MICROACTUATOR PRODUCTION VIA HIGH ASPECT RATIO, HIGH EDGE ACUITY METAL FABRICATION TECHNOLOGY

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ABSTRACT

LIGA is a processing sequence which uses x-ray lithography on photoresist layers of several hundred micrometers to produce very high edge acuity photopolymer molds. These plastic molds can be converted to metal molds via electroplating of many different metals and alloys. The end results are high edge acuity metal parts with large structural heights. The LIGA process as originally described by W. Ehrfeld can be extended by adding a surface micromachining phase to produce precision metal parts which can be assembled to form three-dimensional micromechanisms. This process, SLIGA, has been used to fabricate a dynamometer on a chip. The instrument has been fully implemented and will be applied to tribology issues, speed-torque characterization of planar magnetic micromotors and a new family of sensors.

INTRODUCTION

Microactuators are components which are required for micro electro-mechanical systems or MEMS. These components are typically three-dimensional and involve submicron dimensions. This requirement, submicron geometries, originates from scaling arguments of larger devices. Thus, a shaft which is to be supported in a bushing is typically machined to a nominal diameter of, say, 1 cm with a tolerance of ± 2 micrometer. The implication is that tolerances of better than 100 ppm are being used routinely in the macro-world and are required for low friction, long wear sliding joint performance. If one takes a primitive outlook on microactuators and simply insists that they are miniaturized cousins of their larger counterparts it becomes reasonable to assume that nominal as well as tolerance dimensions must be scaled together. This would then suggest that bushing to shaft tolerances very quickly become submicron issues.

Microactuators are devices which require many materials. The restriction of the material base to those substances which are readily available in integrated circuit technologies is not reasonable and is too confining. This is particularly true for sliding joints where the brittle behavior of silicon and its derivatives is a decided handicap. The exclusion of ferromagnetic metals and their alloys is particularly detrimental because it eliminates an entire class of actuators: magnetic devices. These components in turn profit from multiple metals to provide low loss conductors, hard magnetic materials and the soft counterparts.

Finally there is the issue of manufacturability. The end goal is that of producing highly complex MEMS very much like a VLSI chip. These systems are hopefully candidates for high volume production as for instance in the case of actuators for magnetic recording heads. Reasonable manufacturability with low cost batch processing is required if this type of application of MEMS is to be successful. Special components and proof of concept devices are initially less restricted by these considerations. However, their success as an economically viable system profits also from an early inclusion of manufacturability in the process development cycle.

HIGH ASPECT RATIO PROCESSING VIA LIGA

A possible candidate for high aspect ratio processing and therefore a step in the right direction for three-dimensional fabrication was first suggested by W. Ehrfeld via a processing sequence which he termed LIGA [1]. This process consists of three components. The first part is fundamentally a lithography which can deal with photoresist layers of several hundred micrometer thickness. The implication of a photoresist technology is that of a planar substrate to which the photoresist can be applied. The photoresist thickness requirement cannot be satisfied easily by solvent based systems and spin coating and has been replaced by polymer casting and in situ polymerization. Complete exposure of such thick photoresist layers requires

high energy photons from a well collimated, high brightness source. A synchrotron is nearly perfect for the illuminator and can provide x-ray photons with average wavelengths in the low angstrom range with power densities of several watts/cm^2 and essentially perfect collimation. This type of exposure has the additional benefit that standing wave difficulties are avoided because of the absorption process which x-ray photons use to interact with the photopolymer. Exposure profiles for critical dimensions above 0.1 micrometer are therefore essentially vertical and do not suffer appreciably from diffraction effects even if large gap proximity printing rather than contact exposures are used. The exposed pattern requires a developer which must show very large dissolution rate sensitivity between exposed and unexposed photoresist areas. A suitable chemical formulation for the polymethylmethacrylate or PMMA system has been found [2,3]. This would imply that the first phase of the LIGA process when coupled with a suitable x-ray mask technology can produce photoresist patterns or a plastic mold with edge acuities of better than 0.1 micrometer/100 micrometer structural height. As in all processes there are some negatives. The exposure resolution, i.e. mask to wafer, is better than can be measured. Thus, submicron dimensions can be accommodated if the mask fabrication allows this. However, free standing submicron photoresist structures cannot be developed because of mechanical strain in the PMMA. Buckling typically results during developing. In this sense this process is not a submicron process.

The second phase of the LIGA process involves the conversion of the plastic mold to a metal mold. This is done by first of all modifying the planar substrate to a planar substrate with a suitable plating base. An example would be a sputtered film of titanium at 150 Å followed by a sputtered film of nickel at 150 Å. The prepared substrate is then processed with the previously explained thick photoresist procedure. The plastic mold is filled with electroplated metals or alloys. The plating process when adjusted properly does not disturb the PMMA and forms a negative metal replicate of the plastic mold. Photoresist removal follows and leads to a metal mold which may be the desired prototype or can serve as a mold for other materials.

The third segment of the LIGA process addresses manufacturing issues. It uses the metal mold as the primary mold for injection molding which substitutes for the x-ray lithography process. The injection molding replaces the PMMA procedure and in turn is followed by electroplating and clean-up. More than 1000 molding cycles have been achieved and lead to mass produced, fully attached, high aspect ratio, high edge acuity metal parts.

SLIGA AND ASSEMBLY

The draw-backs of the basic LIGA process fall into two categories: fully attached parts and submicron tolerances. Both can be removed by suitable process modifications.

The LIGA process as explained above can be furnished with a pre-LIGA and post-LIGA sequence to produce parts which are either fully attached or partially attached or free of the substrate. The concept is that of combining surface micromachining with LIGA which will be termed SLIGA [4].

The pre-LIGA sequence involves substrate modifications. Thus, the planar substrate is first furnished with a suitable sacrificial layer for instance soft polyimide. This layer is patterned with an optical mask. The entire substrate is then covered with the plating base and the LIGA procedure follows. There is conceptionally a minor but technically a major modification in the LIGA procedure: The x-ray mask must be aligned to the pattern on the substrate. The required accuracy is fortunately not excessive and therefore alignment in a double sided aligner and subsequent clamping prior to synchrotron insertion is adequate.

The post-LIGA segment deals with the removal of the plating base in those sections of the substrate which are not covered by PMMA. This is done by wet etching and is followed by wet chemical procedures to remove the sacrificial layer. The end results are metal parts with the stated substrate relationships. The free parts in particular are noted to have the property that they do not exhibit geometric distortion due to the sacrificial process. This is the consequence of the fact that electroplating can be adjusted to produce small built-in tensile strain which is on the average nearly constant because the parts are thick enough to avoid interface strained regions.

The parts of interest can be picked up via micromanipulators which use magnetic or electrostatic needle probes. Assembly is completely feasible and does of course enhance the three-dimensional nature of the process. However, this is only a part of the desired goal. Submicron bearing tolerances can be achieved even though the x-ray masks have critical dimensions above 1 micrometer. Two facts support this. Optical masks with incremental critical dimensions of 0.1 micrometer are not very difficult to produce. Therefore, subtraction of optical patterns from two masks or mask regions can be used to produce submicron incremental features. An example would be a shaft of, say, 50 micrometer diameter which is

rigidly attached to the substrate and a gear with an inside hole diameter of 50.1 micrometer which is free and assembled to the shaft. The result is a bushing clearance of 0.05 micrometer which can be utilized fully if the edge acuity of the process is large enough to produce a run-out free metal structure. Fortunately, LIGA processing allows this and the successful result is exemplified in Fig. 1.
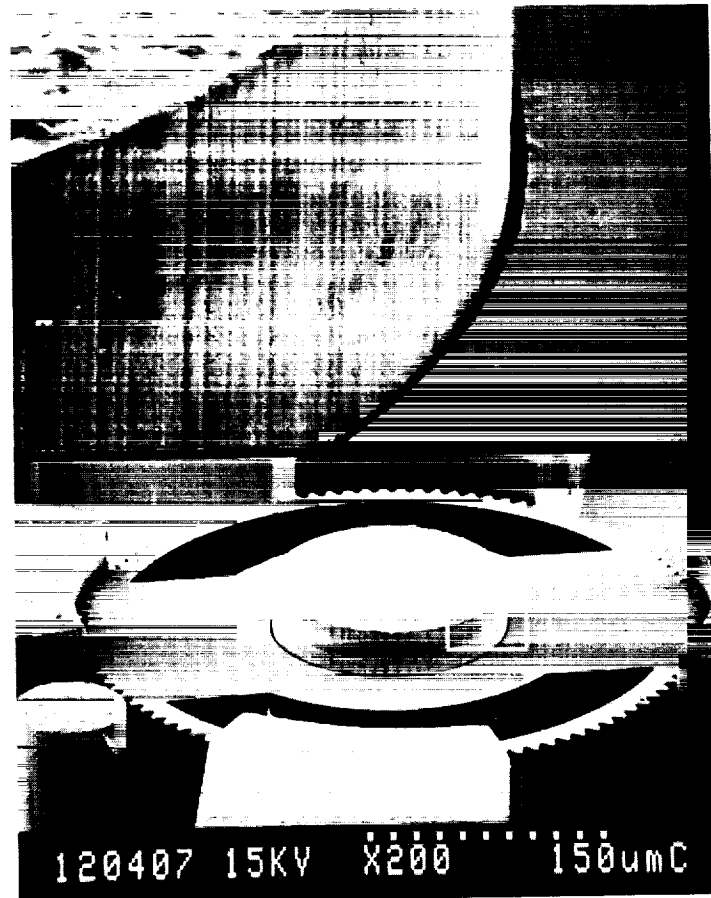

Fig. 1 SEM photograph showing assembled bearing surface for 100 micrometer tall nickel structures and shaft diameter which is 0.5 micrometer smaller than bearing hole.

APPLICATION TO MEMS

Micromechanical components will eventually be used in a MEM system. Since system requirements very often dictate component design the development cycle for MEMS can be shortened by considering a system first and then designing the components which satisfy the system design. For this purpose a detailed investigation of a specific, moderately difficult MEM system has been initiated. The system of choice is a dynamometer which consists of the following parts:

            (1) A Motor
            (2) An Electric Generator
            (3) A Motor-Generator Coupler
            (4) Position Sensors for Rotor Position
and   (5) An Electronic Control Unit.

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The first four components are located on the substrate, the control unit is constructed off-chip.

The purpose of this system is found in part in tribology issues such as friction in MEMS which cannot be calculated but must be measured. The speed-torque characteristics of a planar magnetic micromotor are also of interest and profit from the active load which the generator presents. Finally there is an issue which is predicated on success. A micro-dynamometer of this type is in fact a force measurement system with extreme sensitivity and can therefore usher in an entire new family of sensors for nearly all physical quantities.

The implementation of the dynamometer via SLIGA requires magnetics. The electroplated metal must therefore be ferromagnetic and, for the sake of simplicity, should be an element rather than an alloy. Nickel has been selected as the material of choice. The expected behavior is that of square-loop B-H material with a saturation flux density above 6000 gauss. The first order of business is a tribology issue: can nickel on nickel surfaces be used as bearing surfaces without excessive frictional losses. This question has been answered by designing a reluctance motor with gear take-off [5]. Figures 2 and 3 detail the concept.
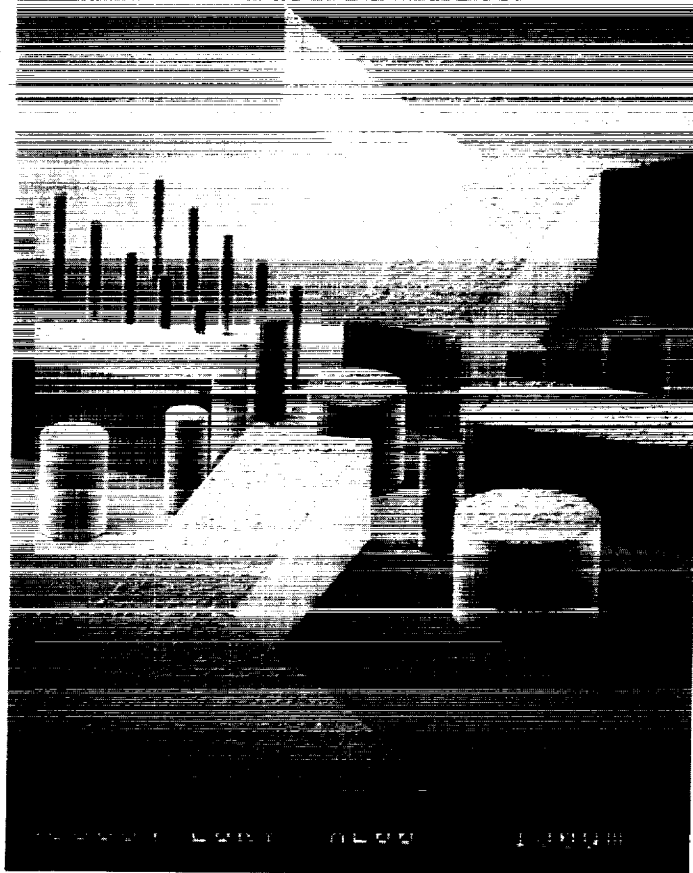

Fig. 2 Nickel stator, height 100 micrometer.

The assembled device as shown in Fig. 3 was tested with an externally supplied rotating magnetic field. Frictional losses required flux densities near 5 gauss for the unloaded rotor. Friction is therefore very low and dynamic ranges of three orders of magnitude can be anticipated. This observation is sufficiently encouraging to proceed with the next phase: coils for current to magnetic field conversion. These coils must of course envelope the pole pieces of the motor and must surround the magnetic circuit of the generator. Figure 4 illustrates the concept.

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Fig. 3 Assembled magnetic motor with gear train. The reluctance rotor and gear train were assembled on to the stator of Fig. 2. The gears have involute tooth geometry with a tooth length of 9 micrometer.

The coil shapes, "U's", which are dielectrically isolated form the magnetic circuit are visible in Fig. 4. The square holes were intended for coil closure via assembly of staple-like nickel pieces. This approach failed because mechanical instabilities and contact problems occured due to spring forces. Fig. 5 illustrates coil closure via hybrid bonding of aluminum alloy wire to the nickel pre-forms. This procedure gives satisfactory results for coils with up to 100 or so turns. This construction procedure when applied to the device shown in Fig. 4 indicates that micro-dynamometer construction is fully feasible.

The remaining issue involves a functional device. This requires not only suitable coil construction but also appropriate magnetic behavior of the ferromagnetic segments of the devices. For a reluctance motor a soft magnetic material with high permeability and low coercivity is very desirable. In this respect nickel is non-ideal. Electroplated nickel layers are further complicated by built-in tensile strain which causes a strong degradation of the B-H curve due to magnetostriction [6]. This problem, a material science issue, is slowly disappearing as plating conditions improve and anneal cycles are clarified. Acceptable magnetic behavior has been achieved and functional testing will occur in the near future.
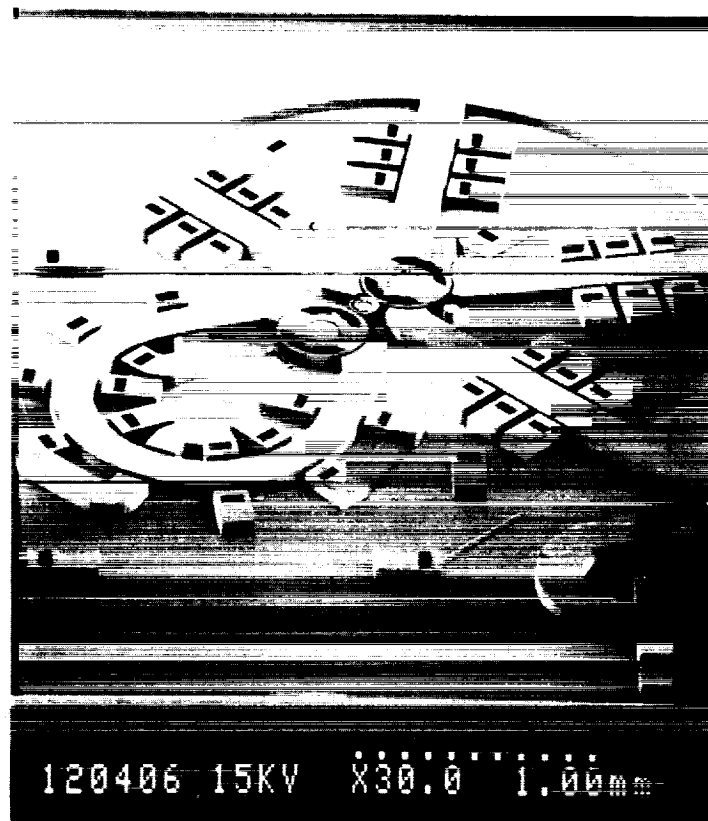
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Fig. 4 Assembled microdynamometer with coil forms prior to coil completion.
The motor with 6 windings per pole pair is located at the upper right hand side of the
SEM photograph and is coupled to a generator at the lower left. The generator has 6
windings which split into a biasing coil and signal coil. Photodiodes have been fabricated
underneath the rotors in the silicon substrate.

CONCLUSIONS

High aspect ratio metal fabrication procedures when combined with assembly offer a technology
for magnetic and electrostatic actuators with increasing three-dimensionality. Submicron bearing tolerances
are particularly noteworthy. They lead to frictional behavior which is lower than expected. The goal: a
fully functional micro electro mechanical system appears to be achievable in the very near future.
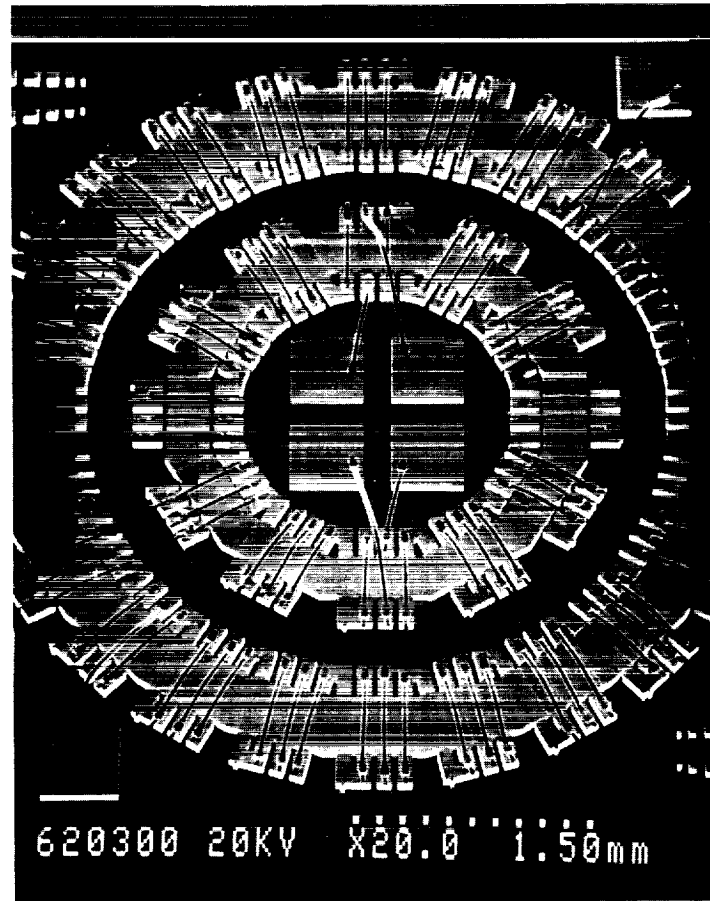
ACKNOWLEDGEMENTS

Fig. 5 Coil test construction via hybrid wire bonding. This SEM photograph shows two split wound toroidal windings about a Ni core. The outer toroid contains 72 turns.

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