ADVANCES IN PHOTORESIST BASED PROCESSING TOOLS FOR 3-DIMENSIONAL PRECISION AND MICRO MECHANICS

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ABSTRACT

This report deals with the recent advances aimed at processing tools for microactuators with force outputs which can approach one Newton and precision manufacturing techniques for larger parts via deep x-ray lithography at the University of Wisconsin - Madison. The work is based on the *a priori* decision to use photoresist in a cost effective manner. The cost and performance issues move the tool into the thick photoresist, to 2000 μm , arena in which additive processing such as electroplating is much preferred over subtractive techniques. Application potential for the tool is very much enhanced if multiple sequential masks can be accommodated. This involves re-planarization and mask alignment issues which are unique to thick photoresist tools.

INTRODUCTION

Recent progress towards finding a processing tool for 3-dimensional structures for use in microactuators and other precision engineering applications has concentrated on high aspect ratio fabrication techniques. These techniques increase the 3-dimensionality of structures by allowing them to be very tall but consequently result in prismatic shapes. LIGA and LIGA-like processes are one such group of high aspect ratio processes which allow tall prismatic structures to be fabricated in a variety of materials.[1,2] The basic LIGA process starts with the exposure of a layer of polymethyl methacrylate, PMMA, attached to a conductive substrate. The exposure is performed by a large flux of highly collimated photons (synchrotron radiation) to allow for deep penetration and sidewall run-outs of 0.1 microns over 100 microns of structure height. The exposed PMMA is then developed down to the conductive substrate and the cavities are electroplated. The remaining PMMA may be removed and the metal structures may be used as is or mass produced by injection molding.

Several issues must be addressed to extend this process to microactuators with one Newton output forces and precision machined parts larger than 500 micron in thickness. These issues include: (i) a photoresist technology and an exposure tool which can exceed 500 microns in height, (ii) re-

planarization of the upper electroplated surface for both height control and the addition of a second layer, and (iii) a multi-layer process which allows alignment tolerances within the resolution of the process. The basic LIGA process is limited to 500 microns of height due to photoresist strain from volume contraction during polymerization and thermal annealing of the PMMA when constrained to a substrate. Strain can cause photoresist adhesion loss and pattern distortion. Electrodeposition rates are diffusion and field dependent. The photoresist patterns will concentrate the field resulting in non-uniform plating rates. Small structures can lead to electrolyte diffusion limitations. Both of these effects result in the inability to control the upper surface of the electroplated structures making multiple levels without re-planarization impossible. A multiple, thick level process requires alignment methods which can align with mask to substrate gaps in the millimeter range, but hold micron tolerances. These tools extend the basic LIGA process to large precision engineered parts and new classes of microactuators which are detailed in the following sections, respectively.

PROCESS TOOLS

THICK PHOTORESIST

Thick photoresist layers can fail because of built-in strain. The strain typically originates from process induced volume changes and adhesion requirements. This adverse effect can be eliminated by using strain-free photoresist sheets and solvent bonding them to the substrate.[2] A final adjustment of the photoresist height via diamond fly cutting produces excellent results. Using this technique, photoresist thicknesses from 50 microns to several centimeters can be attached to a substrate. Because this process requires no thermal cycles, a variety of substrates can be used including ceramics, metals, plastics, and circuit covered wafers.

Exposure of these thick films to submicron tolerances require a photon source with high collimation, large flux, and deep penetration. Synchrotron radiation proves to meet these requirements. Exposure depth depends on the absorption length at the photon energy used. Figure 1 shows the PMMA absorption length for the appropriately filtered photon

Figure 1: Absorption curve of PMMA showing the filtered spectrum peaks of SRC - Madison and NSLS - Brookhaven.

spectrum of the 1.0 GeV Synchrotron Radiation Center, University of Wisconsin - Madison and the 2.6 GeV National Synchrotron Light Source, Brookhaven National Laboratory.

As a consequence, two options exist with the use of high energy exposures. Very thick photoresist samples may be exposed[3], or a multiple number of thin photoresist exposures may be performed at the same time through stacking. The achievable throughput with high energy photons is large enough to make direct manufacturing via deep x-ray lithography and electroplating without injection molding cost effective[4].

RE-PLANARIZATION

Recesses in the photoresist can be filled with metals via electroplating. Plating uniformity can be improved by cell design and operating procedures.[5] However, a perfect deposit is impossible for masks with large, field controlled, and small, diffusion controlled, feature sizes. The difficulty can be removed by overplating followed by lapping and polishing.

A lapping and polishing technique has been developed to control the uniformity and final height of the electroplated structures. Lapping involves removal of material in a controlled condition using fine sized diamond slurry, which is embedded into a lapping plate. This is followed by polishing of the lapped structures. Thus, re-planarization via lapping and polishing produces a photoresist height which is identical to the metal height with mirror like surfaces. The height uniformity of these re-planarized parts can be controlled to $\pm 2 \mu\text{m}$ over an area of $50 \text{ mm} \times 50 \text{ mm}$. The surfaces of the micro

Figure 2: Example of precision engineering: 1.8 cm electrode disk with vertical wall mesh. All tolerances are submicron.

Figure 3: Multiple mask processing, level one and level two are each 150 microns high.

parts have been measured to a flatness of $26 \text{ \AA}$ rms. Figure 2 shows a large precision machined part which was produced by this procedure.

In addition, this re-planarization technique allows the extension of the basic LIGA process to multiple electroplated layers. Figure 3 shows an example of two layer nickel structures fabricated using this technique. Each layer is 150 microns high.

ALIGNMENT

Multiple mask processes require mask to wafer alignment. For thick photoresists, the alignment procedure marks have to be viewed through several hundred microns of thick photoresist. "Alignment by assembly" is a concept which was developed in this research. It currently produces alignment errors of 4 microns and is independent of the photoresist thickness and does not require any expensive optical instrumentation (see figure 3).

DEVICES

Thick photoresist in conjunction with new alignment techniques with controlled z-dimensionality, have allowed new classes of actuators to be considered. These actuators take advantage of the increased 3-dimensionality and higher precision of the process tools.

VERTICAL LINEAR ACTUATOR

Figure 4 shows a first generation electrostatic vertical linear actuator with expected force outputs in the milliNewton range and a vertical displacement of hundreds of microns.[6] The actuator consists of three parts. The upper plate is held up by four springs and contains holes which fit around posts in the lower plate, not visible, attached to the substrate. The lower plate has an electrical connection which is shown to extend out

Figure 4: Assembled vertical electrostatic table-top actuator. This device cannot be constructed without polishing.

of the lower left corner of the device along the substrate. This lower plate is electrically isolated from the upper plate which is attached mechanically and electronically to the four peripheral springs and the lower outer connection ring. A voltage may be applied between the upper and lower plate resulting in electrostatic attraction.

A spring constant of 3.5 Newton/meter was extracted from a force versus vertical displacement measurement. The prototype device shown in figure 4 has a 10 micron post to hole air gap requiring an estimated 100 volts for every 20 microns of vertical displacement. The situation further improves with smaller posts, holes, and air gaps. Fabrication of this device at NSLS can also increase the vertical displacement of the device.

MAGNETIC ACTUATORS

Lapping and polishing has established thickness control of free and fixed metal structures. This has allowed tighter tolerances for assembly. Assembly allows small tolerances through the subtraction of precisely held structures. Assembly also simplifies and increases the 3-dimensionality of the fabrication process. Some examples of recent advances in micro assembly are the assembled micro coil and increasing structural height through stacking.

Figure 5 shows a linear actuator using a single assembled micro coil for each direction of motion.[7] The micro coil has significantly reduced the power required to operate the device, the fabrication time, and actuator size. Powers are in the milliwatt range due to the higher coil packing density. The fabrication time has decreased from several weeks to a few days because an integrated coil technology requires multiple levels and alignment. Since the coil is in the vertical direction, the overall device requires less substrate area.

Figure 5: Magnetic linear actuator using assembled micro coils which are inserted into the magnetic path.

The linear actuator of figure 5 has a $1/d^2$, non-linear, force due to the plunger's complete closure with the magnetic path. This simple actuator can move 100 microns, and generates forces approaching 35 milliNewton at closure. The actuator consists of a shuttle constrained between two electromagnets. The components are all fabricated out of 78 permalloy and are polished to 100 microns in height. The device uses a 500 turn electromagnet coil that can handle up to 100 mA of current. The 1 T saturation flux density of the electroplated 78 permalloy, reached at about 21 mA, allows the maximum predicted force to approach 35 milliNewton. Coil inductance measured against shuttle position was used to determine the force behavior of the actuator. Larger force are possible at larger structural heights.

Other linear actuator versions with more linear force outputs have resonant travel of up to 300 microns at 400 cps with a quality factor in air between 300 to 400. Operation at resonance with 200 micron peak to peak motion is achieved with a power dissipation of 200×10^{-6} Watts.[7]

Figure 6 shows a microdynamometer using the assembled micro coil.[8] This device is a complete microsystems containing both a drive and sense mechanism. At the top is a three phase variable reluctance micro motor which contains a 1 mm diameter 150 micron thick rotor, which drives into a center idling gear of 250 micron diameter. At the bottom is a magnetic breaking gear which can be used to apply a load via a current in an additional micro coil to measure the torque of the rotor. The motor requires only 1 milliwatt of power to keep the three gears spinning. Measured tangential forces at the rotor tip are in the 1 milliNewton range with torque outputs of 1×10^{-6} Newton-meter for 20 mA of applied current.

Figure 6: Microdynamometer with a 3-phase variable reluctance motor, idling gear, and magnetic break.

Figure 7: Peg assembly to increase structure height of a variable reluctance motor. Each layer is 250 μm thick.

Figure 7 shows a micro rotationary device using the assembled micro coil technology and stacking the magnetic path of the device. Micro assembly has allowed to increase structure height without increasing electroplating times. Structure height can be increased with the use of very high energy photons but electrodeposition durations can become increasingly long. An alternative is the peg assembly of stacked electroplated structures. Since this stacking uses assembly, submicron tolerances have been achieved. Each permalloy layer of figure 7 is 250 μm thick and have pegs of a different thickness dropped into the holes visible at the magnetic path edges. The resulting structure is 500 microns high but can be extended with more layers to significantly larger heights. The center post and coils (not shown in this example) have also been stacked to achieve thicker structures.

CONCLUSIONS

Recent extensions to the LIGA and LIGA-like processes have resulted in more efficient large output force actuators and precision machined parts. These new tools have not only simplified the design, fabrication, and testing process, but has also allowed new classes of microactuators and manufacturing techniques. Current work is focusing on the use of these tools to create microactuators, microsensors, and other microsystems.

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