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Micromachining for Microelectromechanical Systems

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ABSTRACT

The various micromachining processes required for microengineering and for the successful realisation of microeletromechanical systems on *Si* are presented. The techniques presented include bulk and surface micromachining, *Si* fusion bonding, and the lithography, electroforming and micromoulding (LIGA) process. The paper also includes discussion on the markets, applications and future trends for microenginerated products.

1. INTRODUCTION

The microfabrication technology which has been key to the success of microchips and microelectronics is now revolutionising the mechanical systems. Using this technology, basic mechanical devices, such as motors, gears, bearings and springs have been miniaturised and integrated on *Si* chips. The miniaturisation of mechanical components brings the same benefits to mechanical systems that microfabrication brought to electronics. Micromechanical devices and systems are inherently smaller, lighter and faster than their macroscopic counterparts and are invariably more precise. Since the devices are fabricated using microfabrication techniques, they can be integrated with electronics to develop high performance closed-loop-controlled microelectromechanical systems (MEMSs).

A generalised MEMS consists of mechanical components, sensors, actuators, and electronics, all-integrated in the same environment. The information provided by the sensors would be processed by the electronics whose output is fed to the actuators to manipulate the environment for the desired purpose. The integrated sensors have the maximum number of applications in MEMSs. The market for integrated sensors is growing more than 16 per cent annually and is about $ 1.1 billion in 1997[1]. The application of other systems include: flow valves, electromechanical switches and relays, gyroscopes, ink-jet nozzles, micromanipulators and connectors, as well as optical components, such as lenses, gratings, waveguides, mirrors, sources and detectors[2]. For instance, a chip that contained over two million tiny mirrors, each individually addressed and moved by electrostatic actuation, has been produced by Texas Instruments[3], USA.

Si is the major material used for micromachining and microengineering because it has excellent material properties, including a tensile strength, Young's modulus comparable to steel, a density less than that of *Al* and a low thermal coefficient of expansion[4]. The evolution of MEMS will depend largely on the advancement of microfabrication technology. MEMS fabrication will require advanced technique for high-aspect ratio and three-dimensional lithography, planarisation, backside alignment and bonding

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alignment. The micromachining processes required for microengineering and for the successful realisation of MEMSs on *Si*, some applications of microengineering as well as its future trends and market potentials are presented.

2. MICROMACHINING

Si micromachining—the fashioning of microscopic mechanical parts from or on *Si* substrate—is an extension of integrated circuit (IC) fabrication technology. Naturally, the standard IC fabrication equipment are used for this purpose. Surface micromachining, bulk micromachining as well as substrate bonding and electroforming in conjunction with X–ray lithography form the integral components of *Si* micromachining.

2.1 Bulk Micromachining Technology

Bulk micromachining of *Si* uses wet and dry etching techniques in conjunction with etch-masks and etch-stops to sulpt micromechanical devices from *Si* substrate. There are two key factors that make bulk micromachining of *Si* a viable technology. The first is the availability of isotropic etchants of *Si*, such as ethylenediamine pyrocatecol (EDP), *KOH* and $H_2N\ NH_2$ which preferentially etch single crystal of *Si* with the given crystal planes. The second is the availability of etch-masks and etch-stop techniques which can be used in conjunction with *Si*-anisotropic enchants to selectively prevent regions of *Si* from being etched. As a result, it is possible to fabricate microstructure in a *Si* substrate by appropriately combining etch-masks and etch-stop patterns with anisotropic enchants.

One of the most important characteristics of the etching process is the directionality (or profile) of the etching process. This characteristic is defined in Fig. 1, where the lithographic pattern is in the x-y plane and the direction is normal to this plane. If the etch rate in the x and y directions is equal to that in the z direction, the etch process is said to be 'isotropic' or 'non-directional,' and the shape of the side wall of the etched feature is shown in Fig. 1(a) & (b) for weak and strong agitation levels,

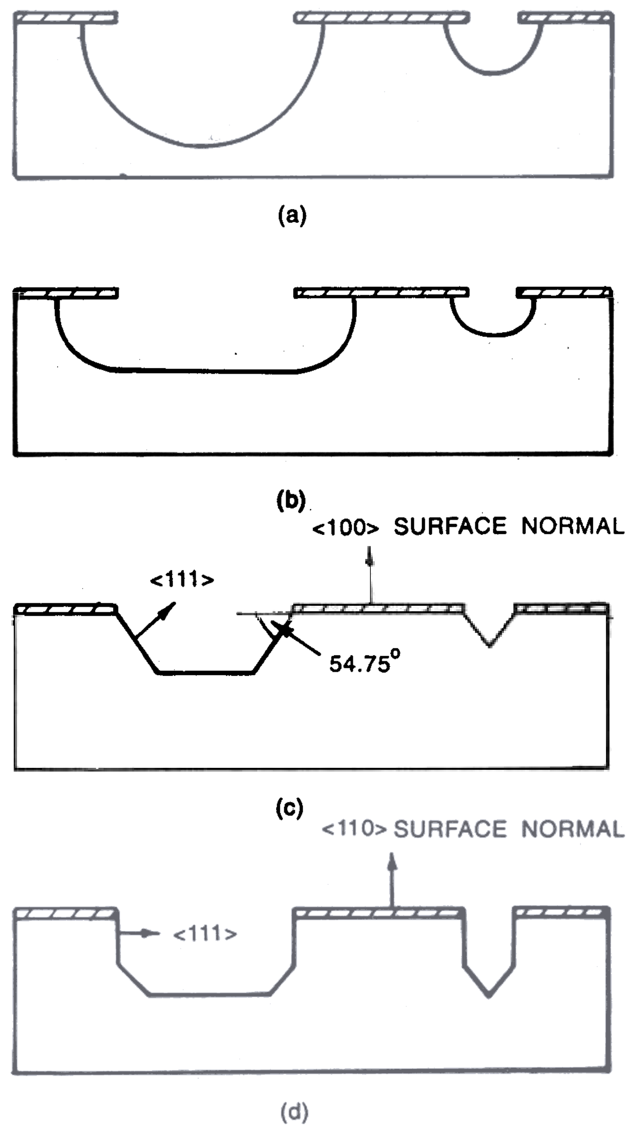


Figure 1. Summary of wet chemically-etched hole geometries commonly used in micromechanical devices: (a) isotropic etching without agitation, (b) isotropic etching with agitation, (c) anisotropic etching on (100) surfaces, (d) anisotropic etching on (110) surfaces.

respectively. The etching of single crystal *Si*, or polycrystalline and amorphous *Si* in HNA (*HF*. HNO_3 and CH_3COOH) etchant systems will result in these profiles. Etch processes which are anisotropic or directional, have etch rates in the z direction that are larger than the lateral (x or y direction) etch rate, as seen in Fig. 1(c). An example of this etch profile is the etching of (100) single crystal of *Si* in KOH/H_2O or EDP/H_2O enchants. The extreme case of directional etching in which the lateral etch rate is zero (referred to here as a vertical profile) is also shown in Fig. 1(d). This profile can be achieved by etching (110) single crystal of *Si* with KOH/H_2O or any *Si* substrate by ion bombardment-assisted plasma etching (reactive ion etching or ion beam milling).

2.1.1 Anisotropic Etching of Silicon

Anisotropic enchants of *Si*, such as EDP, *KOH*, and $H_2N\ NH_2$ are orientation dependent. This means that they etch different crystal orientations with different etch rates. Anisotropic enchants of *Si* etch (100) and (110) crystal planes significantly faster than the (111) crystal planes. Etch rate ratios of about 400:1 for (100) to (111) orientations have been published[5]. The etch rate for (110) surfaces lies between those for (100) and (111) surfaces. SiO_2, Si_3N_4, and some metallic thin films (*Cr*, *Au*, etc.) provide good etch-masks for typical *Si*-anisotropic enchants. These films are used to mask areas of *Si* that are to be protected from etching and to define the initial geometry of the regions to be etched. In terms of etch-stops, two techniques have been widely used in conjunction with *Si*-anisotropic etching. Heavily -boron-doped *Si* (above 7×10^{19} cm^{-3}), referred to as p^+ etch-stop, is effective in practically stopping the etch. Alternatively, the *p-n* junction technique can be used to stop the eptch when one side of a reverse-biased junction-diode is etched away. *Si* etch-stops often form the micromechanical device that is eventually delineated by the etch (Fig. 2).

Figure 2 demonstrates the basic concepts of bulk micromachining by anisotropic etching of a (100) *Si* substrate. For example, for a (100) *Si* substrate, etching proceeds along the (100) planes while it is practically stopped along the (111) planes. Since the (111) planes make a 54.7 angle with the (100) planes, the slanted walls shown in Fig. 2(c) and (d) result. Due to the slanted (111) planes, the size of the etch-mask opening determines the final etch result (e.g., a hole or a cavity). If the etch-mask openings are rectangular (or square) and the sides are aligned to (110) direction (i.e., the direction of the intersection line between (100) and (111) planes), no undercutting of

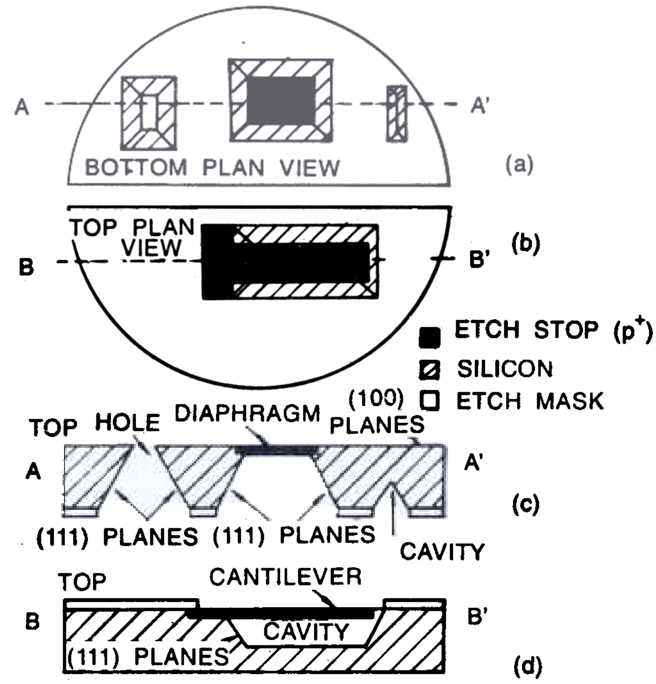


Figure 2. **Schematic drawing of bulk micromachining: (a) bottom plan view of anisotropically etched wafer showing the fabrication of cavities, diaphragms and holes, (b) top plan view of anisotropically etched wafer showing the fabrication of a cantilever beam using etch-stop layers. (c) cross-section, AA' showing the hole, diaphragm and cavity of (a), (d) cross section, BB' showing the cantilever beam of (b).**

the etch-mask feature takes place, assuming that the etch rate of (111) planes is negligible. A bulk micromachined *Si* diaphragm (defined by a p^+ etch-stop) is fabricated by etching from the back side of a wafer (Fig. 2(a) and (c). The width of the bottom surface (or diaphragm) is given by

$$W_b = W_o\ 2l\cot\,(54.75^o)$$

where

W_o is the width of the etch-mask window on the wafer back surface, and l is the etched depth. If (110)-oriented *Si* is etched in $KOH\text{-}H_2O$ etchant, essentially straigh-walled grooves with sides of (111) planes can be formed (Fig. 1(d)).

For convex corners, misalignment with (110) direction, and curved edges in the etch-mask openings, significant under-etching may occur until the etch is limited by (111) planes. In anisotropic etching, the alignment of mask-to-crystal orientation is important. Misalignment will change the etch rate significantly[6]. A-one degree misalignment on (111) direction may increase the etch rate on (near) (111) surface by 300 per cent. Figures 2(b) and (d) show the under-etching characteristics which can be utilised to fabricate suspended microstructure. Figures 2(b) and (d) show a bulk micromachined *Si* cantilever which is fabricated by undercutting the convex corners of the beam geometry (which is defined by an etch-stop) from the front side of a wafer (Fig. 2(b) and (d)). Anisotropic etchants for *Si* are (usually alkaline solutions) used at elevated temperatures. Table 1 lists the most commonly used anisotropic etchants for *Si*.

2.1.2 *Dopant-Dependent Etch-Stop*

The etching process is fundamentally a charge-transfer mechanism, and etch rates depend on dopant-type and concentration. Highly-doped material exhibits higher etch rate because of greater availability of mobile carriers. This occurs in HNA system ($HF.HNO_3$:CH_3COOH or H_2O = 2:3:8)[7], where typical etch rates are 1-3 μm/min at *p* or *n* concentration greater than 10^{18} cm^{-3} and essentially zero at concentration less than 10^{17} cm^{-3}.

On the other hand, anisotropic etchants such as EDP[8,9] and *KOH*[10] exhibit a different preferential etching behaviour. *Si* heavily-doped with *B* (27× 10^{19} cm^{-3}) will reduce the etch rate by about 5 to 100 when-etching with *KOH*; when etching with EDP, the factor is about 250. Figures 3(a) and (b) show the relative *Si* etch rate as a function of *B* concentration for *KOH* and EDP enchants. Etch-stops formed by the p^+ technique are often below 10 μm thick, since the *B* doping is often done by diffusion. Using high diffusion temperatures (1175 °C) and long diffusion times (1520 hr), thick (near 20 μm) p^+ etch-stops may be fabricated. However, this is about the thickness limit for p^+ etch-stops. It is possible to implant a p^+ etch-stop below the *Si* on surface; however, the implant depth is limited to a few microns and a high energy/high current implanter is required. While, it is possible to grow an epitaxial layer on top of a p^+ etch-stop to increase the thickness of the final structure, this is seldom utilised due to the expense of the epitaxial process step.

2.1.3 *Bonding Techniques*

Bonding techniques permit *Si* substrate to be attached to another substrate, usually *Si* or glass, to provide design flexibility, mechanical support,

Table 1. Anisotropic etchants for *Si*

Etchant (Diluent)	Typical composition	Temp (°C)	Etch rate (μm/min)	Anisotropic (100/111) etch rate ratio	Dopant dependence	Masking films (Etch rate of mask)
Ethylenediamine Pyrocatechol (EDP) (water)	750 ml 120 g 100 ml	115	0.75	35	≥ 7 × 10^{19} cm^{-3} *B* reduces etch rate by about 50	SiO_2 (2Å/min) Si_3N_4 (Å/min) *Au, Cr, Ag, Cu, Ta.*
	750 ml 120 mg 240 ml	15	1.25	35: 1		
KOH (H_2O)	44 g 100 ml	85	.4	400:1	≥ 10^{20} cm^{-3} *B* reduces etch rate by about 20	Si_3N_4, SiO_2 (14 Å/min)
KOH ($(CH_3)_2CH$)	50 g 100 ml	50	.0			
H_2N_4 [(H_2O, $CH_3)_2$ *CH*]	100 ml 100 ml	100	2.0		no dependence	SiO_2, *Al*
NaOH (H_2O)	10 g 100 ml	65	0.25-1.0		≥3 × 10^{20} cm^{-3} *B* reduces etch rate by about 10	Si_3N_4, SiO_2 (7 Å/min)

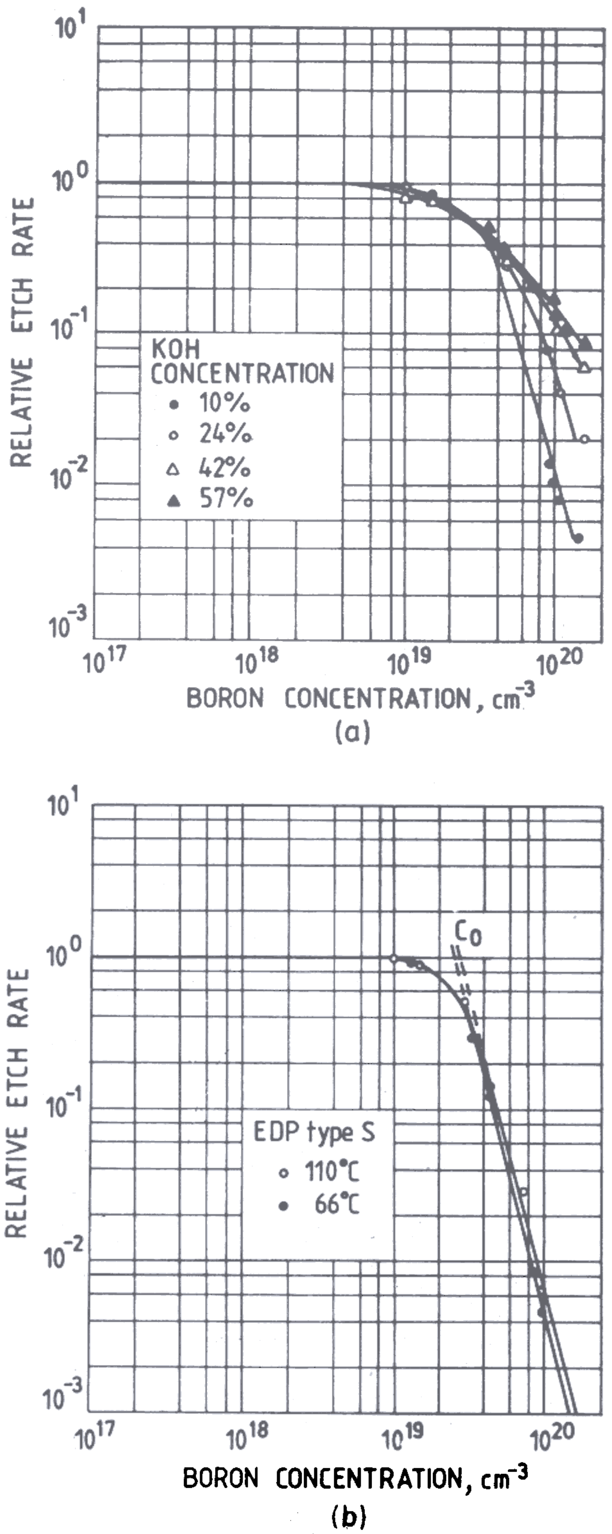


Figure 3. **Relative *Si* etch as a function of *B* dopant concentration for (a) various *KOH* solutions, and (b) EDP.**

electrical connection, and/or thermal sink (or isolation). Wafer-to-wafer bonding is often used in conjunction with bulk micromachining to form sealed or partially sealed cavities between wafers. *Si* fusion boating (SFB), an important recent development, has become the fabrication-technology base for commercially available pressure sensors having applications in industry and medicine[11]. SFB involves cleaning the wafers by standard techniques and then bringing them into face-to-face contact. Van der Walls forces between the surfaces are sufficient to hold the wafers in intimate content. The stack is then annealed at high temperature (near 1000 °C) in an *O* or *N* environment.

Recent study[12] has shown that during *Si* wafer bonding, the initial contact area spreads laterally with a typical speed of 10 mm/s and that this lateral bonding speed increases with decreasing ambient pressure.

Si and glass wafers may be bonded electrostatically by placing them in contact at a lower temperature (below 450 °C) and applying negative voltage (100 to 1000 V) to glass with *Si*. This technique is known as 'anodic bonding'. Since the processing temperature is low, standard metal interconnect materials (*Al*) can be present on one or both wafers. Both anodic and fusion bonding result in permanent bonds.

2.1.4 Bulk Micromachining & Fusion Bonding for Microdevice Fabrication

Si fusion bonding provides new means for constructing three-dimensional structures with excellent thermal stability and mechanical strength. Two such devices are: (i) Microfabricated pump[13] (Fig. 4(a)) made by bonding four *Si* wafers (three of which have been bulk micromachined prior to bonding), and (ii) a microvalve[14] fabricated by fusion bonding of two *Si* wafers (Fig. 4(b)).

The micropump is an example of electric actuation in conjunction with a deformable diaphragm. This micropump employs two check valves which are simply cantilever beam flaps covering micromechanical holes. When the voltage is applied to the counter electrode, the diaphragm deflects upwards, increasing the pump chamber volume and reducing its pressure. The inlet check valve then opens as its cantilever flap bends up due to differential pressure. When the excitation is turned off, the diaphragm returns to its normal position, reducing the pump chamber volume and increasing its pressure. The outlet valve then opens allowing the fluid to exit. In the micropump, the square diaphragm is 4 × 4 mm^2 and 25 μm thick ; the actuator gap is 4μm. Pumping has been demonstrated for actuation frequencies of 1 to 100 Hz. At 25 Hz, a pumping rate of 70 μl/min has been demonstrated when the outlet and inlet pressures are equal. Typical forward-to-reverse flow rate ratio of the check valve is 5000:1.

The microvalve is an example of a bimetallic microactuator fabricated by bulk micromachining and bonding of two *Si* wafers[14]. Heating of the bimetallic diaphragm by passing a current through a heating resistor embedded between the metal and *Si* sandwich causes the metal and *Si* layers to expand. This expansion results in the downward deflection of diaphragm due to mismatch in the thermal expansion coefficients of the metal and *Si*. If heated sufficiently, the diaphragm deflects too much to close-off the valve. The diaphragm in this device is 2.5 mm (in diameter) and 10 μm thick. A 5 μm thick *Al* layer is used as the metal component. Proportional control of flows in the range 0–300 cc/min has been demonstrated with this valve for input pressures from zero to 100 pisi. On/off flow ratios have been greater than 1000. The study has reported that to close the valve at 20 PSIG input, 1.5 W power is required[14].

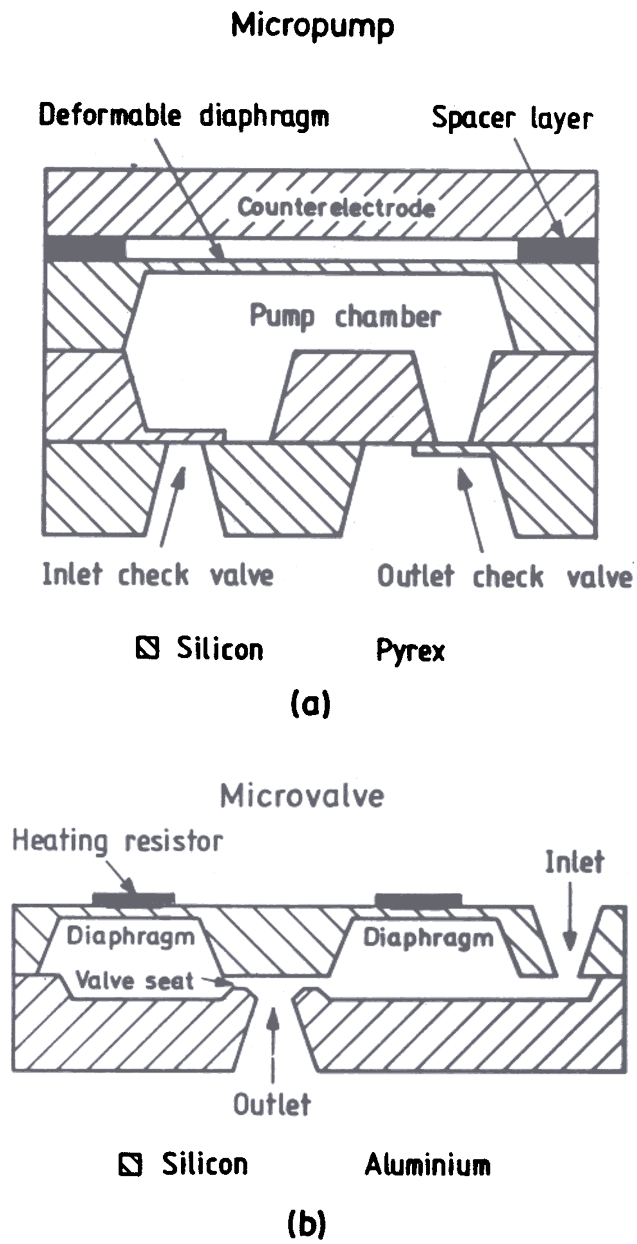


Figure 4. Cross-section of (a) an electrostatic diaphragm micropump, and (b) a bimetallic diaphragm microvalve fabricated by *Si* fusion bonding of four and two *Si* wafers, respectively.

2.2 Surface Micromachining Technology

Surface micromachining relies on encasing the structural parts of the device in layers of a sacrificial material during the fabrication process. The sacrificial material (also called spacer material) is then dissolved in a chemical etchant that does not attack the structural parts. The final stage of dissolving the sacrificial layer is called 'release'. In other words, there are two primary components in a surface micromachining process:

(A) Structural layers—of which the final microstructure are made.

(B) Sacrificial layers—which separate the structural layers and are dissolved in the final stage of device fabrication.

2.2.1 One Sacrificial–One Structural Layer Process

2.2.1.1 Simplest Form

Figure 5 describes one of the simplest forms of surface micromachining in which only two film deposition (one sacrificial and one structural) followed by one patterning step (for the structural layer) are needed for device fabrication. With reference to Fig. 5, the sacrificial layer (SiO_2) is deposited first (Fig. 5(a)), followed by the deposition of the structural layer (polysilicon) (Fig. 5(b)). The structural layer is then patterned (Figs 5(c) and (d)), forming the cantilever and the anchor region. At this point, the release step (etching in *HF* acid when the sacrificial layer is SiO_2) is performed, creating a cantilever suspended over the substrate at a height equal to the thickness of the sacrificial layer. Note that the anchor region is partially underetched during release (Figs 5(e) and (f)).

The key to the success of this process (hereafter referred to as one-mask process) is to select the lateral-dimensions of the parts to be released (cantilever in Fig. 5) such that the sacrificial layer is fully removed from under these parts, while the anchor regions are only partially underetched after release. This is achieved by selecting larger lateral-dimensions for the anchor regions as compared to the areas that must be fully undercut. Since the anchor regions are also undercut during release, control of the release process is important. For example, if the device Figs 5(e) and (f) is released for a sufficient time, the anchor region will be fully undercut, resulting in failure. So, care must be taken in designing the geometry of all devices on the same wafer/die, such that they all release before any of the anchors is substantially undercut.

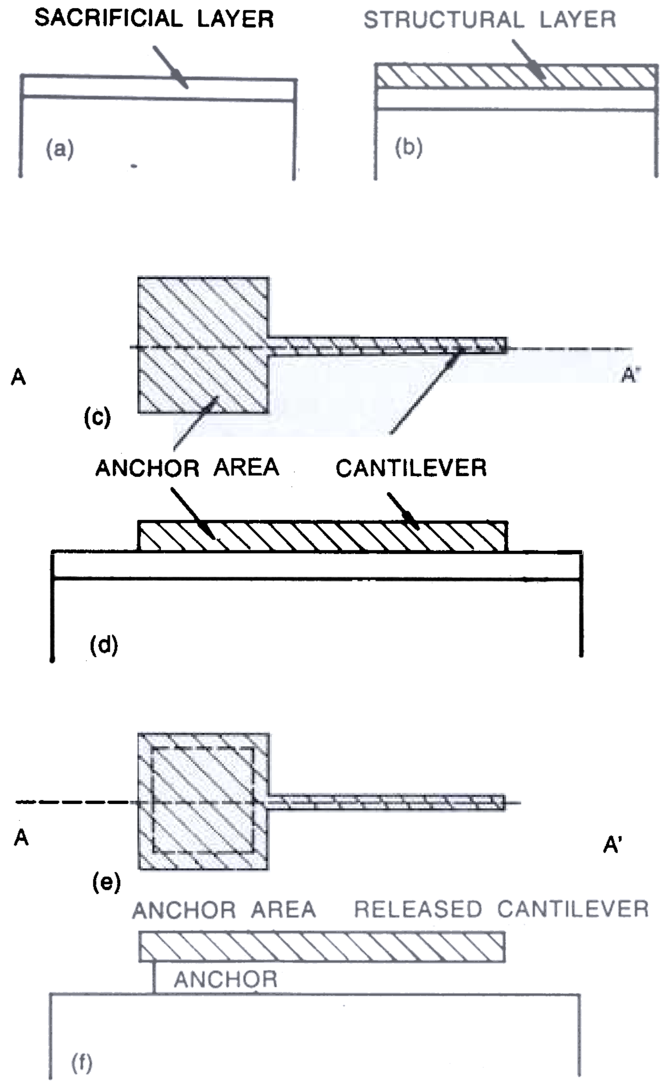


Figure 5. **Schematic demonstration of surface micromachining: (a) cross-sectional view after the sacrificial layer is deposited, (b) cross-sectional view after the structural layer is deposited, (c) top plan view after patterning of the structural layer, (d) cross-section AA' of (c); (e) top plan view after release, and (f) cross-section AA' of (e).**

2.2.1.2 Addition of An Anchor-Definition Step

As shown in Fig. 6, the one-mask process can be augmented with one additional patterning step to provide MEMS designers with added flexibility. This added patterning step, shown in Fig. 6(b), removes the sacrificial layer down to the substrate over selected areas (called anchor regions) prior to the deposition of the structural layer. Over these anchor regions, the structural layer directly contacts the substrate. As a result, it would be possible to anchor the structural layer and the cantilever beam directly to the substrate. This added feature

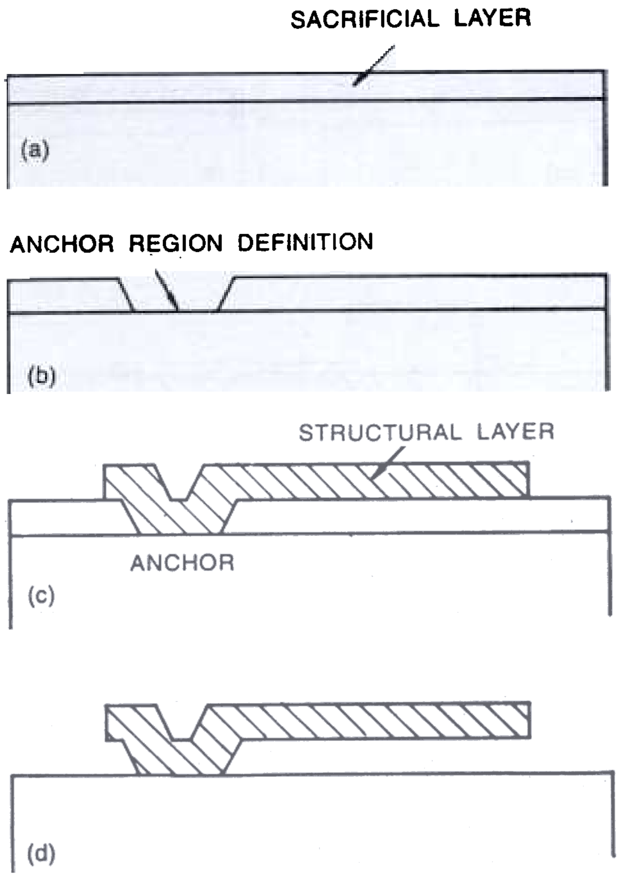


Figure 6. Cross-sectional schematics demonstrating the addition of an anchor definition step: (a) after the sacrificial layer is deposited, (b) after the anchor region is defined, (c) after patterning the structural layer, and (d) after release.

eliminates the need for tight control of the release time because the anchor regions cannot be undercut since the structural layer is directly connected to the substrate.

The anchor size can be selected independent of the release time and the dimensions of the structural parts that need to be undercut. The remaining fabrication process is similar to that described above for one-mask process.

2.2.2 *Process Utilising Two Sacrificial & Two Structural Layers*

The fabrication of mechanisms requires surface micromachining processes that enable the implementation of bearings. Surface micromachining processes incorporating two sacrificial layers and two structural layers are deposited alternatively starting with the first sacrificial layer. This sacrificial layer can be used effectively for the fabrication of bearings and also for the fabrication of mechanisms. These processes are extensions of the simpler single sacrificial/ single structural layer surface micromachining processes.

The fabrication process for a 'polysilicon micromotor' using two sacrificial and three structural layers has demonstrated the versatility of surface micromachining[15]. The micromotor fabrication process requires three polysilicon depositions, two SiO_2 deposition, and one Si_3N_4 deposition, along with six photolithography steps (Fig. 7). These process steps are briefly presented for the purpose of illustrating the versatility of the process.

The first step in this micromotor fabrication process is to establish substrate isolation consisting of a sandwich of 1 µm Si-rich Si_3N_4 over 1 µm SiO_2. Next, a 0.35 µm thick polysilicon layer heavily doped with P is deposited and patterned to form the shield. The first sacrificial SiO_2 layer, 2-3 µm thick, is deposited and the bushing-mold openings are defined. The bushing molds are time-etched to a depth of 1.8 µm (Fig. 7(a)). The 0.5 µm of SiO_2 remaining in the bushing-mold trenches produces a corresponding rotor-stator vertical offset in the final device. SiO_2 layer is then patterned and etched to open the stator anchors, exposing the nitride layer below. A 2.5 µm thick polysilicon layer, heavily doped with P is then deposited and patterned to form the rotor and stator (Fig. 7(b)).

The next deposition is a second sacrificial layer that provides 0.3 µm of SiO_2 on the rotor and stator sidewalls, and nearly 0.5 µm on the top surface (Fig. 7(c). The 0.3 µm coverage on the side walls corresponds to the bearing clearance in the micromotor. Next, the bearing anchor is defined and etched in the SiO_2 sacrificial layers, exposing the electric shield below. A 1 µm thick of polysilicon layer is deposited, heavily doped with P, and patterned to form the bearing (Fig. 7(d)). At this point, the completed device is immersed in HF to dissolve the sacrificial SiO_2 and release the rotor (Fig. 7(e)).

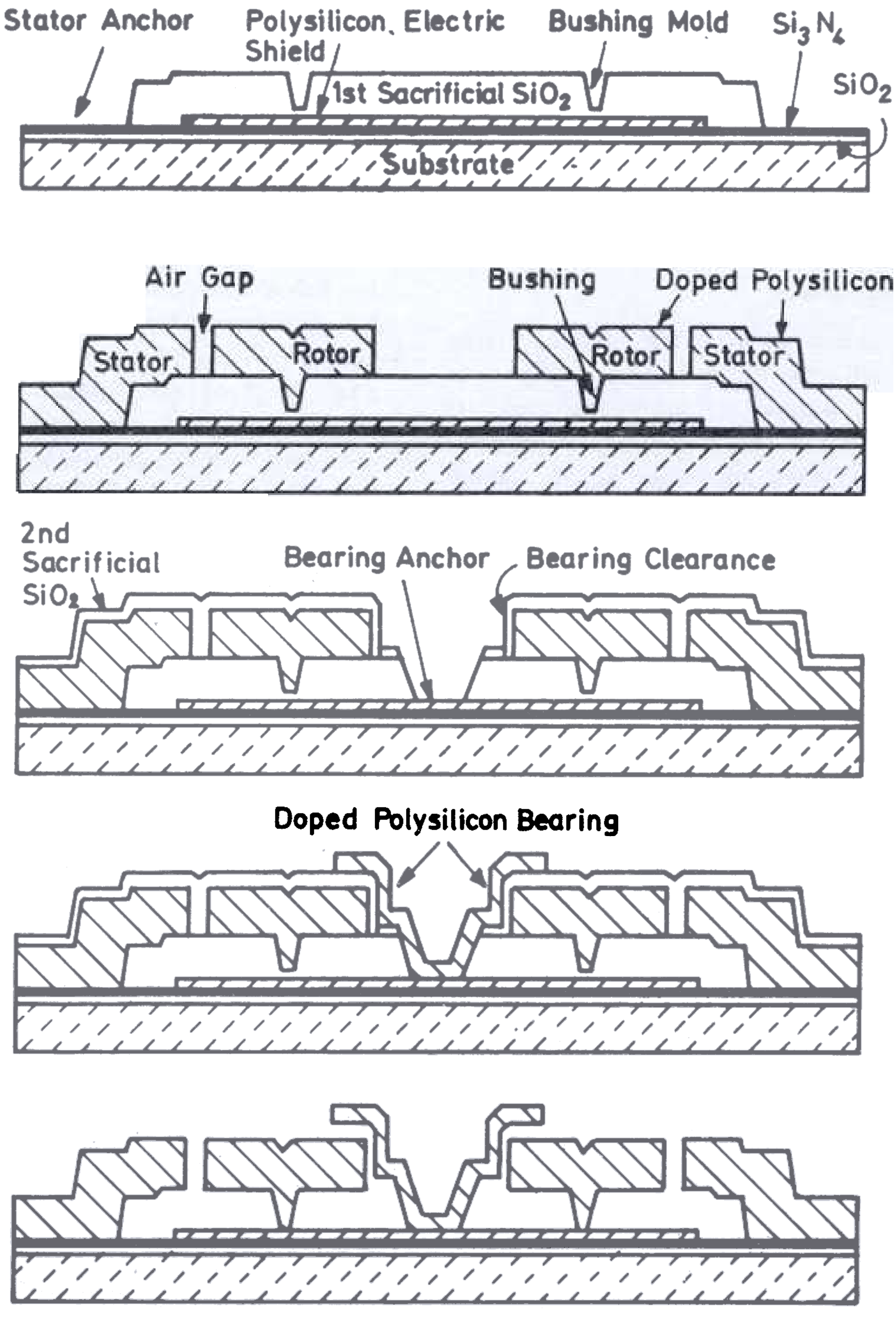


Figure 7. Schematic drawing demonstrating surface micromachining of a micrometer: (a) after the bushing mold and stator anchor are patterned, (b) after the rotor and stator are patterned, (c) after the bearing anchor is patterned, (d) after the bearning is patterned, and (e) completed device.

2.3 Merits & Limitations of Micromachining Process

It is clear that surface micromachining uses successive deposition and patterning of structural and sacrificial materials on a substrate to fabricate micromechanical components. In contrast to bulk micromachining and bonding, the bulk of the *Si* wafer itself is not etched in surface micromachining. In other words, there are no holes through the wafer and no cavities on its back side. Today's automated IC fabrication equipment often uses vacuum pick-ups for transporting and handling wafers. Retooling would be required to process wafers with holes and cavities. Automated resist spinners would also run into problems with wafers incorporating micromachined holes or large cavities on the surface.

Wafers undergoing a surface micromachining process may utilise an IC fabrication facility in 'as is' condition, without disturbing existing IC fabrication processes. This is of critical importance if MEMS is to take advantage of the capital investment in the IC technology. Considering that the future of MEMS technology is based on the integration of electronics with micromechanical devices (for signal processing, signal conditioning, and computation). With the use of surface micromachining, standard approaches to integration of electrical and mechanical devices can be developed. For example, wafers can be processed to fabricate the electronics first, followed by the fabrication of the mechanical components in a compatible process.

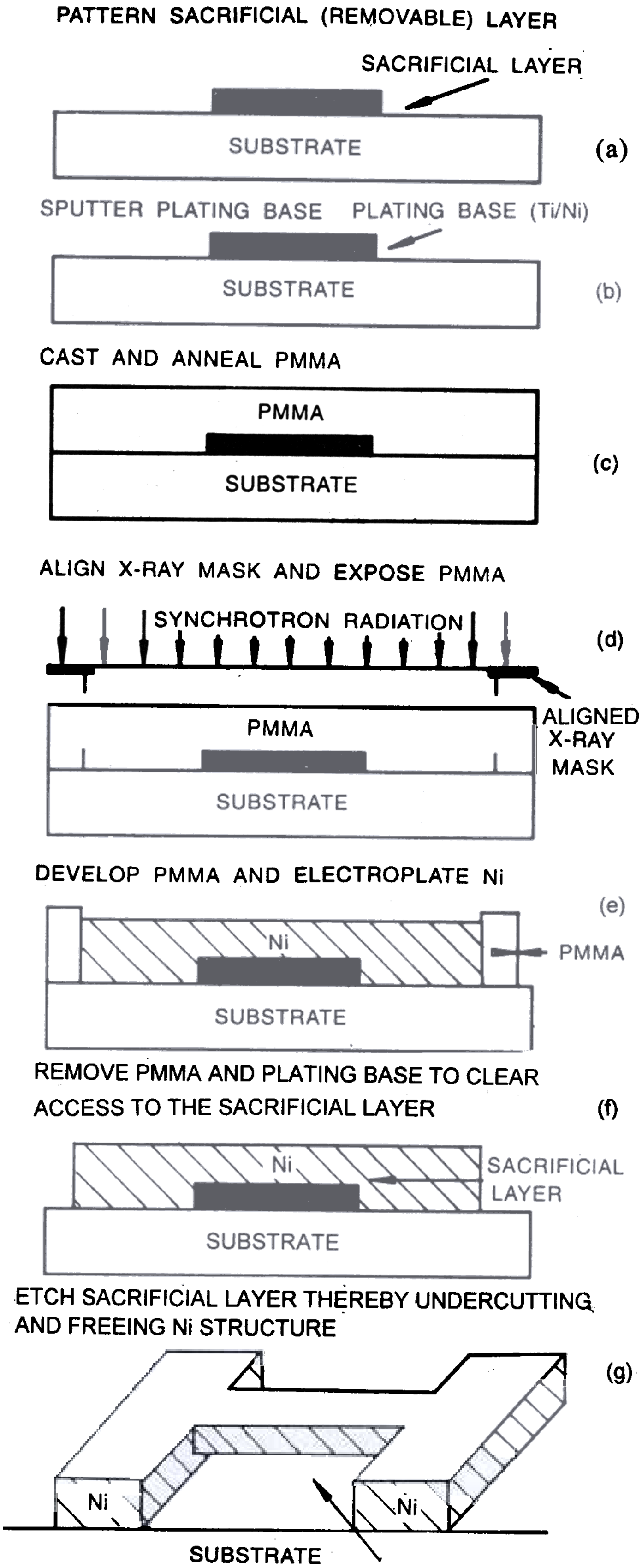
The fabrication of layered structure by surface micromachining provides significant flexibility in the design of micromechanical devices. For example, the fabrication of a rotor on a centre bearing, or in general mechanisms, is not possible in bulk micromachining and would be much more complicated by bonding. Extension of the basic processes described above to incorporate additional structural and sacrificial layers will provide even more flexibility in the design of micromechanical systems.

The above discussion is general, however, it is not intended to prove that surface micromachining is the most superior form of micromachining. Evaluation and selection of a fabrication process is only realistic in conjunction with applications and many issues, including performance and cost must be considered. Indeed, surface micromachining has an important limitation. It is inherently a planar fabrication process, and is therefore limiting for mechanical design.

2.4 LIGA Process

LIGA process is a technique for fabrication of three-dimensional micromechanical structures with high aspect ratios (height/width) having height of several hundred micrometers. LIGA, an acronym for, lithography, electroforming, and micromolding was first demonstrated in Germany[16]. The process combines X-ray lithography with thick-resist layers and electroplated metal layers to form three-dimensional structures. It can also be combined with sacrificial layers[17,18], in which case it is called sacrificial LIGA (SLIGA)[18]. The basic steps in SLIGA are presented in Fig. 8.

Processing starts with the deposition and patterning of the sacrificial layer. Requirements for the sacrificial layer include good adhesion to the substrate, good coverage of the sacrificial layer by a plating base, resistance to X-ray damage, and ease of removal during etching. Because the LIGA process involves temperature not greater than 200 °C, polymide films meet all of the sacrificial layer requirements. Following deposition, the polymide is patterned and then covered by a plating base that will be used later as a seed for electroplating of core material. The plating base (seed) shown in Fig. 8 consists of 150 Å of *Ti* (adhesive metal) and 150 Å of *Ni*. Both of these films are sputtered. The next step involves the application of a thick photoresist layer (the photoresist can be as thick as hundred micrometers, depending on the type of structure desired). The photoresist should have high selectivity between the exposed and unexposed areas, which, in turn, should produce vertical walls. This requirement can be satisfied with polymethylmethacrylate (PMMA) combined with aqueous developing system. After the application of PMMA, it is exposed to X-ray photons from a synchrotron. The synchrotron generates high energy X-ray collimated photons needed to achieve complete exposure of the thick photoresist. The X-ray mask is also specially designed and constructed of a basic material



← **Figure 8. SLIGA process**

(membrane) that is X-ray transparent. Si_3N_4 or tensile polysilicon films can be used for this purpose. In addition, a patterned layer of Au on the membrane serves as an absorber. The combination of membrane and absorber allows locally-exposed patterns that produce vertical photoresist walls after the development of PMMA.

Development of PMMA is followed by electroplating of a core material (Ni) and subsequent removal of PMMA, and the plating base in selective areas. The final step in SLIGA is etching of the sacrificial layer thus producing a suspended structure (bridge in Fig. 8).

Further evolution of LIGA process has led to polyamide-based processing[19], which does not require the use of synchrotron. This simplification of the technology will play an important role in future applications.

It should be emphasised that the LIGA process greatly expands micromachining capabilities, making possible vertical cantilevers, coils, microoptical devices, microconnectors, actuators, and so forth. A review of LIGA process and its potential application for fabricating microsensors is given in the paper[20].

3. FUTURE TRENDS FOR MICRO-ENGINEERED PRODUCTS

With the exception of bulk micromachining and a few microsensors, MEMS technologies are still at the developing stage. A recent survey[21] has revealed that the US is currently, the largest single market and supplier of Si microengineered devices with more than 50 per cent of the world market, Europe and the Far East account for about 20 per cent each. The industrial, aerospace/defence, automotive and medical are the four market sectors for these devices. The automotive sector is currently (and predicted to remain) the largest single market for Si-based sensors. The details of the applications of microengineered product used in different industrial sectors are given in Table 2.

Table 2. Industrial sectors for microengineering devices and MEMS

Industry sector	Market area	
Automotive	MAP sensors account for 90 % Engine management Air mass flow sensors Anti-lock brakes Tyre and brake condition sensors	Active suspension Air bags Knock sensors
Defence & aerospace	Engine management Attitude and barometric accelerometers	Smart weapons Closed loop
Industrial	Process control Factory automation Pressure sensors Condition monitoring (vibration sensors)	HVAC Robotic-based sensors Tactile sensors
Medical	Specialised tools for microsurgery Neural interfaces Accelerometers for pace makers Microcutting tools *In vivo* electrochemical catheter sensors, O_2, CO_2, pH	
Other markets	Optical technology—fibre comms, data storage Research Mechanical Eng. Consumer—white goods, musical instrument, sports goods Office equipment and communication	

Analysis of market potential for microengineered devices is exceedingly difficult, because in most of the cases, the devices do not yet exist, and have not even been imagined by potential users. But, the applications for microengineering can be split into four areas (Table 3).

3.1 Sensors

So far, microengineering as a manufacturing technology has been applied successfully to sensors. The pay-off in terms of miniaturisation, improved performance, and reduced production-cost have transformed the market, particularly for pressure sensors. Microengineered versions of a variety of other sensors have also been built. These are either at various stages in the process of becoming commercially available, or are already so. Some sensor applications can take advantage of the device-to-device and batch-to-batch repeatability of wafer scale processing to remove expensive calibration procedures.

3.2 Actuators

The first application that was identified for microengineering was sensors. The notion of using these techniques for actuators has been developed, and therefore, the explosion of application in this area is only the beginning. An example of this, is the ink-jet printer, where mircoengineering has been applied to the mass production of highly accurate ink-transfer mechanisms. The areas of application are expected to include the healthcare industry with the use of implantable micropumps and valves for drug delivery and microtools, for surgery.

3.3 Microstructure

There is a diverse range of mechanical objects that fall neither into the sensor nor the actuator category. They are the best described as microstructure. These items are often no more than arrays of simple shapes, such as grooves, holes, nozzles and grids. Its applications are being exploited, since in many instances, the processes involved are very simple, and the accuracy, speed and repeatability of manufacture are phenomenal compared to ordinary machining. Importantly, design changes are usually simple and cheap to implement in many instances, requiring no more than a new photolithographic mask.

Table 3. Applications for microengineered devices

Area	Details of application	
Microengineered sensors	Pressure sensors Microphones Accelorometers Flow meters Gas sensors-various Ion sensors	Microcalorimeters Biosensors-various Microelectrode arrays Chemical sensors-various Radiation detectors-various Moisture sensors
Microengineered actuators	Micropumps Pressure pulse ink-jet actuators Micro-tweezers High frequency scanning mirrors Optical communication elements	Micro-active catheters Relays Thermal ink-jets/heads Micromotors Fluidic amplifiers
Microstructures	Microelectronic component cooling Microholders for biomolecules Blood capillary simulators Microtips-scanning force microscopy Optical elements Fluid isotope separaters *Si* vacuum electronic valves Microcollimators Microconnectors (electrical and optical) Microsieves	
Microsystems	The most exciting future for microengineering lies in the combination of microsensors, microactuators, microstructures and electronics to form complete microsystems.	

3.4 Microsystems

The most exciting future for microengineering lies in the combination of microsensors, microactuators, microstructures and electronics to form complete microsystems.

4. WORLD MARKET FOR MICROMACHINE & MICROSTRUCTURE

World-wide revenue for micromachines and microstructures (including pressure sensors, accelerometers, and flow sensors) will grow at a 19.1 per cent compound annual rate, from \$ 871 million in 1991, to about \$ 2.97 billion in 1998. Revenues for 1993 are estimated at about \$ 1.16 billion. Global revenues for *Si* micromachined microstructures (excluding sensors) are forecast to accelerate at 29 per cent p.a; \$ 19.3 million in 1991; \$29.4 million in 1993; \$116.2 million[21] in 1998. The revenue split from various industries is given in Table 4.

Table 4. Revenue split for micromachines and microstructures from various industries

	Actual estimate (%)		Projected (%)
	1991	1993	1998
Automotive	33.7	38.8	54.2
Medical	22.4	23.2	24.9
Industrial	1.5	1.3	0.7
Aerospace & defence	11.9	10.3	5.3
Process control	25.5	22.	12.5
Energy/environment	1.7	1.5	1.0
Education/research	0.8	0.7	0.4
Other	2.6	2.1	0.9

5. CONCLUSION

Micromachining and MEMS technology promises to bring the benefits of microfabrication to mechanical components, thereby allowing sophisticated systems to be miniaturised and fabricated at low cost. Although aerospace, process and automotive industries are already making use of micromechanical parts, such as pressure sensors and accelerometers, microfabrication techniques suited for more complex, three-dimensional structures will be required for continued growth of the MEMS. Thus, 'Microrobots performing surgery might still be a long time away, but even now microengineering is carving out a real market—which is set to boom'.

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