

MICROMECHANICS VIA SYNCHROTRON RADIATION

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A significant portion of micromechanics deals with actuators: devices which modify their environment. Manufacturing techniques for this class of devices involve 3-dimensionality, tolerances, IC-compatibility, a broad material base and cost effectiveness. Photoresist based processing with x-ray exposures via synchrotron radiation has many of the required attributes for actuator manufacturing. This is particularly true for exposures with 20 KeV x-rays where structural heights to 10 μm have been obtained and where x-ray mask issues simplify. Tests with this type of tool have brought significant advances in linear actuators and have been used to fabricate a micro electro mechanical system, a dynamometer on a chip, for magnetic micromotor testing.

I. INTRODUCTION

Micromechanical devices fall into two categories: sensors and actuators. Sensors are devices which measure some property of their environment. They should do this non-invasively. This implies small physical size and low power dissipation. Both attributes are shared with microelectronic devices. The successful adaptation of microelectronic processing procedures for sensor fabrication is therefore not surprising. Actuators are devices which modify their environment. A good actuator with defined performance specification does this at minimum physical size and minimum power dissipation. This implies that an actuator may in fact not be a physically small device but is constructed by using micromechanical tools. An appropriate tool for actuator fabrication must address at least five issues. Thus, actuators are always three-dimensional devices. The processing tool must recognize that. If a microactuator is a scaled version of a larger device the tolerances must also scale. Since typical mechanical tolerances are in the 100 ppm range the microactuator tool must accommodate this. The material base for microelectronics is relatively small and inadequate for actuators. A good actuator tool must be able to accommodate materials which extend from metals to ceramics to polymers. Actuators are components. Systems which use these components are of economic benefit. Control issues for systems made from actuators demand electronics. In some applications, for instance, capacitive sensing, co-fabrication of microelectronic components must be possible for the actuator tool. In other cases co-packaging of commercially available microelectronics is adequate. The fifth point is perhaps the most important one: the actuator processing sequence must be cost effective. Since many actuators and microactuators may

be fabricated using precision engineering tools which are typically serial, photoresist based processing tools may meet the cost effectiveness requirement because they are fundamentally parallel.

All photoresist based processes use a mask to transfer geometric information to a photoresist layer which is located on a planar substrate. The exposed or unexposed photoresist regions are removed during development. The geometry which is produced is therefore prismatic and actuators based on photoresist technology are prismatic actuators. The performance for this type of device may be estimated. Thus

$$F_{\text{out}} \leq \rho_E V_A \quad (1)$$

where F_{out} is the output force, ρ_E the stored energy density and V_A the active volume in which the energy is stored. The active volume may be related to the physical volume, V , by a filling fraction, α .

$$\alpha = \frac{V_A}{V} \quad (2)$$

However, since the geometry is prismatic the physical volume becomes the product of the actuator area, A , and the structural height, H . Hence, Equation (1) becomes

$$\frac{F_{\text{out}}}{A} \leq \rho_E \alpha H \quad (3)$$

The output force per unit chip area is a figure of merit for a particular design. It depends on the actuation mechanism which is used: electrostatics, magnetics or pneumatics and hydraulics. The energy density increases from electrostatics to hydraulics. The required three-dimensionality does the same thing which explains the large activity in electrostatics. The filling fraction is in part related to the resolution of the lithography process. A large structural height improves performance. A high performance actuator tool is therefore identified as a thick photoresist technology with high geometric resolution.

II. LIGA-LIKE PROCESSES

Thick photoresist processes must face the initial difficulty of photoresist application. The traditional spin coating in a single coat is not very feasible because of solvent evaporation problems. Multiple coats reduce yield and increase processing cost. The first successful attempts to produce photoresist thicknesses of 500 μm or so were

reported by W. Ehrfeldt and his co-workers [1]. He used the in situ polymerization of poly methyl methacrylate or PMMA to form an x-ray sensitive photoresist layer, which he used in a process called LIGA. His application procedure, a form of casting, has the problem that polymerization involves a volume shrinkage, roughly 20%, and that this shrinkage together with the adhesion requirement results in a heavily strained photoresist. This problem, strain induced due to polymer shrinkage, is the nemesis of many thick photoresist processes and limits the maximum attainable height.

The strain issue for thick photoresists has recently been solved by using a solvent bonding approach [2]. In this technique commercially available, cell cast photoresist sheets of convenient thickness are used. These sheets are essentially strain free and can be analyzed for strain and molecular weight prior to usage. They are next cut to size via water jet machining and are then solvent bonded to the selected substrate. After curing the height is adjusted by precision milling. Figure 1 illustrates the result.

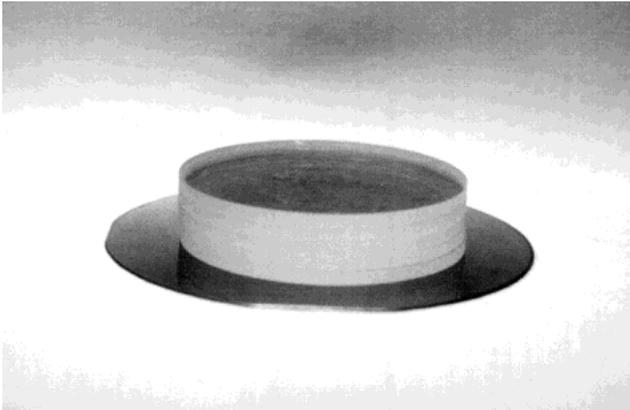


Figure 1: 2" diameter PMMA disks on a 3" silicon wafer. The absence of wafer bending is noteworthy. The photoresist height is 1.6 cm.

The photoresist of Figure 1 must be exposed through a suitable mask. This requires photon energies which are associated with absorption lengths which are comparable to the photoresist thickness. For PMMA, a photoresist with reasonable mechanical properties, poor optical sensitivity and excellent optical resolution, this can only be done by using x-ray photons. The type of photon follows from Figure 2.

Since the absorption length is roughly 100 μm at 3,000 eV exposure depth at this energy are restricted to 500 μm or so. This condition changes to 5 cm at 20,000 eV where the absorption length is 1 cm. The dose which is required for

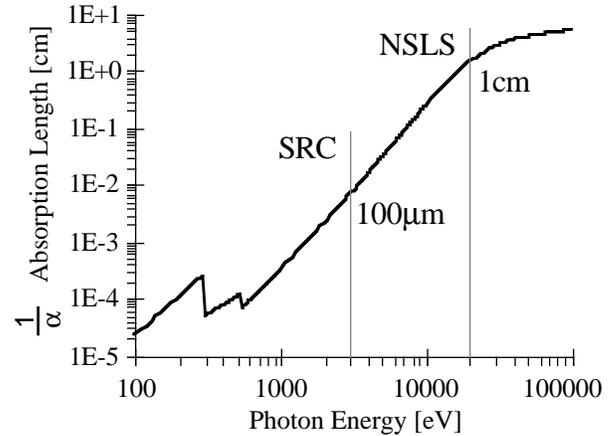


Figure 2: Absorption length for PMMA versus photon energy.

PMMA and a particular developer is 1.6×10^3 Joules/cm³. Since this dose is large a high brightness source, synchrotron radiation is required. In fact, Figure 2 refers to Aladdin, the Wisconsin storage ring at 1 GeV and Brookhaven's 2.6. GeV machine for hard x-rays. The use of x-rays for exposure eliminates the standing wave problem which limits optical exposures. The use of synchrotron radiation contributes excellent collimation which results in vertical photoresist flanks.

A comparison between low and high energy exposures results in conclusions which favor high energy fluxes. The mask for low energy exposures involves a mask blank which is typically 1 μm in thickness and made of low atomic number material, say, Si₃N₄. The absorber is gold at 2 to 4 μm thickness. The mask by necessity involves a small area and yields a cost effective tool only if x-ray exposures are minimized. This normally requires injection molding from an x-ray generated master die. The A in LIGA stands for Abforming or injection molding.

High energy exposures use a mask blank which is simply a standard silicon wafer. The absorber is again gold in the 10 to 50 μm range. A large area mask is therefore possible. This mask can be used to expose photoresists on both sides of a wafer which produces perfect front to back alignment. Moreover, several of these wafers can be stacked and exposed at the same time. The need to use injection molding lessens and, under the right circumstances, disappears as a cost issue.

The exposed photoresist is developed. Since a free standing photoresist sheet can be used PMMA parts with submicron tolerances can be produced. This is illustrated in Figure 3.

If the photoresist is attached to a substrate with a plating base the photoresist recesses can be filled with electroplated metals. This converts the PMMA mold to a metal mold of fully attached parts. This process, electroplating, is represented by the letters GA in the acronym LIGA and completes the original LIGA processing sequence.

The LIGA process as outlined here does not meet the requirements for an actuator processing tool. The process is basically 2-dimensional and obtains its tolerances from the x-ray mask and the ability to print and develop the PMMA. This is troublesome for mechanically weak shapes, for instance optical gratings, which must survive developing and plating. The process does have a large material base. It becomes cost effective via injection molding and via high energy exposures.

The process can be improved by combining surface micromachining and LIGA. In this process, SLIGA, sacrificial layers are used to form metal parts which are either fully attached, partially attached or can be removed from the substrate. Since the metal parts are quite thick they do not distort when freed. Thus, free parts may be assembled onto fixed parts. Assembly improves the tolerance issue because assembly in effect subtracts two mask dimensions from each other. Since incremental mask tolerances are typically submicron, devices with submicron assembled tolerances can be produced. This is particularly important for bushing clearances where $0.25\ \mu\text{m}$ tolerances have been achieved with shaft diameters of $100\ \mu\text{m}$ and rotor holes of $100.5\ \mu\text{m}$ at structural heights of several hundred micrometers. The extreme edge acuity of the x-ray exposure permits this excellent performance. Assembly does of course also improve the 3-dimensionality to the processing tool. This aspect of the tool will increase dramatically when SLIGA with multiple, sequential x-ray masks; MEMS-LIGA; becomes available. This should occur within the next few months.

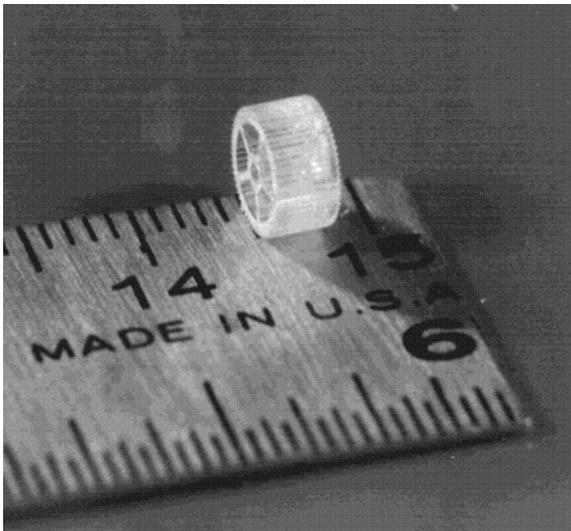


Figure 3: PMMA parts

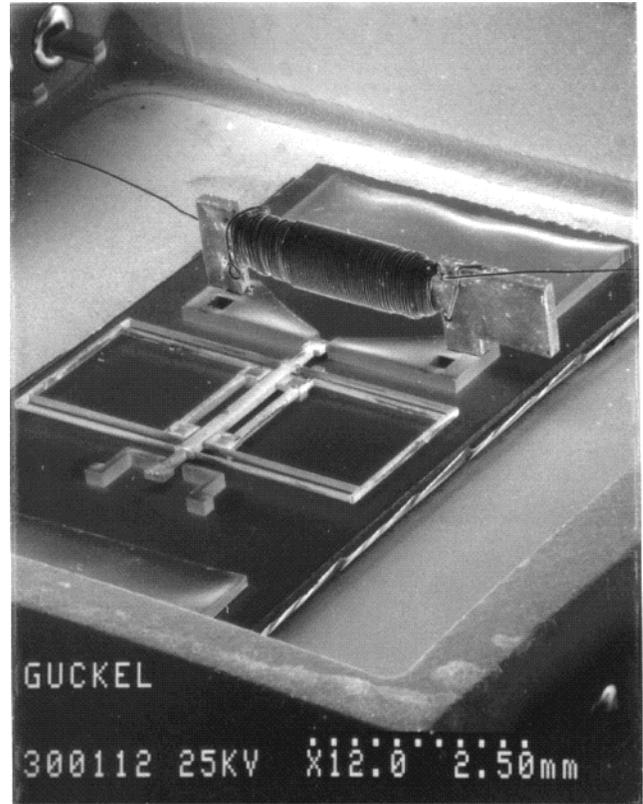


Figure 4: Linear magnetic actuator.

III. MAGNETIC ACTUATOR PROGRESS

The SLIGA processing sequence is being tested by constructing electromagnetic actuators. The material of choice for this project is a permalloy with 78% Ni and 22% Fe. This alloy was chosen in order to minimize magnetostrictive effects which compromise magnetic properties. The measured as plated magnetic behavior for the alloy involves a saturation flux density of 10,000 Gauss with a coercivity of 0.3 Oersted and a permeability of roughly 2000. The material is therefore a soft magnet. The permalloy also has good mechanical properties: it is hard and has high yield strength. Because of this it makes a very good material for mechanical springs which play an important role in actuator construction.

Linear actuators have application areas which extend from microrelays to positioning systems. The "right" actuator for these areas is required to have a throw in excess of $100\ \mu\text{m}$ with a position independent output force of at least 1×10^{-3} Newton. It should move $100\ \mu\text{m}$ in 1 millisecond and cannot consume more than 10×10^{-3} watt. A device which meets and exceeds these specifications is shown in Figure 4 [3].

The device uses magnetic pole pieces and spring mounts which are fixed to the substrate. The spring with a spring constant of $3\ \text{N/m}$ is fabricated separately and assembled on the spring mounts with a tolerance of $0.25\ \mu\text{m}$. The coil is fabricated by winding up to 1000 turns of $25\ \mu\text{m}$ diameter magnet wire on a SLIGA permalloy staple.

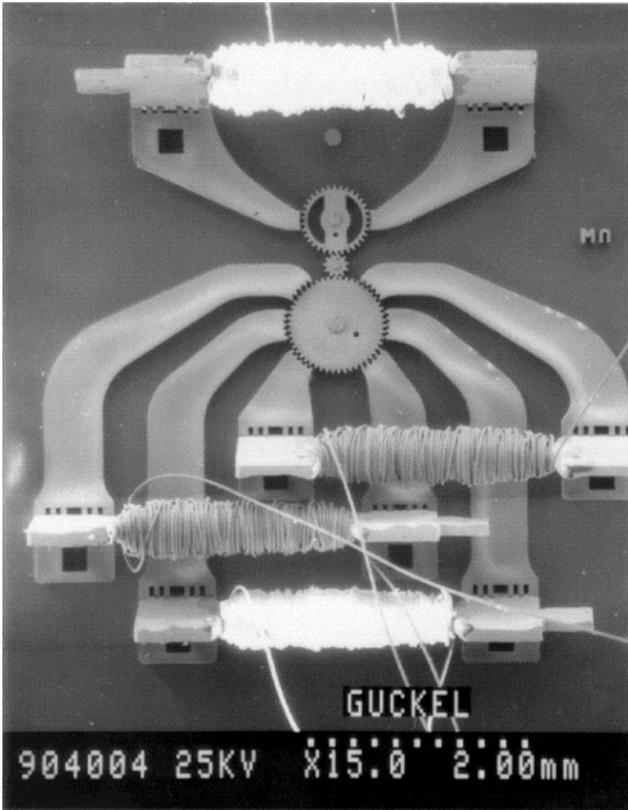


Figure 5: Permalloy dynamometer formed from three phase motor, idler gear and electromagnetic brake.

It is then inserted into the pole pieces and forms an inductance of several millihenry at closure with 10 Ohms per 100 turns of resistance. The change in inductance with position is near 1×10^{-6} henry per micrometer of travel. This allows not only inductive position sensing but also experimental output force measurements which are useful for closed loop operation. The device has a fundamental resonance at 400 cps, a quality factor of 400 in air and consumes 200×10^{-6} watt at resonance with a movement of $350 \mu\text{m}$. The measured performance is acceptable for several practical applications.

In rotational machines the transition from components to systems has been achieved. Figure 5 shows a recent result which is in the form of a dynamometer.

The driver in this case is a three phase reluctance motor with a rotor which has 50 involute gear teeth. These teeth interact with a stator with teeth in order to form a stepping motor which can move one rotor tooth at a time. This start-stop motion is difficult to achieve in small devices because of stiction problems. If the motor is excited with 3-phase sinusoids steady rotational speeds are achieved and coupled into the idler gear. The idler drives the brake gear which is located in an electromagnet which controls the motor load via DC-current through its coil. The desired speed range extends to 10,000 rpm with maximum input currents of 20 mA and tip force outputs in the millinewton range. The machine is needed to collect data on the behavior of micromotors under load.

IV. CONCLUSIONS

LIGA or LIGA-like processing forms a tool which has major implications on not only actuator and microactuator fabrication but also on precision engineering where it competes favorably with precision discharge machining techniques. The experimental and theoretical feasibility studies for high energy x-ray exposures have produced results which have improved the utility and cost effectiveness of this type of manufacturing. Practical high performance actuators are but one of many possible products which this type of activity can and will provide.

V. REFERENCES

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