Laser Processes for MEMS Manufacture

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This paper discusses the use of excimer lasers in the manufacture of microelectromechanical devices and systems, with emphasis on two application areas: laser micromachining of polymer masters for replication in metal by electroplating (Laser-LIGA), and laser-assisted manipulation of microparts for hybrid assembly. As a master fabrication method, laser micromachining offers advantages over conventional UV lithography in terms of materials flexibility and 3-dimensional capability. However, these advantages are offset by higher cost and lower throughput. We have been using a combination of laser micromachining and UV lithography to produce relatively complex multi-level fluidic devices, with laser micromachining being used only for layers requiring greater structural height and/or 3D profiling. Process details and examples of prototype devices are presented. Laser-assisted assembly is a new technique based on release and transport of parts by ablation of a sacrificial layer, using light incident through the substrate. We have been using this approach to assemble microelectromechanical devices from parts fabricated on separate substrates. Fundamental aspects of the process are discussed, and results are presented for hybrid electrostatic micromotors assembled by laser-assisted transfer of nickel parts.

Keywords: microelectromechanical systems; laser ablation; laser micromachining; laser-LIGA; microturbines; laser-assisted assembly; laser-induced forward transfer; micromotors

1. Introduction

The field of MEMS (microelectromechanical systems) is concerned with the development of integrated systems of sensors, actuators and electronics that can be manufactured by batch processes of the kind found in the semiconductor industry. Unsurprisingly, the field has been dominated up to now by silicon and silicon-related processes. However, it has proved necessary also to develop alternative techniques that can broaden the materials base and allow structures and devices with more 3-dimensional form to be realised. These alternative techniques include a range of laser processes.

Over the past twenty years a large number of laser-based fabrication techniques have been developed. These include laser micromachining, laser-assisted chemical etching (LCE or LACE), laser-assisted chemical vapour deposition (LCVD), pulsed laser deposition (PLD) and various surface modification processes [1]. Laser-based techniques for manipulation, assembly and joining of small parts have also been developed [2]. Many of these processes have become well-established in specific industrial applications. For example, laser micromachining has for some time been used to manufacture ink jet printer nozzles. However, up to now laser processes in general have not been widely exploited by the MEMS community.

This paper focuses on two MEMS applications of excimer lasers we have been pursuing at Imperial College over the past six years. The first is laser machining of polymer masters for subsequent replication in metal, a technique we have been using to develop microturbine devices. The second is microassembly based on laser-assisted release and transfer of parts. Process details and device examples are presented in each case.

2. Laser-LIGA and related processes

The LIGA process originated in Germany in the late 1980s. “LIGA” is a German acronym based on the three main process steps involved: Lithographie, Galvanof ormung (electroplating) and Abformung (molding). The idea is to produce a polymer structure by lithography, and then replicate it by electroplating to produce a tool for injection molding or embossing. This allows mass replication of the original structure in a range of materials including metals, plastics and even ceramics.

In the original LIGA process, synchrotron radiation is used as the lithographic light source, allowing structures with extreme precision, structural height and aspect ratio to be produced. However, a variety of cheaper alternative
methods have also been investigated for producing the polymer masters or molds, including conventional UV lithography (so-called “UV-LIGA”), plasma etching, and laser micromachining (“Laser-LIGA”).

2.1 Single-level metal processes

The first Laser-LIGA process was demonstrated by IMM (Institut für Mikrotechnik, Mainz) in 1995 [3]. In this process a PMMA master was formed by scanning-spot excimer laser ablation of PMMA at 193 nm wavelength. A conducting seed layer was deposited over the resulting polymer structure to allow replication by electroplating. At around the same time we were working on an alternative process based on projection ablation of PMMA at 248 nm wavelength. Our process, developed as a collaboration between CMF RAL (Central Microstructure Facility, Rutherford Appleton Laboratory) and Imperial College, was a partial LIGA process in that it did not include a mass-replication step; the electroplated metal parts derived from the resist mold were used in the final device. This approach can be economically viable as a laser-based manufacturing route if the master is formed by projection ablation rather than by direct-write with a scanning spot.

**Fig. 1** Outline of process used to fabricate microturbines from single-level laser-micromachined PMMA molds.

Figure 1 shows an outline of our PMMA process, which was used to fabricate simple radial flow microturbines. PMMA films of well-defined thickness were cast onto titanium substrates using techniques borrowed from x-ray LIGA. Cavities for the turbine rotors and stators were formed by projection ablation using a KrF excimer laser, and filled with nickel by electroplating from the exposed titanium surface. After depositing a polymer sacrificial layer over the rotors, a thick backing plate was applied by further electroplating. The resulting structures were separated from the substrate by thermal shock, and the resist was stripped using a chlorinated solvent. The rotors were mounted on their respective stators by manual assembly. Details of the process were reported in [4].

Figure 2a shows a nickel turbine rotor produced by the process in Figure 1. This image clearly demonstrates the potential of Laser-LIGA to produce high quality metal artefacts; the sidewall roughness determined by stylus profilometry is below 100 nm (Ra value). Figures 2b and 2c show an assembled turbine under test, with the rotor stationary (Fig 2b) and rotating at ca 50,000 rpm under a compressed air drive (Fig 2c). Unlike their silicon counterparts, nickel turbines of this type are highly robust and can be run continuously for periods of several days.

**Fig. 2** (a) SEM image of nickel microturbine rotor (dia 470 µm, height 150 µm) fabricated by replication of a laser-machined PMMA mold (photo courtesy of CMF RAL); (b) and (c) optical micrographs of assembled turbines showing stationary and air-driven rotors.

2.2 Multi-level metal process

Most LIGA work to date has been limited to single-level structures such as those in Fig. 2, imposing severe restrictions on the kinds of devices that can be realised. For example, in the case of a turbine it is not possible to fabricate a rotor with an integral shaft. We have been developing a multi-level metal process with a view to fabricating more advanced devices, in particular turbines that incorporate bearing structures and allow coupling of power to or from the outside world. Figure 3 shows an outline of the current process, which involves repeated
application of a basic process cycle comprising: (1) seed layer deposition; (2) resist deposition and patterning; (3) electroplating. A mixture of conventional UV lithography and laser micromachining is used, with the laser being reserved for layers requiring significant structural height ($\geq 50 \mu m$). This combined approach is faster and more economical than using laser micromachining for all levels.

Fig. 3 Generic process for fabricating multi-level metal structures by replication of molds.

**Laser processing of dry film photoresists**

Use of appropriate resist materials is key to the success of processes such as the one in Figure 3. In addition to delivering the necessary lithographic resolution, the resist at each level should be easy to deposit to the required thickness, and show good chemical and mechanical stability during the subsequent electroplating and seed layer deposition steps.

Regarding resists for laser-machining, PMMA is not well suited for multi-level work because the casting techniques involved are complex, and adhesion to commonly used seed layer materials is relatively poor. Sheet material can be applied by adhesive, but this results in a resist layer with non-uniform characteristics. Similar considerations apply to other polymers commonly used for laser machining, such as polycarbonate. Conventional wet optical photoresists can be used for thinner layers (up to $20 \mu m$), but thicker layers are difficult to deposit and prone to stress-cracking following electroplating.

We have been using a combination of spin-coated positive photoresist for layers patterned by UV lithography, and laminated dry film photoresist for laser-machined layers. Dry film resists, which were developed for the printed circuit industry, can readily be deposited using a hot-roller laminator to form uniform layers with thicknesses in the range 50 to 200 $\mu m$. Once cross-linked by UV flood exposure, these materials show relatively good ablation characteristics at either 248 or 193 nm wavelength. Figure 4 shows the measured variation of etch depth per pulse against fluence at 193 nm for Morton LM5000 series dry film. The resist is a strong absorber at this wavelength, with a removal rate of around 0.2 $\mu m$ per pulse at a typical operating fluence of 0.4 J/cm$^2$.

An advantage of laser micromachining over UV lithography is that it can allow precise control over the sidewall angles in the resist mold [5]. Figure 5a shows the observed variation of sidewall angle with fluence and dose (number of pulses) for 25 $\mu m$-wide trenches etched in a 100 $\mu m$-thick layer of LM5000 resist. This data was obtained using an Exitech Series 7000 workstation incorporating an LPX 110i excimer laser operated at 193 nm. The projection lens used was a 15X, 0.28 NA reflecting objective, illuminated by a fly’s eye homogeniser with an effective NA in the image space of 0.2. By varying the fluence, the wall angle could be varied over a 20 degree range centred on zero (vertical). Full depth, vertical trenches were obtained with an exposure of 600 pulses at 0.38 J/cm$^2$. Figure 5b shows optical micrographs of three of the trenches used to derive data for Figure 5a. Note that undercut sidewalls (wall angle < 0) can be achieved only in a system where there are off-axis components in the illumination at the mask plane. This is an important, if secondary, role of the fly’s eye homogeniser.

One issue that complicates the use of laser micromachining in a multi-level process is that of laser damage to underlying layers. In cases where the laser machined resist is deposited over a thin seed layer, laser exposure of the seed layer at the end the machining step can cause it to rupture (because heat is not easily removed from the illuminated region). Even when the underlying metal layer remains intact its plateability may be reduced by laser damage. This problem can be alleviated by using relatively thick seed layers that can be wet etched to remove any laser-damage before
plating; copper seed layers work well in this respect. Stripping of the resist at the end of the process can also be problematic, as most polymers that ablate well (including dry film resists) are cross-linked and difficult to remove by wet chemical processing.

![Graph showing sidewall angle variation with dose and fluence](image1)

**Fig. 5** (a) Measured variation of sidewall angle with dose and fluence for 100 µm-deep, 25 µm-wide trenches in LM5000 resist, and (b)-(d) optical micrographs of cross-sectioned trenches (600 pulses at E=0.25, 0.5 and 0.75 J/cm² respectively).

**Multi-level microturbines**
We have used the process in Figure 3 to fabricate a range of radial flow reaction microturbines [6]. These are six-level nickel devices in which the key levels are: (1) rear bearing; (3) rotor disc; (4) rotor blades and volute; (6) front bearing. Levels 2 and 5 are sacrificial layers that separate the rotor from the front and rear plates of the stator. The blade molds are formed by laser machining of an 80 µm-thick layer of dry film resist, with all other molds being formed by UV lithography in 15 µm-thick layers of Hoechst AZ4562 positive photoresist. The total structural height of the device is 155 µm. Figures 6 shows an optical micrograph of a completed device after resist removal. Figure 7 shows SEM images of the rotor and rear bearing of a partially-fabricated device; here the resist was stripped after level 4 plating. A key feature of the design is that contact can be made to both ends of the shaft, making coupling of the rotor to an external drive or load relatively straightforward.

![Optical micrograph of six-level nickel microturbine](image2)

**Fig. 6** Optical micrograph showing top view of six-level nickel microturbine after removal of resist.

![SEM images of six-level turbine](image3)

**Fig. 7** SEM images showing details of six-level turbine: (a) rotor (dia 1 mm, height 95 µm) with blades formed from laser-machined molds; (b) rear bearing formed from UV lith molds; (c) and (d) details.

### 2.3 Halftone projection ablation for 3D molds

The idea of using binary pixels to achieve a greyscale effect is well known from the printing industry. The same idea has been used to achieve variable transmission in projection lithography [7]. A halftone mask comprises an array of pixels, each with an aperture of well-defined area on an opaque background. For example, the aperture may be a

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rectangular window as in Figure 8a. The pixel array is effectively a 2-D diffraction grating, but if the pitch $p$ of this grating is such that only the zeroth diffraction order passes through the optical system, it will behave as a simple attenuator. The relevant condition is $p < \frac{M \lambda}{NA}$, where $\lambda$ is the laser wavelength, and $M$ and $NA$ are the magnification and numerical aperture of the projection lens. The transmission in this case is equal to the ratio squared of the window area to the pixel area or $(\frac{wh}{p^2})^2$ in Figure 8a.

For some time we have been investigating the use of halftone masks with projection ablation [8]. Halftone ablation provides a powerful alternative to mask or substrate dragging for the production of polymer structures with complex surface relief. Figures 8b and 8c show examples of stepped multi-level and continuous relief structures produced in LM5000 resist. These structures were produced in a single micromachining operation with fixed mask and substrate. The maximum depth in each case is around 30 $\mu$m. We are currently using this technique in collaboration with Exitech Ltd and Thales to make multi-level diffractive optical elements [9].

![Fig. 8](image)

Fig. 8 (a) Halftone principle; (b) and (c) SEM images of stepped and continuous relief masters formed in LM5000 photoresist by 193 nm ablation using a halftone mask.

3. Laser-assisted assembly

Assembly is increasingly recognised as one of the key issues facing MEMS technology. While many devices can be fabricated monolithically (i.e. by applying a sequence of process steps to a single wafer), for more complex devices it is sometimes necessary to adopt a hybrid approach, combining parts fabricated on separate substrates. In the past this kind of hybrid assembly has been based largely on manipulation of individual components. Recently, however, batch assembly methods offering higher throughput have started to emerge. Most notable among these are the various self-assembly processes in which parts are released into a carrier fluid and assembled onto a target substrate, with alignment to the target occurring spontaneously through free energy minimisation (see for example [10]).

3.1 Assembly of freely moving parts

At Imperial College we have been developing an alternative assembly method based on direct laser-assisted transfer of parts between substrates [11]. Figure 9a shows the basic principle. Component parts are fabricated on a UV-transparent carrier with a polymer sacrificial layer. The carrier is aligned over a target wafer, and parts are transferred to their respective target sites by ablation of the sacrificial layer, using a single pulse of UV light incident through the carrier. Residual sacrificial material on the released parts is removed following transfer, either by normal laser ablation or by plasma ashing. Selective transfer of parts can also be achieved by masked exposure of the carrier, as shown in Figure 9b. This allows redistribution or pitch-adjustment in situations where the parts on the carrier and target are arranged on different grids. It also allows the carrier to support more than one type of component.

![Fig. 9](image)

Fig. 9 Laser-assisted assembly process: (a) batch assembly by parallel transfer; (b) serial assembly by step-and-repeat.

The laser-driven release step in Figure 9 is an impulse coupling event in which polymer material ablated from the sacrificial layer expands and cools, imparting a mechanical impulse to the carrier and released parts. This process is rather inefficient in energetic terms, so the final kinetic energy of the parts is only a small fraction of the incident laser energy. Nevertheless, the process can be relatively
violent. For example, for small nickel pads (2 x 2 mm², 100 µm-high) released from fused silica carriers with polyimide sacrificial layers, the minimum practical release velocity with a KrF excimer laser pulse was found to be of the order of 1 m/s² [11]; this is the velocity acquired in free fall from a height of about 5 cm. Some reduction in this value would help make the process more controllable, and reduce the risk of damaging the parts during transfer.

Initial demonstrations of the process in Figure 9 were performed using a purpose-built alignment and exposure rig, shown schematically in Figure 10. The carrier and target substrate are held on annular vacuum chucks and viewed from beneath by a microscope attached to a CCD camera. The substrates are aligned using micropositioners, and then brought into proximity by inflating a bellows between the upper chuck and the outer frame. Spacers are used to establish a well-defined proximity gap. The entire rig is mounted on a motorized X-Y stage, allowing step-and-repeat under control of a personal computer.

We have used the apparatus in Figure 10 to assemble arrays of axial gap wobble motors based on the design of Paratte and de Rooij [12]. In this class of micromotor the rotor moves in the manner of a flipped coin, with the driving field occupying the region between the rotor and the underlying stator. Figure 11a shows a cross-sectional view of our device. The stator comprises four levels: (1) a circular array of 8 electrodes with associated contact pads; (2) an annular spacer that prevents the rotor from shorting to the electrodes; (3) a bush to raise the rotor centre; (4) a shaft to guide the rotor motion. The rotor is a single-level nickel structure with a diameter of 1 mm and a thickness of 12 µm.

Arrays of component parts were fabricated on 3”-diameter fused silica wafers by UV-LIGA processing, and assembled in step-and-repeat mode using a single initial wafer alignment. Figure 11b shows a CCD camera image of a motor in the pre-alignment phase of assembly. The camera is looking up through the stator at the rotor which is slightly off-centre. Figure 11c shows an assembled micromotor, viewed from above. Assembled devices were examined under an optical microscope, and showed no signs of plastic deformation (of the rotor) or laser damage due to impact of the rotor on the stator.

3.2 Bond-and-release process

The process in Figure 9 is suitable only for transferring freely-moving parts to the target wafer. For fixed parts the ’bond-and-release’ variant shown in Figure 12a is more appropriate. Here the parts are fixed in position on the target before release from the carrier. Fixing might be achieved by, for example, reflow soldering or thermosonic bonding. In principle these methods can allow parallel joining of multiple parts, although in practice the scope for large-area array thermosonic bonding is limited.

Over the past three years we have been developing a process of the type shown in Figure 12a as a method for transferring metal studs onto flip chip integrated circuit dies [13]. For this work, the lower chuck of the assembly rig in Figure 10 has been replaced by a heated stage with a central viewing window, while the upper wafer chuck has been replaced by an ultrasonic bonding head.
The modified apparatus has also been used to attach rotor-retaining caps to wobble motor stators. Nickel caps were fabricated on a silica carrier, and their ends were coated with a 3-µm-thick layer of electroplated gold to give a bondable surface. The carrier was diced into samples small enough to be mounted on the ultrasonic head (6 x 6 mm²). Caps were then applied to individual stators that had been sputter coated with a thin gold layer for bonding. After bonding, the ultrasonic head was moved away and the carrier was separated from the cap by laser-driven release. Figures 12b and 12c show a stator before and after successful attachment of a rotor-retaining cap.

The stators shown in Figure 12 are non-functioning because the gold bonding layer was applied over the entire surface. A next generation of devices is currently being fabricated in which the gold bonding layer on the stator side will be applied locally to the shaft by electroplating.

4. Discussion

Silicon-based technologies for MEMS are now well established, highly sophisticated, and widely available through foundries. Silicon has achieved a dominant position in the field as a result of its good electromechanical properties, the wealth of existing process technology, and the possibility of monolithic integration of mechanical and electronic functions. However, silicon-based processes do have their limitations, particularly in terms of materials flexibility and 3-D processing capability. Lasers could make a key contribution in these areas as a result of their ability to interact with a wide range of materials, and to process non-planar surfaces.

This paper has briefly reviewed two laser processes that have been under development at Imperial College. A LIGA-type process combining UV lithography and laser ablation has been demonstrated that is capable of producing high-quality 3D nickel parts. This process is currently being applied to the development of axial-flow microturbines. A novel MEMS assembly process has also been developed, based on laser-driven transfer of parts between substrates. To date this approach has been successfully applied to assembly of electrostatic micromotors, and transfer bumping of integrated circuit dies. These applications have involved transfer of both fixed and moving parts. Further applications of the process in MEMS assembly are currently under investigation.

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