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MEMS

Keywords: Micromachining, Microfabrication, Integrated Sensors, Microsensors, Microactuators

Background

Micro electromechanical systems (MEMS), also referred to as microsystems or micromechatronics, comprise the coupling of micromechanisms with microelectronics. Micromechanics, another often used term, refers to the design and fabrication of micromechanisms that predominantly involve mechanical components with sub-millimeter dimensions and corresponding tolerances of the order of 1 micrometer or less. The types of systems encompassed by MEMS represent the transduction need between signal and information processing and the mechanical world. This coupling of a number of engineering areas leads to a highly interdisciplinary field that is commensurately impacting nearly all branches of science and technology in fields such as biology and medicine, telecommunications, automotive engineering, and defense. Ultimately, realization of a "smart" MEMS may be desired for certain applications whereby the information processing task is integrated with the transduction tasks yielding a device that can autonomously sense and accordingly react to the environment.

Motivating factors behind MEMS include greater flexibility in device form factor with typical complete packaged devices occupying volumes well less than 1/20 cm^3. In addition, repeatability and economic advantages can follow in accord with batch fabrication schemes such as those used in integrated circuit processing that has formed the basis for MEMS fabrication. Many technical and manufacturing tradeoffs, however, come into play when deciding whether an integrated approach is beneficial. In some cases, the device solution with the greatest utility defaults to a hybrid approach where mechanical and electronic processing is separated until a packaging step. Two broad categories of devices follow from the transduction need addressed by MEMS and include the "input" transducer or microsensor, and the "output" transducer or microactuator. The specifications for these two categories of devices entail unique fabrication methods that have evolved over the past 30 years and have resulted in correspondingly unique process technology and manufacturing methods.

MEMS Attributes

An ideal sensor extracts information from the environment without perturbing the environment. Thus, minimal energy exchange is desired. At the same time fast response and high sensitivity with minimal power requirements are important sensor attributes. All of these qualities are fundamental to microsensors and the degree to which they may be exploited is a direct consequence of mechanical scaling behavior. An example of how this behavior may be capitalized is demonstrated by the progress in integrated pressure sensors. Early micromachined pressure transducers with 25 micron thick membranes and up to $1cm^2$ area consumed $5(10)^{-3}$ Watts of power with a piezoresistive transducer with a force sensitivity near $1(10)^{-2}$ Newtons. Reduction of the deflection membrane thickness to 1 micron resulted in a linear size reduction of near 100 and corresponding force sensitivity increase to $1(10)^{-6}$ Newtons, with slightly reduced piezoresistive power dissipation. Changing transduction mechanisms from piezoresistive to a micromachined vacuum encapsulated resonant microbeam, typically 200 microns long, 40 microns wide, and 1 micron thick, that optically senses force via a shift in resonant frequency reveals a force sensitivity improvement to better than $1(10)^{-10}$ Newtons with an input power requirement of 10^{-13} Watts. These improvements may be further extended in sensing concepts that are being implemented based on tunneling and atomic force microscopes and ultimately in magnetic resonance force microscopes with 60 nanometer thick resonant beams where $1(10)^{-18}$ Newton (tens of attograms equivalent mass) forces have been resolved and a thermal noise-limited sensitivity of $1(10)^{-19}$ Newtons is anticipated.

Actuators and corresponding linkage mechanisms are three-dimensional devices that operate via changes in stored energy. The goal is a certain force versus displacement character that implies a volume-controlled device. Direct scaling of macroscopic counterparts suggests potential problems for micromechanisms in behavior that is affected by surface to volume ratio changes. These issues include substantially minimized inertial effects that occur with size reduction, and the relative greater influence of friction, surface tension and air damping that become more significant relative to mass particularly when compared to a one horsepower motor or engine, for example. Microactuators and mechanisms based on planar batch integrated circuit fabrication techniques are constrained to essentially two-dimensional elements which challenges micro-mechanism design. So-called high aspect-ratio micromachining (HARM) has been consequently developed to provide more tools to alleviate the two-dimensional constraint. High aspect-ratio processing also aids manufacture of inertial sensors, for example, in defining proof masses for applications such as seismic sensing.

Microfabrication Technology

The development of process tools and materials for MEMS is the pivotal enabler for integration success. A material is chosen and developed for its mechanical attributes and patterned with a process amenable to co-electronic fabrication. Two basic approaches to patterning a material are used. Subtractive techniques pattern via removal of unwanted material while additive techniques make use of temporary complementary molds within which the resulting structure conforms. In either case, the goal is precision microstructural definition. Both approaches use a mask to transfer a pattern to the desired material. For batch processes this step typically occurs via photolithography and may in itself entail several steps. The basic process is to apply a photoresist, a light sensitive material, and use a photomask to selectively expose the photoresist in the desired pattern. A solvent chemically develops the photoresist patterned image at which point it may be used as a mask for further processing.

Subtractive processing is accomplished via chemical etching. Wet etching occurs in the liquid phase and dry etching or gas phase etching may occur in a vapor phase or plasma. A key issue in subtractive patterning is selectivity which is defined as the ratio of etch rate of the material desired to be removed to the masking material or any other material that may be present but desired to be substantially unaffected.

Bulk Micromachining

An omnipresent material in MEMS due to its use as a semiconductor for microelectronics fabrication is single crystal silicon. In terms of material mechanical stability, silicon is also an outstanding material possessing exceptional linear mechanical response and resistance to aging effects prevalent in metals and plastics. Single crystal compound semiconductor materials, such as gallium arsenide, are also of interest due to their use in photonics and microwave circuitry but are not as widely developed as silicon technology. In either case, these substrate materials are immediately attractive for use in MEMS if precision mechanical structures can be constructed from them in a fashion that is non-interfering with their electronic function. A primary microfabrication technology that has been used for most commercial devices in the current market is termed bulk micromachining, which is the process of removing, or etching, substrate material. The important aspect to precision bulk micromachining is etch directionality. Two limiting cases exist and are defined as isotropic, or directionally insensitive, and anisotropic, or directionally dependent up to the point of being unidirectional. All cases may be illustrated with single crystal silicon. (Fig.1) In many instances, photoresist possesses insufficient integrity as an etch mask and an intermediate layer of material is required to be patterned and used as a mask layer. The use of a 1 micron thick layer of silicon dioxide or silicon nitride, for example, commonly serves as this mask layer. Isotropic silicon etching may be carried out in liquid chemistry such as a mixture of hydrofluoric acid and nitric acid whereby the silicon is oxidized by the nitric acid and the hydrofluoric acid converts the resulting silica to a soluble silicon fluoride compound. A nearly directionally independent etch rate results that may be influenced by agitation. (Fig 1a.) Alternatively, a plasma with a gas such as sulfur hexafluoride may be used to realize dry silicon isotropic etching and non-plasma vapor techniques also exist with xenon difluoride vapor.

Many crystalline materials such as quartz and silicon may be etched preferentially along certain crystal orientations. This attribute may be exploited to chemically machine geometry defined by crystal planes. In the case of silicon, the etch rates in the <100> and <110> crystal directions can be several hundred times greater than in the <111> direction. This type of liquid etching may be accomplished with various alkaline chemistry such as potassium hydroxide (KOH) and tetra methyl ammonium hydroxide (TMAH). The results for a [100] oriented silicon substrate are sidewalls angled at 54.7 degrees with respect to the substrate surface representing the [111] crystal planes. (Fig. 1b.) A variety of additional orientations are possible with the restriction that crystalline based anisotropic etching is limited to faceted structures. Nevertheless, anisotropic etching in conjunction with microelectronic processing has yielded a tremendous number of useful micromachined devices including disposable ink-jet print heads, pressure transducers, accelerometers, and microelectrode arrays.

Extending the bulk micromachining tool further, anisotropic silicon plasma etching sequences have been devised to allow arbitrary planar geometry to be nearly perfectly transferred into vertically defined prismatic cuts. (Fig. 1c.) This capability yields great flexibility in defining mechanical elements with the drawback of a substantially increased tool cost over liquid and vapor phase chemical etching. An extension of bulk micromachining to yield further structure flexibility is afforded through wafer-to-wafer bonding techniques. Two or more wafers containing etched geometry are aligned and bonded using direct fusion bonding, anodic bonding (with the assistance of a high voltage), or use of an intermediate adhesive layer. Resulting structures include precisely defined cavities for pressure transducers, microchannels for microfluidic handling and a batch approach to packaging, a particularly troublesome and expensive part of interfacing mechanical behavior with electronics.

Surface Micromachining

An alternative processing approach to bulk microfabrication was driven by the desire to reduce the substrate area required to be devoted to the mechanical component fraction thereby increasing the number of device "die" per wafer. The approach, termed surface micromachining (SMM) realizes mechanical structure by depositing and patterning mechanical material layers in conjunction with sacrificial spacer material layers.(Fig. 2) In contrast to bulk micromachining where a substrate thickness may be between 250 and 750 microns thick, these deposited films, realized through deposition processes such as sputtering, evaporation, and chemical vapor deposition (CVD) have thickness of the order of one micron. A substrate material, such as silicon is used as the basis material for these depositions. The first step in the basic process is to deposit or grow a material to be used as a sacrificial material such as a silicon dioxide layer.(Fig. 2a.) The sacrificial layer is patterned to open anchor regions for the structural layer (Fig. 2b.) that is subsequently deposited (Fig. 2c.). Polysilicon is commonly used for SMM structural layers with others that include silicon nitride, silicon carbide, and diamond-like carbon. The structural layer is patterned (Fig. 2d.) and the sequence of sacrificial and structural depositions and patterning may be then be repeated to enable multilayer geometry. The consequence of this repeated process, however, is an increase in topological variation that ultimately poses problems for patterning. Thus, planarization steps may be inserted to maintain a reasonably flat surface on which to continue to perform microlithography. Ultimately, the last step in SMM is a release etch of the sacrificial material to render the mechanical structure which in the case of this example is a clamped-clamped beam that may be used in a resonant stain gauge for example. (Fig. 2e.)

Micromolding

An additional microfabrication approach particularly well suited for a large variety of materials is based on additive microfabrication. Again a sacrificial material is used, but its function is to serve as a mold to which a deposited material conforms. This scheme enjoys the same benefits that accrue from photolithography based microfabrication. A photoresist is commonly used as the mold form that may be as thick as a typical substrate or several hundred microns. A common mold filling process is electroforming (mold defined electroplating) due to the fairly rapid deposition rates that are possible (on the order of one micron per minute) as well as the many different metals that may be deposited at relatively low temperatures (less than 50 degrees Celsius). The use of thick photoresist enables fabrication of high aspect ratio geometry with an appropriate lithography tool. Various thick photoresists are available including polyimide and epoxy based materials with corresponding long absorption at conventional ultraviolet photolithography wavelengths.

A radically different approach to defining a batch micro-mold has been demonstrated with the use of x-rays generated from a storage ring emitting synchrotron radiation. This type of light source generates very high x-ray flux densities with excellent collimation and with an appropriate x-ray mask enables diffraction free patterning with essentially no variation from a planar microlithographic pattern. The photoresist appropriate for this deep x-ray lithography scheme is poly methyl methacrylate (PMMA), or Plexiglas. An extension of this process, coined the German acronym "LIGA" (LIthographie, Galvanoformung, Abformung) uses deep x-ray lithography defined photoresist to electroform a metal master mold that may be subsequently used as an injection molding plate for further plastic mold fabrication. The resulting mold based process accommodates many materials including elemental metals such as nickel, copper, gold, silver, and aluminum as well as metal alloys such as nickel-phosphorous and soft ferromagnetic materials such as nickel-iron (Permalloy). The molding of more complex materials has been explored with ceramics such as alumina and rare-earth permanent magnet material, as well as glasses and other plastics. Thus, an additive micromolding scheme allows integration of materials commonly used for macroscopic mechanisms.

MEMS Design

The successful use of any microfabrication process is predicated on the ability to control the mechanical properties of the deposited layers and implement these data in appropriate design models. Material properties of deposited materials are not only substantially different from their bulk counterparts, but also vary depending on deposition conditions. Diagnostic structures must therefore be prepared to measure mechanical properties such as yield strength, bulk modulus, and internal strain. Mechanical test microstructures that may be microfabricated with the same process as the actual device of interest have been developed and are used to measure these properties "on chip." The MEMS designer is then faced with the task of identifying appropriate models that identify all physical behavior occurring in the microsystem. This task can be daunting due to the interconnectivity between the many different energy transfer mechanisms but may be reduced by computer aided design (CAD) tools that have been emerging and are tailored for MEMS design problems.

The path to consolidating micromachining sequences with microelectronics and components from other fields such as photonics is termed process integration. Careful process sequence ordering is required to mediate the effects of high temperatures and different chemistry present for disparate and sometimes incompatible microelectronics and micromechanical processes. The solution to these problems has been demonstrated by the many application results.

Example Applications

A highly successfully marketed device that is fabricated with both bulk and surface micromachining is the integrated pressure transducer. One SMM based pressure transducer, for example, can measure absolute pressure ranges as high as 10,000 psia (pounds per square inch absolute) and as low as a few psi. (Fig.3) The process sequence uses SMM techniques to form a polysilicon plate covered cavity that is vacuum-sealed using a reactive deposition and sealing sequence. Plate deflection is monitored with carefully located polysilicon piezoresistors. Applications areas include manifold air pressure sensing in automobile engines, HVAC monitoring, and blood pressure sensing. Similar processing has resulted in the integration of SMM polysilicon proof masses with microelectronic processing yielding single chip force-feedback accelerometers capable of measurement ranges from a few g's to hundreds of g's. Bulk micromachined single crystal silicon versions exist that are able to measure several hundred thousand g's attesting to the robustness of microsensors.

Using SMM technology to implement microactuators has resulted in steerable micromirror arrays with as many as 1024x768 pixels on a chip that have revolutionized digital display technology. One device in this category is constructed from four levels of polysilicon and contains 100 micron square mirrors separated by 1 micron that may be tilted up to 10 degrees.(Fig. 4) Further electrostatic microactuator designs are possible and may be extremely intricate such as a torsional ratcheting actuator fabricated with five polysilicon levels. (Fig. 5) These types of devices are suited for a variety of micropositioning applications. Use of deep x-ray lithography based processing has produced precision metal magnetic microactuators. One example microactuator directly switches a single mode optical fiber in a 1x2 switch configuration.(Fig.6) All integrated devices of this sort point to a prime obstacle in that the packaging required to accommodate the mechanical world interface with a centralized information network is unique and requires novel design and testing approaches to be economically feasible.

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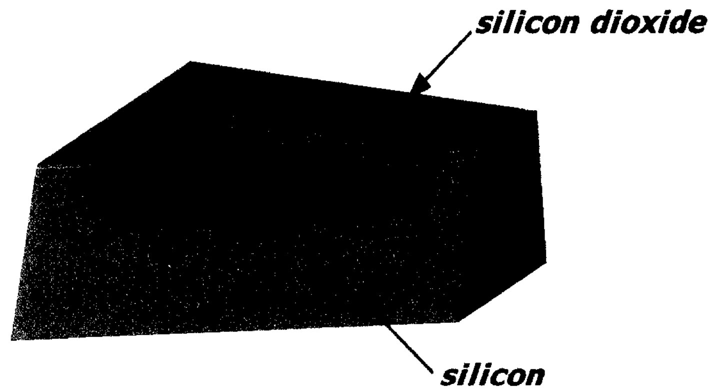
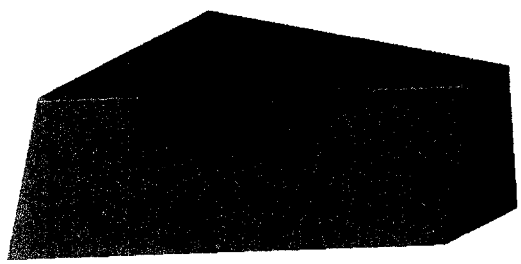
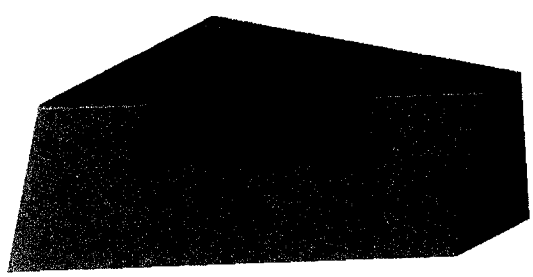
Sandia MEMS: http://mems.sandia.gov



a.) isotropic etching

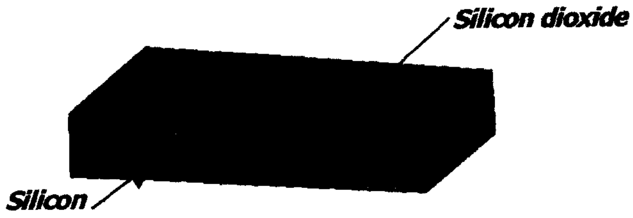


b) anisotropic crystal etching



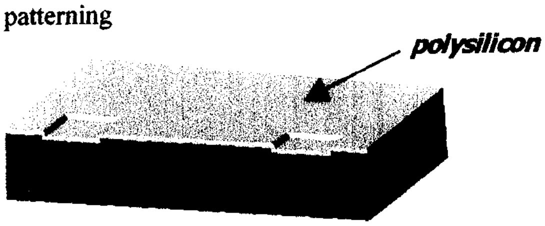
c) vertical anisotropic etching

Fig. 1 Silicon etching processes

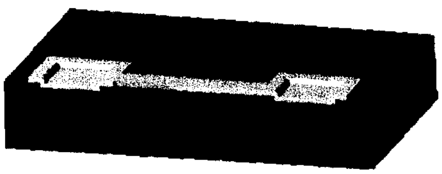


a) Thermal oxidation of silicon

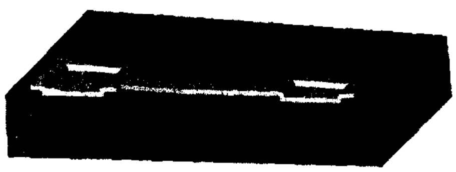
b) Silicon dioxide patterning



c) Polysilicon deposition



d) Polysilicon patterning



e) Release - oxide etching

Fig. 2 Basic surface micromachining (SMM) process

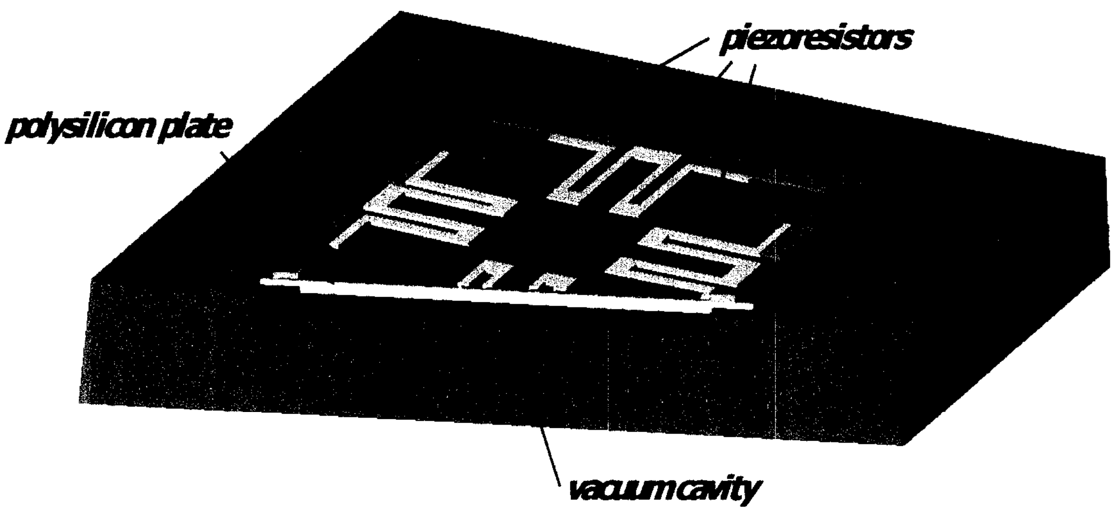


Fig. 3 Surface micromachined pressure transducer.

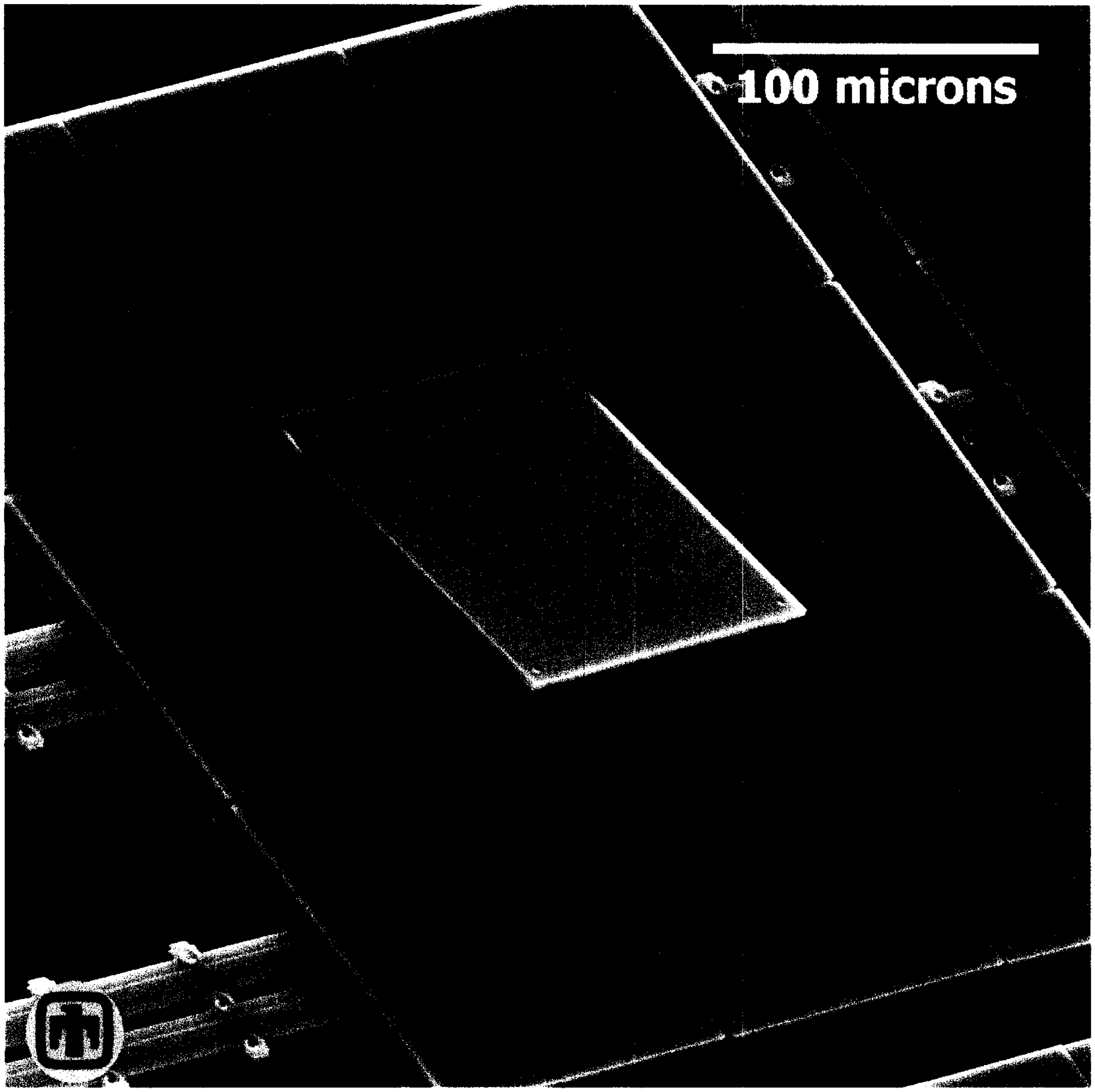
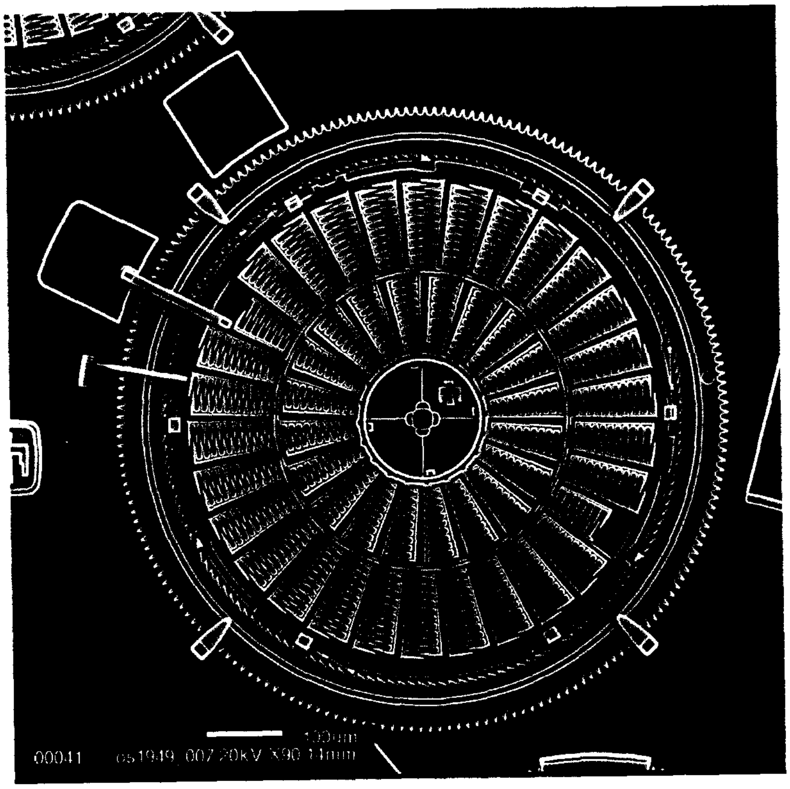
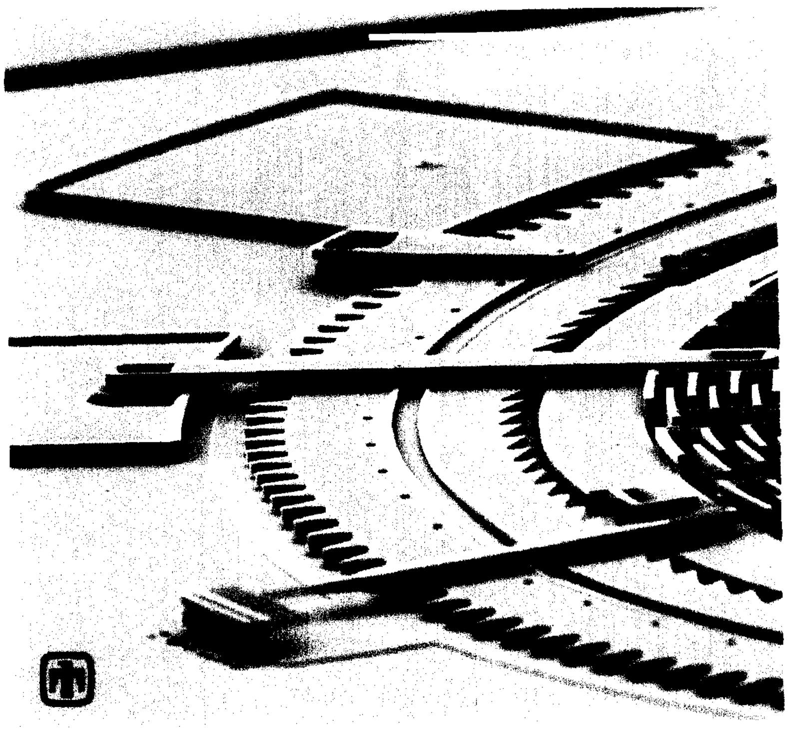


Fig. 4 Surface micromachined movable mirror array.



a.)



b.)

Fig. 5 Overview (a) and close-up (b) of SMM fabricated torsional ratcheting actuator.

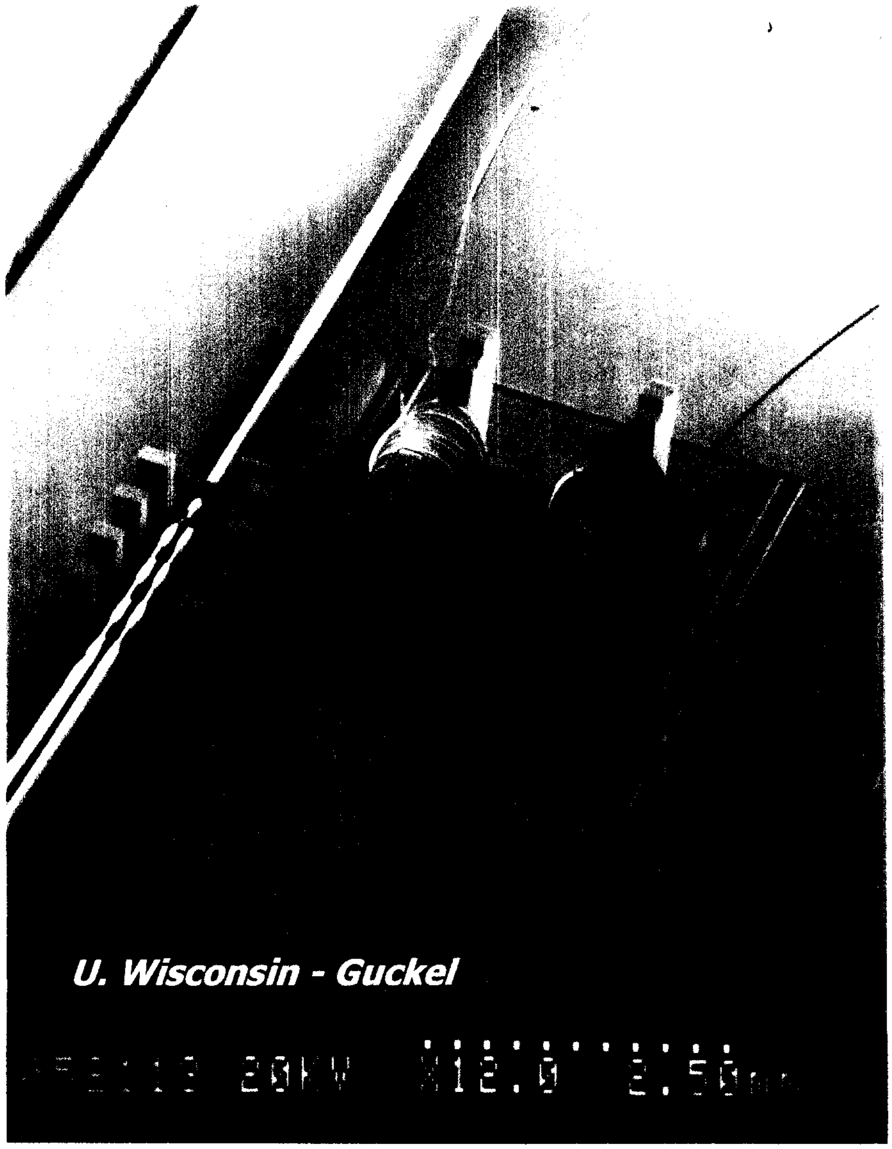


Fig. 6 Deep x-ray lithography fabricated magnetic 1x2 optical fiber switch