA (German acronym for LI: Lithographie, G: Galvanoformung, A: Abformung) process actually originated from Prof. Ehrfeld at KfZ Karlsruhe (Germany) in the late 70s [13]. In this process, three-dimensional microstructure and parts can be made from metals, plastics and ceramics by using lithography, electroforming and plastic molding. It is specifically useful for high-aspect-ratio 3D microstructuring. The basic process diagram as shown in Fig. 7 consists of the following steps [3, 13, 14].

(a) First a thick radiation-sensitive plastic layer several hundreds of microns thick is applied to a metallic base plate or to an insulated plate (Si-wafer) with an electrically conducting cover layer (SOI), used as substrate. It is polymerized either directly on the base plate or glued to it. In some cases, PMMA (polymethyl methacrylate) sheet can be bonded to the base plate. To form the microstructure, an absorber pattern of a mask is transferred into the plastic layer or PMMA sheet by deep X-ray exposure using the Synchrotron radiation source with characteristic wavelength between 0.2 and 0.6 nm.
(b) Next, the irradiated areas of the exposed plastic or PMMA can be removed by solvent action during the developing process. The plastic or PMMA microstructures having thickness more than several hundreds of micron with high aspect ratio are thus realized.
(c) The cavities of the resist structure are filled by electro plating/deposition, preferably with the metal, e.g. Cu, Ni or Au.
(d) The plastic or PMMA molds are removed by using a solvent or developer after X-ray exposure again. Then, Cu, Ni or Au metallic microstructures/parts with high aspect ratio are realized.
(e) Using these metallic microstructures as micro mold, further micro molding can be carried out for multiple plastic micro parts by using injection molding, resin casting or

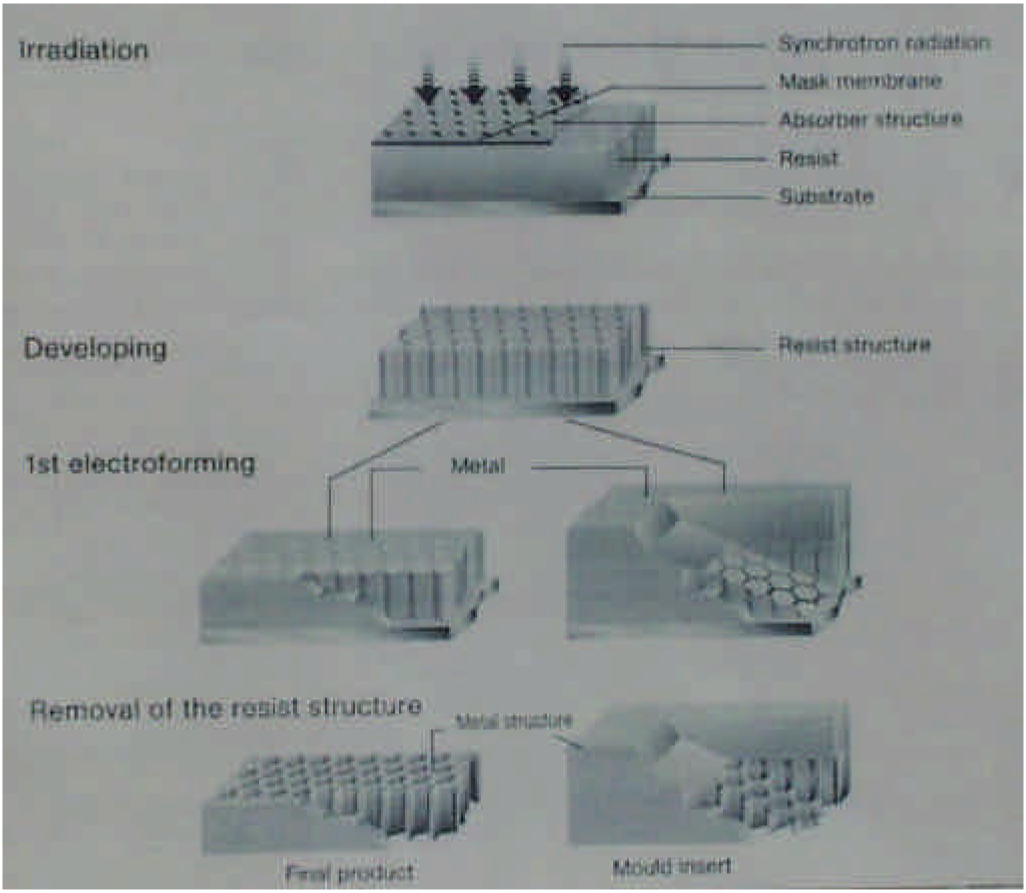

FIG. 7. X-ray deep etch lithography [3].

hot embossing. These plastic parts can also serve as ‘lost forms’ for the production of ceramic microstructure/parts.

The individual process as outlined above consists of the following steps:

1. Deep X-ray lithography
   a. X-rays mask
   b. Synchrotron radiation source for X-ray irradiation
   c. X-ray resist
   d. Limiting factors/problems
2. Electro-plating
   a. Nickel/Gold/Copper
   b. Alloys: Permalloy (Nickel–Iron: exhibits magnetic properties), Nickel-Cobalt (higher hardness), Shape memory alloy (Nickel–Titanium)
   c. Other metals/alloys according to the need

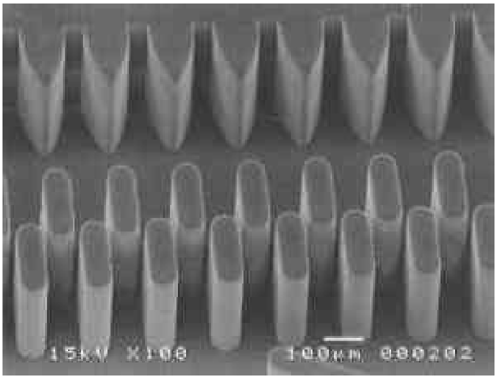

FIG. 8. Plastic injection mold micro product using LIGA process [15].

3. Molding
   a. Forming of the microstructure mould
   b. Injection molding
   c. Reaction injection molding
   d. Hot embossing
4. Example

By performing the plastic injection molding with a mold cavity mounting a precision Ni-stamped fabrication using the LIGA process, mass production of high-precision micro parts has been realized (Fig. 8) [15].

4. Lithography in microstructuring

Lithography is a rapidly growing technique and has widely been used for miniaturization and high-density integration of the semiconductor devices. However, with the unrelenting demand for ULSI technology, it has strived for higher resolution using different shorter wavelength sources and advanced projection techniques. At present, the following improved techniques are in use to achieve a line width in nm range. (a) Optical projection lithography, (b) EB-lithography, (c) Ion beam lithography, (d) EUV lithography, and (e) X-ray lithography.

In the optical projection lithography, usually a laser radiation is made to illuminate the appropriate object (mask), which is imaged on the substrate (wafer) with a large numerical aperture reflective optics (Schwartzschild objective). To achieve production throughput at dimension approaching the regime of X-rays and particle beam lithography, a higher resolution is required, which can be achieved by a combination of approaches [16]: (a) by increasing the numerical aperture, (b) by shortening the wavelength, and (c) by inventing a photoresist material with nonlinear photo-response/characteristic. A record resolution of less than 40 nm line width has become feasible by using 193 nm wavelength light from an excimer laser coupled with the phase shift mask lithography [17].

On the contrary, both electron beam and ion beam lithography are used mostly in direct write mode. In the EB lithography, the proximity effect due to the backscattering of elec-

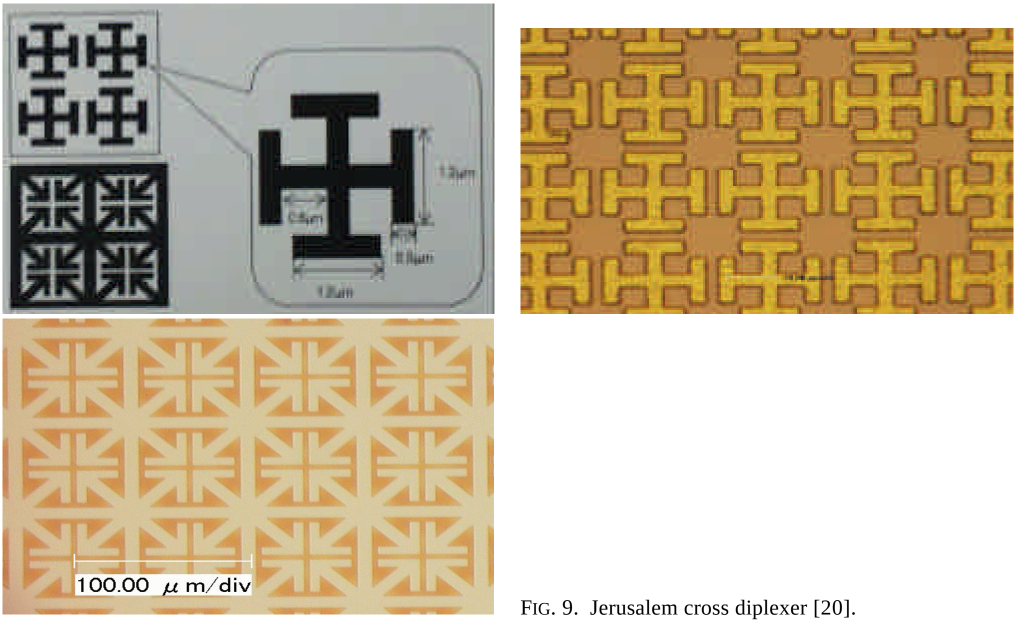

FIG. 9. Jerusalem cross diplexer [20].

trons puts limitations in the ultimate line width resolution. But in ion beam lithography, due to larger mass of ions, this problem does not arise. However, this is good only for thin-layer patterning. Besides, recently electron and ion beam projection lithography techniques have been introduced to improve the production throughput. However, their implementation is still in the initial stage.

With the current pace in technology, it is foreseen that the semiconductor manufacturing will use the EUV: 11–13 nm and soft X-rays: 1–4 nm lithography. Here one should note that a major difference from the deep X-ray lithography in the LIGA process mentioned previously is the X-ray wavelength and the mask. For the LIGA process this is typically 0.2–0.6 nm so as to penetrate a thick plastic resist or a PMMA sheet. The gold absorber for the mask has to be much thicker for this short X-ray, namely, 10 *m*m, instead of 0.5 *m*m thick absorber used with soft X-rays: 1–4 nm [18].

Besides the conventional application in the semiconductor industries, these techniques have recently been applied to fabricate various micro-optical components [19] and photonic bandgap structures [20]. Photonic bandgap structures exhibit frequency band where the electromagnetic wave is forbidden or cannot propagate, irrespective of propagation direction. It is basically a periodic structure where the electromagnetic wave can pass through it in some frequency bands and stop to propagate in some other frequency bands. It consists of a periodic pattern etched into metallic/silicon/glass substrate plate. Figure 9 shows two such typical designs of Jerusalem cross diplexer having submicron features generated with the direct-write EB lithography and to be used as frequency selective surfaces in the near-infrared region [21]. They are composed of one or more periodically metallized planar sheets designed to selectively transmit or reflect incident e.m. waves in a certain frequency band. The IR reflection/transmission spectra strongly depends on the physical dimensions of the designed pattern. However, for the fabrication of thick metal mesh membrane filter, LIGA technique can also be applied.

The basic theoretical background of understanding the IR transmission or reflection properties through these structures is based on the following facts: (1) generation of surface plasmons through e.m. irradiation of the metallic membrane surface, (2) the plasmons create an electric field on either side of the membrane (evanescent field), and (3) the short-range optical diffraction of evanescent wave. The e.m. power flow through these sub-wavelength apertures/structures is governed by the streamlines of the Poynting vector through the opening [22, 23].

5. Conclusion

This study demonstrates that laser, LIGA and lithography techniques are becoming indispensable tools in the semiconductor manufacturing and micromachine industries. Covering a wide spectrum of advanced techniques, a wide range of application areas in the micro- and nano-processing regimes has become feasible. The new field of microrapid manufacturing based on the LIGA injection molding technique is itself challenging in reducing the time lag for the microproduct development process.

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