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Progress in magnetic microactuators

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Abstract Magnetic microactuator construction has benefited from two processing extensions: stacking in the vertical and horizontal direction and multiple X-ray mask sacrificial layer LIGA. Vertical stacking requires height control of electroplated structures. This has been achieved by material insensitive lapping and polishing techniques. Structural heights of more than 1 mm have been achieved with 300 µm low-energy exposures. This has resulted in actuators with output forces to 100 mN and throws to 2 mm.

Re-planarization after electroplating without photoresist damage enables second layer photoresist application via solvent bonding and fly cutting. Exposure of the substrate with a second X-ray mask becomes useful if the second mask can be aligned to the substrate. This has been accomplished with sufficient accuracy via mechanical techniques.

A variety of magnetic actuators have been constructed. All of them use assembled rather than integrated coils. The performance of the assembled coils is adequate for position sensing in linear actuators and has resulted in a closed loop control device.

1
Introduction

Magnetic microactuators have progressed enough to generate commercial interest. The reason for this is, in part, an achieved performance issue and, in part, the positive attributes of magnetic devices per se. Perhaps, the most important attribute involves packaging. Since magnetic devices have low input impedances, they are current rather voltage driven; leakage impedances which are package induced become unimportant. This and the fact that low voltages are involved makes packaging feasible and affordable. Magnetic microactuators are Integrated Circuit friendly. This term is used when needed microelectronic control components are off the shelf items and/or can be co-fabricated. A third property involves the expected failure mode. Corona breakdown is absent and flux saturation leads to gentle failure. Finally there are future expectations. The addition of permanent magnet technology to the present soft magnetic materials will produce an environment for many new devices.

2
Microactuator fabrication

Actuators are devices which do work on their environment. They are three-dimensional structures with tight tolerances, typically 100 ppm, and are fabricated from many different materials. Actuator markets are cost constrained. Cost effective fabrication insists on parallel processing with fast prototyping in an IC friendly environment.

The assumption that photoresist-based fabrication satisfies the parallel processing requirement leads to prismatic geometries, i.e. geometries in which the area $A(x, y)$ does not change in the vertical or z-direction. For this type of geometry, actuator energy storage can be written as

$$U = \rho_{\mathrm{m}} \alpha H A \tag{1}$$

where $\rho_{\mathrm{m}} = \frac{1}{2}\bar{H} \cdot \bar{B}$ is the energy stored in the volume in the HA, α the filling fraction, i.e. the ratio of the volume in which U is stored to the total actuator volume, and H the height of the device. Since the gradient of U defines output forces and the time derivative of U defines power, it is highly desirable to make U/A as large as possible.

A high resolution, large α, photoresist with large height, H, or photoresist thickness will accomplish this. A coil technology which leads to flux saturation in the energy storage volume maximizes the magnetic energy density, ρ_{m}. It is now very tempting to claim that LIGA [Becker et al. (1986)] is ideally suited for actuator fabrication because of the achievable photoresist height and low run-out for prismatic photoresist shapes. This is simply not true. LIGA fails on three-dimensionality and tolerances. In order to get around these problems LIGA and surface micromachining may be combined to form SLIGA [Guckel et al. (1991)]. This leads to electroplated metal shapes which are fully attached to the substrate or are locally attached or are free. Free and fixed parts may be assembled. Assembled structures provide more three-dimensionality and solve the tolerance problem by pattern subtraction which leads to submicron tolerances for very prismatic shapes. Assembly and submicron tolerances lead to stacking and vertical assembly for which the actuator height, H, is the result of n assembled layers of height [Guckel et al. (1996)]. This type of approach to large structural heights requires planarization after electroplating. This very difficult task for which the final height of the PMMA (polymethyl

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methacrylate) and metal should not differ by more than 100 Å has recently been completed at the University of Wisconsin – Madison [Guckel et al. (1996)]. It is enabling technology for horizontal assembly which is used for devices with large areas.

The ability to planarize without damage to the existing photoresist is essential if multiple X-ray masks are to be used. The reason for this is found in the fact that in thick photoresist processing re-application of the photoresist is impossible. If the planarization process treats the photoresist and metal equally; i.e. there is no height difference between polished photoresist and metal; the application of the second layer of PMMA by the solvent bonding and fly cutting technique [Guckel et al. (1995)] becomes feasible. A second X-ray mask may expose this second photoresist layer over metal defined with the first mask. The second mask may also be used to expose the first and second layers of PMMA if exposure energies are properly adjusted. High photon energies, greater than 5000 eV, with proper filtering for the low-energy part of the synchrotron radiation spectrum, are typically required. But high-energy exposures are also required for cost effective fabrication without injection molding or stamping [Guckel (1995)]. Multiple exposures simply add to the need for high-energy photon fluxes.

M̄ultiple ĒX-ray M̄asks S̄LIGA; MEMS-LIGA requires alignment between substrate and mask. A study of alignment techniques [Emmerich (1995)] has recently been completed. Optical techniques are not very feasible because alignment marks are difficult to see if they are under thick photoresist. An additional draw-back involves high-energy X-ray masks which are typically opaque in the visible spectrum. A mechanical technique which involves peg and hole concepts and uses the inherent accuracy of SLIGA has been implemented and gives adequate results [Emmerich (1995)].

The process advances which have been reported here lead to the flow diagram of Fig. 1. This diagram indicates extensive use of X-ray lithography. The corresponding diagram for LIGA or SLIGA with injection molding or stamping does exactly the opposite. It minimizes the use of X-ray lithography and produces an environment in which non-X-ray based processes can compete.

Figure 2 shows the result of MEMS-LIGA with two masks and two planarization steps. The metal is electroplated nickel.

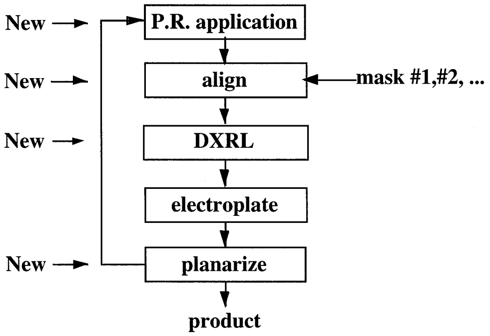

Fig. 1. Process flow diagram for multiple X-ray mask SLIGA

Fig. 2. LIGA with two, aligned X-ray masks

3
Actuator coil issues

All magnetic actuators use coils to convert current to magnetic flux. The number of coil turns determines the drive current which is needed to saturate the energy storage volumes: the stator–rotor gap volume. Reasonable coils must have winding densities which result in current geometries which approach a current sheet. Since the coils must envelope the magnetic circuit, normally the stator, integrated coil fabrication is a three-dimensional problem which involves at least two optical masks and one X-ray mask. Integrated coils result in a single conductor layer which at best covers 50% of the stator area with coil conductor. This type of coil has a lot of leakage flux and normally requires large drive currents. It can only be justified for a well understood prototype which is going into high volume production. For the study of magnetic microactuators, coils which are fabricated separately from the actuator and then assembled are much preferred. The construction technique: up to 2500 turns of 25 μm diameter magnet wire on a SLIGA defined permalloy core, is discussed in some detail elsewhere in this conference [Klein and Guckel (1997), Fischer and Guckel (1997)].

Coil performance even for assembled coils is somewhat marginal. Frequency limitations arise mainly from eddy currents in the core. This limits the frequency for constant inductance to about 5 kHz. At this frequency the inductive reactance, ωL, is always less than the low frequency wire resistance. The input impedance is therefore mainly resistive with a low quality factor. This is somewhat unfortunate because the inductance of, say, the electromagnet in a linear motor changes with plunger position. This property may be used as a position sensor if the inductance at some displacement, x, can be measured. This has recently been achieved via novel electronic techniques. A measured $L(x)$ may be used to become part of a closed-loop control system for predetermined positioning of the actuator. This has also been achieved if the linear actuator is loaded externally. The load can either be measured or the force applied to the load can be determined from

$$F(x) = \frac{1}{2} I^2 \frac{\mathrm{d}L}{\mathrm{d}x} \qquad (2)$$

Maximum output forces with 1 mm high structures are now in the 100 mN range. Maximum throws of 2 mm have been achieved. This leads to energy storage of 200 μJ. Devices of this type typically switch in the millisecond range or produce roughly 0.2 W. These numbers are adequate for practical applications.

4
Future expectations

The fabrication tool as described here has produced very good results. It will be improved still further. The acid test is the transfer of the tool to industry which has just now started.

The devices and their performance are described as better than ever. However, there are some problems. Nearly all devices are variable reluctance structures fabricated from soft magnetic material. This is restrictive. Thus, the best rotational motors are reluctance motors which are, of course, synchronous. This is not desirable in many applications. An effort to produce an induction motor, an asynchronous machine, is progressing very slowly. Permanent magnetic machines would eliminate most difficulties and, most importantly, would improve the efficiencies to reasonable levels.

Continued progress in this field requires better materials. A non-conducting soft magnetic material would extend the frequency response of the coils. Even more important is the availability of a non-conducting permanent magnetic material. Both materials obviously cannot be electroplated and, therefore, require process changes in MEMS-LIGA.

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