Toward Milli-Newton Electro-and Magneto-Static Microactuators

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Abstract

Microtechnologies can potentially push integrated electro-and magneto-static actuators toward the regime where constant forces in the order of milli-Newton (or torques in the order of micro-Newton Meter) can be generated with constant inputs within a volume of 1.0X1.0x0.02mm with "conventional" technology. "Micro" actuators are, by definition, actuators with dimensions confined within a millimeter cube. Integrated microactuators based on electrostatics [2]-[5] typically have force/torque in the order of sub-micro-Newton (sub-nano-Newton-Meter). These devices are capable of moving small objects at MHz frequencies [5]. On the other hand, suppose we want to move some one cubic millimeter object around with 100G acceleration, a few milli-Newton force will be required. Thus, milli-Newton microactuators are very desirable for some immediate applications, and it challenges micromechanical researchers to develop new process technologies, designs, and materials toward this goal.

Technologies for High-Aspect-Ratio Microstructures Most of the surface-micromachined microtransducers are polysilicon-based microstructures [1]. These structures, being IC-processed flatelanders, have small vertical stiffness and, in the case of lateral gap actuators, small in-plane force/torque and relatively large fringe field components in the vertical direction [2]-[5]. Together, these cause large vertical movements which are not always desirable. Fortunately, stiffness goes as cube of the thickness, and usable force/torque go linearly with the thickness while keeping those undesirable vertical fringe fields nearly unchanged. Thus, alternative material/process for thick-structure micromachining, techniques that increase structural thickness without sacrificing the minimum in-plane features, are developed to overcome the inherent planar IC process and thickness limitations of thin film deposition techniques [6]-[11]. Among these, plated material can have some desirable properties such as ferromagnetism and lower stress as compare to as-deposited CVD or sputtered thin films. To make these metal structures, a photoresist material is deposited on a seed layer and patterned into a "stencil" through which structures are electroplated before removing the resist stencil and the seed layer underneath. The plated metals conform to the photoresist profile and form smooth sidewalls, and typical plating rates are large enough to make hundred micrometer thick structures feasible. Although synchrotron light sources preferably with storage rings are required in the deep x-ray technology[6][7], many efforts [8]-[11] have been on fine tuning some more "conventional" lithography techniques to achieve an aspect ratio toward 10:1 with less perfect resist sidewall profiles. In the following, we will call a technique fine tuned from conventional technology and produce 20 μm thick structures with 2 μm gaps an "advanced" lithography technique.

Area Efficient Approach to Milli-Newton Actuators One should fully exploit the two planar dimensions before pushing the third (out of plane) dimension further from those advanced lithography techniques. This can be achieved in an electrode tree structure with interleaved branches which connected to interdigitated fingers. In this approach, each pair of fingers form an energy storage cell, which popularizes the whole area and efficiently convert electrical field energy into force or torque, and maintain a constant output vs. input relation within a small operation range. In the case of electrostatics with advanced lithography process, one can estimate that in a 1mm by 1mm area, with 20 μm thick structures, 6 μm wide electrodes, 2 μm air gaps, (smaller gap is achievable with specific process[12], but a conservative value is taken here), 10 μm branch width, branch separation of 25 μm for the interdigitated fingers and 5 μm otherwise, and a maximum voltage of 100V one can get a lateral force of 1.1 mN. The device has a top plate to hold all the mover electrode branches together. The plate could be either metal or process-compatible dielectric material. Assuming a 5 μm separation between the plate and stator electrode branches, the vertical force is 0.3mN. The vertical stiffness, being at least three order of magnitude larger than their polysilicon version, should be able to take the load without much difficulties. Also, ground plane might not be necessary in these thick structures as observed in [11] again because of the stiffness in the vertical direction.

Magnetic Pole Finger Device Comparing magnetic actuators to electrostatic actuators with similar dimensions, the force ratio is equal to energy density ratio $[cB/E]^2$, where c is the velocity of light, B and E are the maximum magnetic and electrical field. In the sub-millimeter region, some practical values are B=1.1T (Bs of Permalloy 22 wt. % Fe, 78 wt. % Ni) and E=50 volts across 1 μm. Here, magnetic actuators have a typical force advantage of 10 times over electrostatic ones. Isotropic magnetic materials with low Hc, low Br and high Bs should be used for an ideal linear relation between the B and H, and for a maximum force before magnetic saturation. The proposed magnetic pole finger device is a "quasi dual" to interdigitated electrodes, and can achieve the magnetic saturation limit on the pole faces and have high linearity for fine lateral movements. Assuming the same technology as used in the electrostatic actuators described in the last paragraph except with single-branch one-mm-long Permalloy, the lateral force will be 1.6mN, and the saturation field Bs is achieved in the air gap with 70mA current through a 50 turns coil. Thus, a single magnetic branch of the tree generates more force than electric tree described in the last paragraph, and a lateral force of 16mN can be generated if deep x-ray process is used. The 2 μm gap used in this case is more for the purpose of reducing the magnetrode pitch than increasing the magnetic field in the air gap which can be achieved by increasing current in the coil. It seems to be superior to electrostatic actuators except an area efficient design is hardly feasible without field saturations. Besides, the coil structures, needed to generate mmf, will either take large area or complicate the fabrication process. Thus, the trade off is between high voltage vs. high DC power, high area efficiency vs. high energy density, and conducting material vs. soft magnetic material. In either case, by using area efficient designs, or magnetic pole finger devices, microfabricated actuators will be able to move one-cubic-millimeter objects around with an acceleration approaching 100G.

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Micro Structures and Micro Actuators for Implementing Sub-millimeter Robots

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Abstract

There are many advantages to shrinking robots and mechanical actuators to the same size as the parts to be manipulated. Extremely delicate forces can be applied, robots can be readily parallelizable, and the relative accuracy required can be markedly reduced. This talk considers some initial ideas towards implementing practical sub-millimeter robotic systems, in particular, fabrication of multi-degree-of freedom silicon actuators. The micro-robot will use silicon structures that can be folded out of the plane of the wafer. One of the major difficulties in building millimeter scale micro-robots is overcoming forces due to friction and wiring. Friction forces can be reduced by using flexures instead of rotary or linear sliding joints, and using fluid lubrication, such as an air-bearing. Mobile devices on a sub-millimeter scale working in a fluid medium could be useful for manipulation and testing of small material samples. The power requirements for such robots working at low speeds are very favorable.

1. Introduction

In the not too distant future, mobile micro-robots, such as depicted in Fig. 1, may be batch fabricated using silicon and photo-lithographic techniques. The silicon may be used for on-board intelligence, and in addition for electro-mechanical sensor and actuator systems. This micro-robot-on-a-chip has been popularized by Brooks and Flynn [1989]. These robots may see wide application in micro-tele-operation for very small inaccessible areas, and in the massively parallel handling of small biological or electromechanical elements.

An integrated system for manipulating dry parts in the plane using multiple mobile manipulation units was proposed by Pister et al [1990]. This device consists of a 1 cm^2 substrate with an air bearing to support individual $1mm^2$ platforms (see Fig. 2). The individual platforms are driven in the plane by electrostatic forces, and could carry grippers, probes for sensing, or tools for processing. By incorporating capacitive position sensing of the platforms, an integrated micro system for parts handling could be made on a single chip.

2. Three Dimensional Micro-Mechanical Structures

To be useful, silicon micro-robots will need tools to interact above the plane of the wafer, not just in it. One promising approach, called "silicon origami" [Shimoyama, 1992] or micro-hinges [Pister, et al 1991] allows planar fabrication, followed by 3 dimensional assembly of structures. This paper examines some of the new tool making capabilities obtainable with this process.

Current integrated micro systems are limited by the mostly planar micro-machining techniques available. For some applications, it will be necessary to have sensors and actuators that extend far beyond the surface of the device, e.g. micro-robots. For example, a sensor or probe may need to be sufficiently far from the sensor surface to avoid boundary layer effects.

One way to build three dimensional devices is to use new fabrication techniques, for example, Laser-assisted Chemical Vapor Deposition (LCVD). In LCVD, a focussed laser beam activates chemical species which can either locally deposit or etch a structure depending on the gas medium used in the reaction chamber. Complicated structures such as a boron spring [Westberg et al, 1991] and stepped pits with controlled slopes [Bloomstein and Ehrlich, 1991] have been demonstrated with LCVD. Volume resolution of $1 \mu m^3$ has been obtained.

While LCVD is very flexible for machining three dimensional structures, it is inherently a serial process, and hence much slower than photo-lithographic fabrication. An alternative approach is to perform conventional two dimensional processing, and then to assemble (post-process) three dimensional structures from planar components. These components could be bonded to each other using, for example, welding techniques [Fedder and Howe, 1991].

One method to simplify three dimensional assembly is to fabricate components that can be constrained to rotate or slide into place. Pister et al [1991] have shown hinged structures that can be rotated out of the plane to build three dimensional structures. (A similar method was independently developed by Shimoyama [1992]). A simple example is shown in Figure 3, with a $2 \mu m$ thick plate rotated out of the plane, and held in place by friction in the hinge. A typical sensing application which requires sensors away from the surface is a hot-wire anemometer for measuring air flow. Figure 4 shows a 3 axis hot-wire anemometer, assembled by folding 3 orthogonal hinge structures out of the plane. (The anemometer structure extends approximately $200 \mu m$ above the substrate). One advantage to the hinged 3 dimensional structures, compared with LCVD, is that all the planar lithographic resolution is maintained.

Standard surface micromachining, has high planar resolution, low vertical resolution, and limited vertical range (typically less than 5 μm). These characteristics make surface micromachining an excellent choice for planar applications, but have limited utility for three dimensional designs. We present a process in which structures are fabricated using surface micromachining, and then rotated out of the plane of the wafer on integrally fabricated hinges. The resulting structures have high resolution in both the planar and vertical directions, and have a vertical range from 10 μm to more than a millimeter. This hinge-based method allows the benefits of high resolution surface lithography while providing access to the third dimension with higher vertical resolution than previously possible. Drawbacks of hinge-based designs include the need for post-process assembly, and incompatibility with typical MOS processes.

2.1. Process

The simplest version of the hinge fabrication process is a three mask, double layer polysilicon process with oxide sacrificial layers (Figure 5). A sacrificial phosphosilicate glass (PSG) layer is deposited on a bare substrate, followed by an undoped polysilicon layer (*poly1*), and a doping PSG layer. All depositions are by low pressure chemical vapor deposition (LPCVD). The polysilicon is patterned in a plasma etcher. This polysilicon etch defines the majority of the structural components, including the hinge 'pins', about which most structures will rotate . A second sacrificial PSG is deposited and both the first and second sacrificial oxides are patterned in a plasma etcher. This etch defines contacts between the second polysilicon layer and the substrate, as well as contacts between the two polysilicon layers. A second layer of polysilicon (*poly2*) is deposited and patterned. This second polysilicon etch defines the 'staples' which tie the first polysilicon layer to the substrate, as well as forming additional structural components. Finally, the sacrificial layers are removed in a concentrated HF etch, the wafers are rinsed in deionized water, and air dried at room temperature. Perforations are used in the larger structures to allow complete release in the 1 minute release etch.

Typical film thicknesses for the sacrificial and doping PSG layers are between 0.5 and 2.5 μm. Polysilicon layers are typically between 1 and 2 μm thick. If the structures are intended to be electrically active (e.g. the anemometers discussed below), the substrate is passivated with a 0.5 μm thermal oxide and 0.1 μm LPCVD nitride before the first sacrificial oxide is deposited.

Dimples can be added to the polysilicon layers by patterning part way through the sacrificial layers with BHF. These dimples are not strictly necessary, but help prevent the polysilicon layers from adhering to the substrate and to each other after release. Portions of *poly1* can be anchored to the substrate, if desired, by etching contacts in the first sacrificial PSG before the *poly1* deposition.

If the total thickness of the two sacrificial oxide layers is greater than the thickness of the first polysilicon layer, then the pin of the hinge will be able to slide between the two legs of the *poly2* staple. This sort of 'play' in the hinge is not generally desirable, and can be eliminated by using a timed BHF etch immediately following the patterning of *poly1*. This timed etch undercuts the sacrificial oxide under the hinge pin, and due to the poor step coverage of low temperature LPCVD oxide, indirectly reduces the second sacrificial oxide thickness near the pin as well. This results in a partially encased *poly1* pin, under (and almost inside) a *poly2* staple. Since the hinge location is now determined by the *poly1* pin rather than the *poly2* staple contacts, we refer to this as a 'self-aligned' pin.

2.2. Design

Given the three mask process above, it is possible to make several different types of hinges, as illustrated in Figure 6. The simplest of these is the 'substrate hinge', which consists of a *poly1* plate and hinge pin constrained by a *poly2* staple. The staple is attached to the substrate at two contact points, and the plate is free to rotate a full 180 degrees off of the substrate. Note that the freedom of the plate to rotate may be limited by the geometry of the pin and staple. If the width of the pin is greater than the sum of the thicknesses of the *poly1* and sacrificial oxide layers, then the pin will be unable to rotate a full 90 degrees without contacting the substrate and staple.

The substrate hinge is used to hinge *poly1* plates to the substrate. To hinge plates to each other requires a different type of hinge. Two *poly1* plates can be hinged together using a 'scissor hinge'. *poly2* strips are attached between interdigitated *poly1* fingers, preventing the two *poly1* plates from pulling apart, and allowing the plates a relative rotation of roughly 180 degrees. This type of hinge can only fold 'concave-down'. A similar scissor hinge, illustrated in the figure, hinges two *poly2* plates together and folds 'concave-up'.

Unlike substrate hinges, there is no 'pin' in a scissor hinge. Given the typical film thicknesses used, a substrate hinge which is intended to rotate 90 degrees must have a pin which is no more than 2 μm wide. Scissor hinge geometries are not constrained by the film thickness of the structural or sacrificial layers. As a result, scissor hinges can be made with all geometries much wider than 2 μm, making them much stronger than substrate hinges.

2.3. Assembly

After the release etch, the structures are rotated into their final positions. This is currently accomplished at a probe station using standard electrical probing equipment to rotate the structures into position. A sharp probe tip is slid under a released structure and raised to lift the structure off of the surface of the wafer, and rotate it into the desired position. By inter-locking two hinged structures, the final position of the structures can be accurately controlled.

Assembly is a labor intensive process (e.g. the gripper requires roughly 10 minutes for assembly), however we are working on designs which require no manual assembly. Hydrodynamic forces may prove to be very useful in automating the assembly process. We have observed that many structures rotate 90 degrees or more during the post release rinse, and a directed stream of air from a capillary tube has a similar effect on released structures.

2.3.1. Micro Probe

Another out of plane sensing capability provided by the hinge structure is shown in Figure 7. A probe for electrical testing can be made with an intrinsic spring, and electrical contact to substrate through hinges. This structure has not been tested.

2.3.2. Parallel-Plate Gripper

Recently, planar (roughly 2 µm thick) micro-grippers have been fabricated with a gripping range on the order of 10 µm, [Kim, Pisano, Muller, 1991]. The hinge technology offers the opportunity to produce micro-grippers of a scale difficult to obtain with previous micromachining processes. Grip surface dimensions and gripper openings measured in hundreds of microns are possible, while actuating resolution is on the order of microns. The structure in Figure 8 is a parallel-plate gripper consisting of four separate pieces. The two jaws of the gripper are folded up separately and locked in place at one end by another plate with two slots in it. The jaws are suspended at the end of 400 µm-long beams, each of which is 20 µm-wide. A 1 mm-long tendon travels from each jaw and locks into the vertical handle. When the handle is pulled back, the tendons pull the jaws open. When the handle is released, the spring force of the support beams closes the jaws. In the 'closed' (rest) position the jaws are actually 100 µm apart. Over 100 cycles of up to 0.5 mm opening have caused no damage to the gripper.

2.4. Actuation of Hinge Structures

The rotary hinge joints have very high friction, and elastic joints, such as a cantilever beam, will be much easier to drive. There are several options for actuating these elastic joints, including shape-memory-alloy [Ikuta, 1990], electromagnetic [Wagner and Benecke, 1991], and electrostatic drives. Although the forces are very small, low voltage electrostatics is perhaps the easiest to implement on the hinge process with few additional masks. Figure 9 shows a single degree-of-freedom actuator, which consists of a movable plate supported cantilever beam, and a fixed plate.

A useful range of motion for this actuator is 0° to 10°. (Assume that the hinge joint is locked in place). When a potential difference is applied between the fixed and moving plate, the plates are attracted to each other. To estimate the order of magnitude of this force, we can assume that the plates are approximately parallel with a gap of 10µm. A typical plate size would be 200 µm ($= a$) square, with plate thickness 2 µm ($= h$). Then the electrostatic force normal to the plate (F_z) for 10 volts applied between the plates, is given by

$$F_z = \frac{\partial}{\partial z} \tfrac{1}{2} C V^2 = \frac{V^2}{2} \frac{\varepsilon_o a^2}{h^2} = 2\times10^{-7} N \ . \tag{1}$$

The actuator is unidirectional without the restoring force of the cantilever. The cantilever spring should be soft for the plate to be "pulled-in", yet strong enough to support the weight of the plate. Using a 2 µm thick polysilicon layer, a 200 µm long beam of square cross section will have appropriate compliance. The approximate spring constant for such a polysilicon beam will be about $4\times10^{-2} Nm^{-1}$ [Lin et al, 1991]. The mass of the plate is $m_{plate} = \rho_{Si}\, l \times w \times d$, where ρ_{Si} is the density of silicon, $2.3\times10^{3} Kgm^{-3}$. For a square plate , 200 μm on each edge, 2 μm thick, the mass of the plate is approximately $2\times10^{-10} Kg$, with weight of $2\times10^{-9} N$. The displacement of the cantilever beam due to the weight of one plate is:

$$\delta = \frac{K_{beam}}{m_{plate}\, g} = \frac{2\times10^{-9} N}{4\times10^{-2} Nm^{-1}} = 5\times10^{-8} m \ , \tag{2}$$

which is negligible, only 0.1% of the unactuated gap. Because of the inverse square relationship between F_z and the gap, the 10 V potential will be sufficient to drive the plates together.

To build multi-degree of freedom robots, a network of these single degree-of-freedom actuators and elastic joints needs to be interconnected, for example, as proposed by Shimoyama et al [1991]. A possible interconnection scheme for these actuators is shown in Figure 10, where the left figure shows a stack unactuated, and the right figure shows an actuated stack. The plates are supported by cantilever beams that connect to scissor hinges on each side of the plate. Although the figure shows a planar manipulator, alternate plates could be orthogonally stacked in the plane, to give a 3 dimensional manipulator. For 200 μm plates, the gravitational force for even a stack of 20 plates would cause only a 10% deflection of the bottom plate in the stack.

There are many problems to building this type of stacked structure using the hinge process. A recent paper by Pister [1992] provides some strategies for building this device. Thin and flexible polysilicon ribbon cable can be fabricated to wire up all the plates to external connections. These connections would loop around the scissor hinge and not exert any force when operation. Self-assembly catches can be added so that structures fold up and latch into place during sufficient excitation, for example, by a rinsing step. Polysilicon piezo-resistive strain gauges can be used to measure force or position of the joints (the bending of the cantilever), and thin film transistors can be added to the plates to control plate addressing. Many problems remain to be worked out, but there is hope for an implementable stacked actuator design.

3. Summary

A new surface micromachining process has been developed which allows the fabrication of a wide variety of three dimensional structures. The three mask process allows structures to be hinged to the substrate as well as to each other. By fabricating the structures in the plane of the wafer, conventional lithographic techniques can be used to define features with high resolution. These structures can then be rotated out of the plane of the wafer and assembled into three dimensional designs with detailed features in three dimensions. Several structures have been fabricated and tested, including a hot wire anemometer and a gripper. Given the variety of electrical and mechanical devices which can be integrated with this relatively simple process, the outlook for sophisticated electromechanical systems, including micro-robotics, seems promising.

Acknowledgments

Partial funding for this research was provided by the Semiconductor Research Corporation under grant 91-DC-008, the Berkeley Sensor and Actuator Center, and the National Science Foundation under grants NSF-IRI-9157051. The author thanks K.S.J. Pister for his valuable contributions and collaboration.

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Figure 1. Idealized Micro-Robot Operating in Fluid Medium

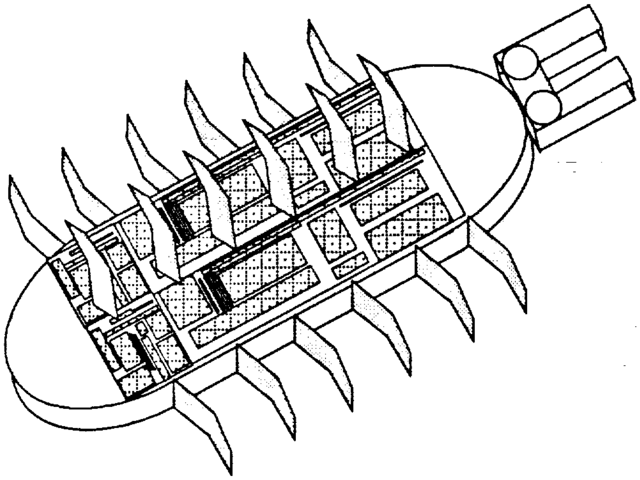


Figure 2. Probing platforms floating on air bearing

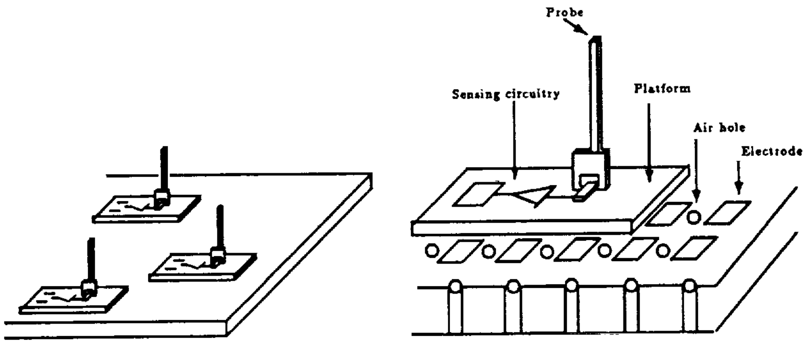


Figure 3. Polysilicon beam with polysilicon staple-type hinge folded out of plane.

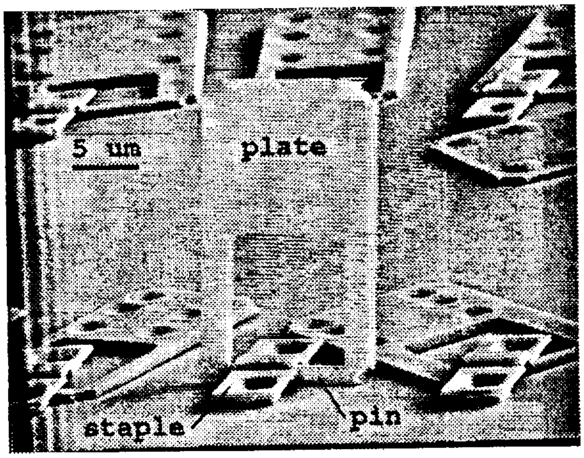


Figure 4. Three axis hot-wire anemometer constructed from 3 hinged sections

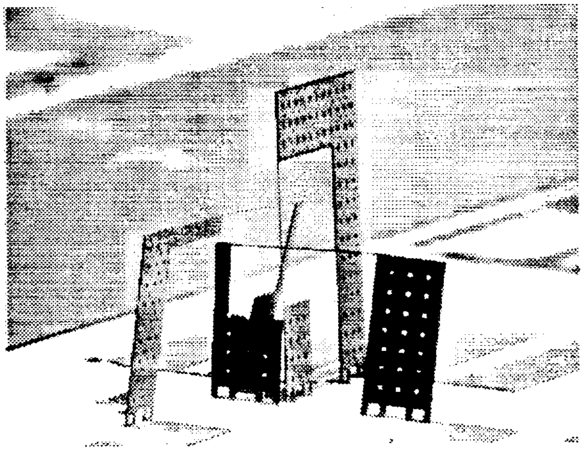


Figure 5. The hinge process sequence At top is shown a cross section after poly 1 has been patterned and the second layer of PSG deposited. Following this, contacts are etched through both layers of PSG. Next, poly-2 is deposited and patterned. Finally, the oxide is removed in a sacrificial etch, and the poly-1 ler is free to rotate out of the plane of the wafer.

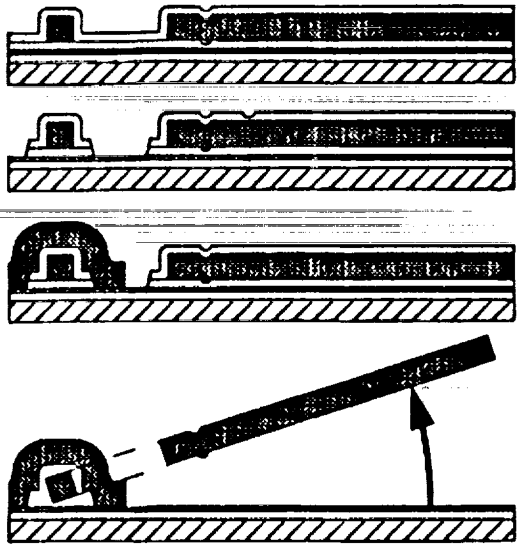


Figure 6. Three basic hinge types (A) A substrate hinge, which is used to hinge released structures to the substrate. (B) A 'concave down' scissor hinge, used to hinge released structures to each other. (C) A 'concave up' scissor hinge.

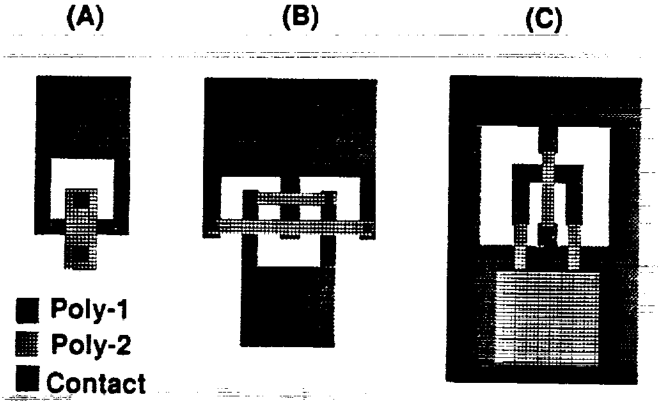


Figure 7. A Compliant microprobe, The total length of the spring is 3 mm.

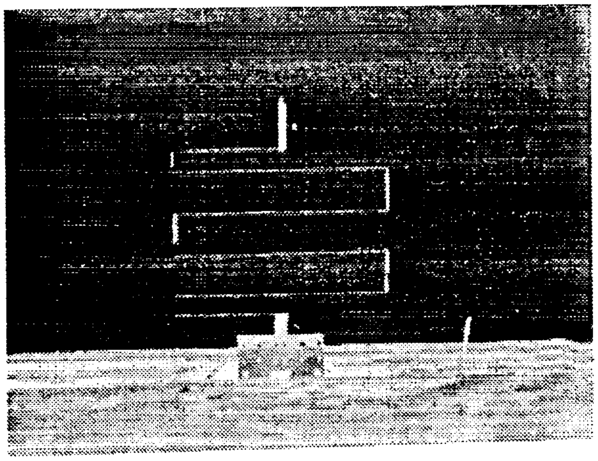


Figure 8. A parallel plate gripper. The gripper is normally closed, with a gap of 100 μm between the plates. Pulling the vertical bar (left side) causes the jaws to open. Opening of 0.5 millimeter is possible with no damage to the device.

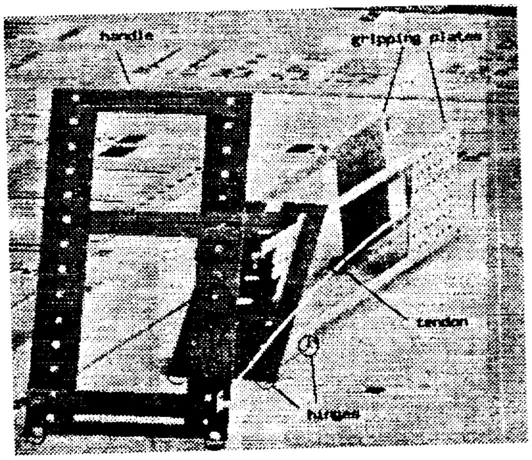


Figure 9. Single hinge type actuator (1 DOF)

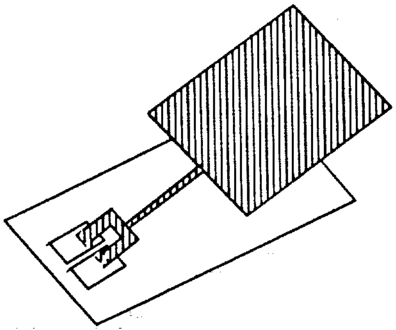
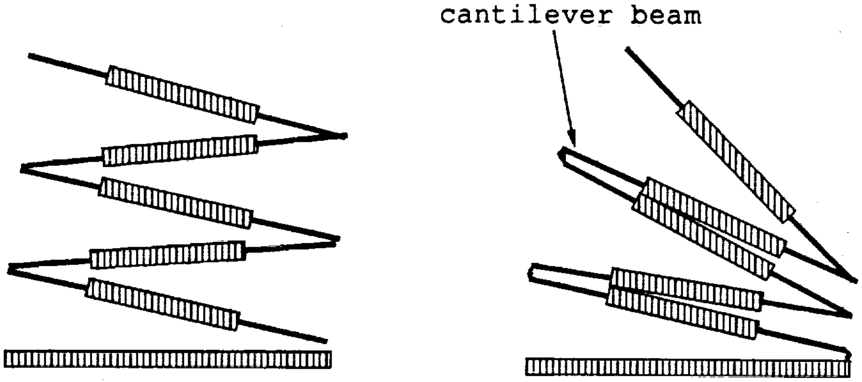


Figure 10. Stacked hinge type actuators



Microtechnologies
and
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MICROTECHNOLOGIES OF THE FUTURE