LATERALLY DRIVEN ELECTROMAGNETIC ACTUATORS

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ABSTRACT

Linear actuators are potentially useful devices if output forces near or above 10 milliNewton can be produced with total travel in the 250 μm range. These two goals, when combined with required positional accuracies and packaging considerations, can be achieved for magnetic actuators which are fabricated by LIGA-like processing tools.

Preliminary actuator design and fabrication has centered on permalloy structures with 100 μm height. Twenty turn current to flux converters with 10 ampere-turn capability are used to drive a ferromagnetic, spring supported slider into a coil gap. Total travel of 250 μm with 0.28 milliNewton of force has been achieved with 1 Newton/meter spring constants. Since the structure can be extended easily to 3000 μm, the design goal is within reach.

The manufacturing technique has anticipated optical excitation by photodiode inclusion. These devices in shuttered and un-shuttered form can meet the drive current needs and may produce self resonant behavior when excited by unmodulated light.

INTRODUCTION

The commercial viability of micro electro mechanical systems, MEMS, requires that at least three major issues are addressed. The first one of these involves the potential market. MEM systems based on linear actuators fit well into a variety of applications. Micro relays, especially surge protection devices, have a large market potential if contact resistance and high voltage isolation problems can be overcome. This implies that relay closure forces should be in the 1 gram or 10 milliNewton range and that relay throw must exceed 100 micrometer. Similar output force requirements with even larger throws are needed for micro pump and micro valve applications. Output force and throw requirements increase even more for optical applications and normally add positioning requirements as additional complications.

A second problem area comes from the interplay between system requirements and components which fit into a system. Packaging issues need to be resolved early and so will compatibility questions with drive and control circuitry. Packaging difficulties reduce as the impedance level of the MEM components decrease and gain additionally from low rather than high voltage requirements. Microelectronic compatibility issues are very complicated and are mostly cost driven. However, the need to sense some actuator function normally requires that electronic devices are co-fabricated with the MEM structures.

Finally there is the manufacturing tool problem. Cost effectiveness is a major issue and becomes very troublesome if the system is a replacement for an existing system rather than a MEM system with unique attributes. The required three dimensionality in the tool and tight tolerance requirements with multi material capability produce major challenges not only to tool selection but also tool development. The required tool attributes clarify somewhat if one assumes that the selected manufacturing technique is based on a photoresist technology. This results in prismatic geometries and results in actuator output forces of the form

$$F_{OUT} = \rho_E V_A \qquad (1)$$

where ρ_E is the energy density; i.e. $\frac{1}{2}\mathbf{D} \bullet \mathbf{E}$ or $\frac{1}{2}\mathbf{B} \bullet \mathbf{H}$ for electrostatics and magnetostatics respectively; and V_A is the active volume of the actuator in which ρ_E is stored. This volume may be written as

$$V_A = \alpha V_{PH} = \alpha H A_{PH} \qquad (2)$$

where α is the filling fraction or the effectiveness with which the physical volume V_{PH} with area A_{PH} and height H was used. This notation leads to

$$\frac{F_{OUT}}{A_{PH}} = \rho_E \alpha H \qquad (3)$$

as a primitive figure of merit for the actuator and/or the processing tool.

Equation (3) suggests that photoresist processes with large structural height lead to better actuators. If these processes also are characterized by high geometric resolution the filling fraction, α, will increase which improves the figure of merit. The energy density should be as large as possible which favors magnetics slightly. However, as stated earlier, anticipated packaging, reliability and compatibility issues shift the actuator mechanism significantly toward magnetics.

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LINEAR ACTUATOR CONSTRUCTION

The linear actuator which is of interest here is aimed at the markets which have already been mentioned. The technical goals are for output forces in the 1 milliNewton range with throws, total travel, of 250 µm. The device is generic in the sense that it solves several needs. The device is mildly specialized by a specific application which involves an optical grating which is re-configured by the actuator. This is best done with a device which produces an output force which is constant with displacements. Furthermore, since the grating can serve as a spring, the actuator type involves a spring return design.

The actuator mechanism which has been selected here involves magnetics. The material of choice for the magnetic portion of the actuator is permalloy with a composition of 78% Ni and 22% Fe. The alloy is produced by electroplating and behaves as a soft ferromagnetic material with as plated coercivity of less than 0.3 Oersted, saturation flux density of 10,000 gauss and permeability of 2000. The maximum energy density for this alloy is $4(10)^5$ Newton/m^2.

The actuator consists of three main sections: the electric current to magnetic field conversion structure; an electromagnet with an air gap, and the ferromagnetic slider which moves into the gap and the spring constraint. There are at least two major technical problems: the construction of the electromagnet with enveloping coils and the spring design and manufacturing issue. Both difficulties benefited from previous experiences. Thus, the magnet design is based on earlier experiences with similar issues for rotational machines [1] and very much improved magnetic material processing. The design of the springs and their support is based on unsuccessful actuator design with sliding friction. Therefore, the linear actuator which is reported on here was designed without sliding surfaces. This is possible if the slider-spring combination is rigidly locked to the substrate at two or more supports and elevated above the substrate in all other regions. Vertical magnetic forces in the gap can be used to produce the desired levitation. This behavior of magnetic actuators is very desirable and is not available in electrostatics due to pull-down forces between the slider and the substrate. The remaining major issue is that of a suitable spring material. This problem was solved more or less by accident. The magnetic behavior of the permalloy is consistent with material which is nearly amorphous. This type of crystallinity has been used in polysilicon for excellent, long term stable mechanical flexures[2]. The same results have been obtained with the permalloy which is used here where spring designs with maximum strain levels of 0.5% have produced excellent results and are considered to be conservative.

There are two unusual aspects of the actuator which have been incorporated in the design. One of these recognizes the fact that photodiodes are devices which operate well as current supplies for low impedance loads. They can be designed to drive the device from unmodulated light and, in a slightly more complicated situation, can produce self-resonances. Since quality factors of several hundred can be anticipated resonant applications are particularly attractive for low power operation. The limitations which this imposes on the actuator is that of fixed frequency operation. This can be overcome in a push-pull design where the effective spring constant can be controlled electronically which in effect tunes the resonant frequency. Both attributes have been incorporated into the current design and will be reported on separately.

CONSTRUCTION TECHNIQUE

The construction tool which has been used to produce experimental actuators is that of x-ray assisted processing based on LIGA[3]. The modifications and extensions which have been used to improve the processing tool fall into two categories: photoresist processing and assembly[4].

In typical LIGA processing, the x-ray sensitive photoresist is applied by casting and in-situ polymerization. The polymer shrinkage and confinement by the substrate surface combine to produce a highly strained photoresist layer which is difficult to anneal. This mechanical strain limits the resolution of the process and reduces the yield significantly. The problem has been removed by using cell cast sheets of optimized polymethylmethacrylate, PMMA, machining it to size and solvent bonding the strain free material to the substrate of choice. Typical PMMA thicknesses are in the few millimeter range. The desired photoresist thickness is achieved by milling the polymer layer to the desired value, mild annealing to remove tool strain, and if so desired, mechanical polishing. This technique has been used to produce photoresist thicknesses from 50 µm to several centimeters.

Exposure of these extreme photoresist thicknesses is possible if proper x-ray photon energies are used. Thus, at 3000 eV the absorption length in PMMA is roughly 100 µm which would imply maximum, reasonable exposure depths to, say, 500 µm. On the other hand, 20,000 eV photons have absorption lengths of 1 cm in PMMA and have been used to expose to 10 cm depths[5].

Assembly enhances the three-dimensionality of high aspect ratio processing[6]. It can and has been used to produce submicron tolerances in assembled structures for x-ray exposed devices because LIGA-like processing produces vertical pattern variation of less than 0.1 µm per 100 µm of structural height. The thick photoresist processing which is being used here has maintained this highly desirable attribute and if anything has produced better sidewall finishes as Fig. 1 illustrates.

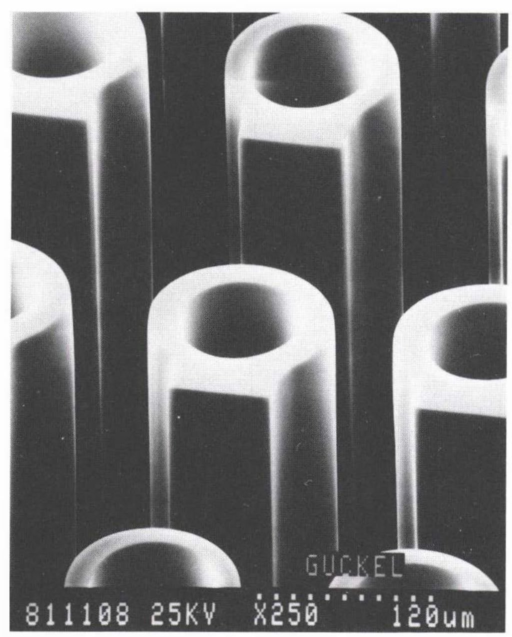

Fig. 1 3.2 mm high PMMA posts after developing.

ACTUATOR RESULTS

The physical layout of the linear actuator is shown in Fig. 2. The electromagnet uses 20 turns. It is designed in such a way that flux saturation occurs for air gaps of 10 μm with a fully closed slider at 100 μm of structural height. Maximum allowed terminal current is 500 mA which produces an mmf of up to 10 ampere-turns. The details of the construction technique for the magnet are given in reference [1]. The magnet design has been verified by two and three-dimensional numerical calculations. Output forces of 280 μN at 100 μm structural height indicate that the design goal of 1000 μN can be reached easily at 500 μm height. The instability which a displacement of the slider in the gap can cause is prevented by spring design and four posts which prevent the slider from contact with the magnet pole faces.

Figure 2 employs three photodiodes. The two large ones are for DC-biasing. A shuttered photodiode under the slider acts as a position sensor and can also be used in connection with a simple phase shifting network to attempt self-resonant excitation with unmodulated light. The spring-slider combination to accomplish this is shown in Fig. 3.

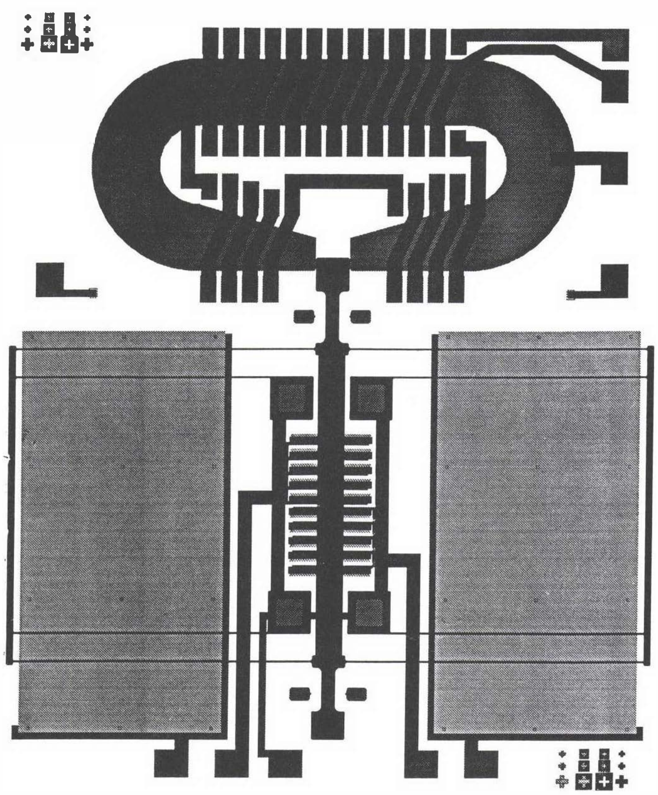

Fig. 2 Layout for single sided linear actuator with photodiodes

The spring design involves spring constants of roughly 1 Newton/meter with 250 μm of total travel. Since the spring is very tall the system becomes very stiff in the substrate direction. Assembly of the spring to square posts has proven to be quite simple and has produced rigid supports for the slider. Fig. 4 illustrates the structure just before wire bonding. The device which is shown in Fig. 4 is the push-pull version of the actuator.

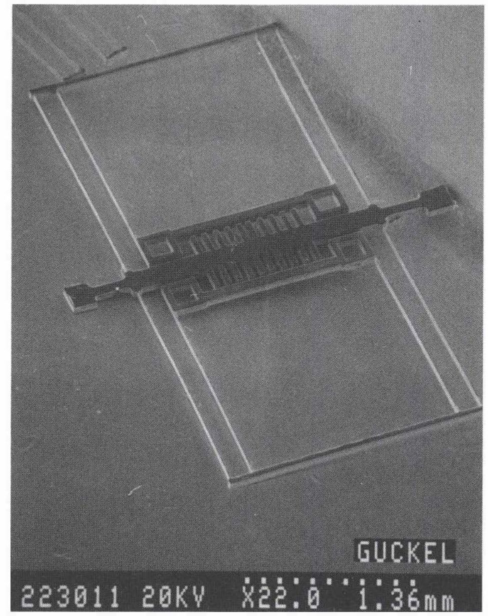

Fig. 3 Shutter-slider with springs prior to assembly.

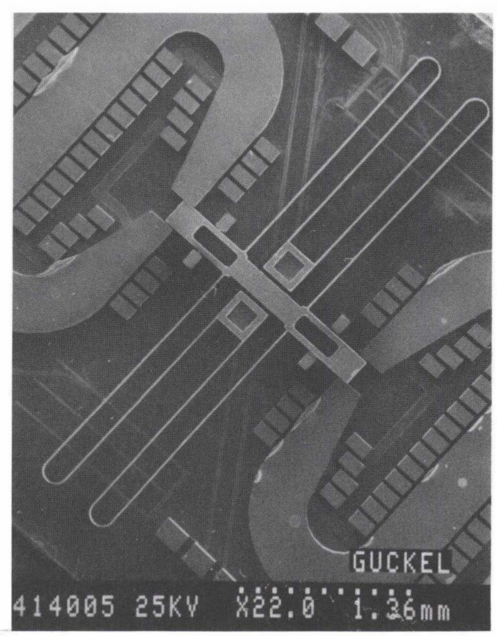

Fig. 4 Assembled double-sided actuator.

The DC-displacement of the actuator is very close to predicted values. Thus, 300 mA of DC-current into 5 ohms produces 200 μm of travel. Further improvements will occur with better coil construction techniques.

The fundamental resonance of this type of actuator is low because the total slider mass approaches 1 milligram. This produces typical resonances near 230 cps with quality factors of 40 in air. Oscillation amplitudes of 120 μm peak-to-peak with 5mA of excitation have been obtained and involve power dissipation in the 100 μWatt range.

CONCLUSION

The results which have been achieved so far indicate that linear actuators with sufficient force output and travel are feasible. The preliminary structures will improve with better coil fabrication techniques. Very much reduced device areas will result from modified LIGA-like processing sequences which emphasize three-dimensionality. The availability of permanent magnets is anticipated and will do much to reduce power dissipation in the devices.

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