

# INTRODUCTION

Imagine a machine so small that it is imperceptible to the human eye. Imagine working machines with gears no bigger than a grain of pollen. Imagine these machines being batch fabricated tens of thousands at a time, at a cost of only a few pennies each. Imagine a realm where the world of design is turned upside down, and the seemingly impossible suddenly becomes easy—a place where gravity and inertia are no longer important, but the effects of atomic forces and surface science dominate. Welcome to the microdomain, a world now occupied by an explosive new technology known as MEMS.

## 1.1 What is MEMS TECHNOLOGY?

Micro-Electro-Mechanical Systems (MEMS) is the integration of mechanical elements, sensors, actuators, and electronics on a common silicon substrate through the utilization of microfabrication technology (Fig. 1). MEMS is truly an enabling technology allowing the development of smart products by augmenting the computational ability of microelectronics with the perception and control capabilities of microsensors and microactuators. MEMS is also an extremely diverse and fertile technology, both in the applications it is expected to be used, as well as in how the devices are designed and manufactured. MEMS technology makes possible the integration of microelectronics with active perception and control functions, thereby, greatly expanding the design and application space.

Microelectronic integrated circuits (ICs) can be thought of as the “brains” of systems and MEMS augments this decision-making capability with “eyes” and “arms”, to allow microsystems to sense and control the environment. In its most basic form, the sensors gather information from the environment through measuring mechanical, thermal, biological, chemical, optical, and magnetic phenomena; the electronics process the information derived from the sensors and through some decision making capability direct the actuators to respond by moving, positioning, regulating, pumping, and filtering, thereby, controlling the environment for some desired outcome or purpose (Fig. 2).

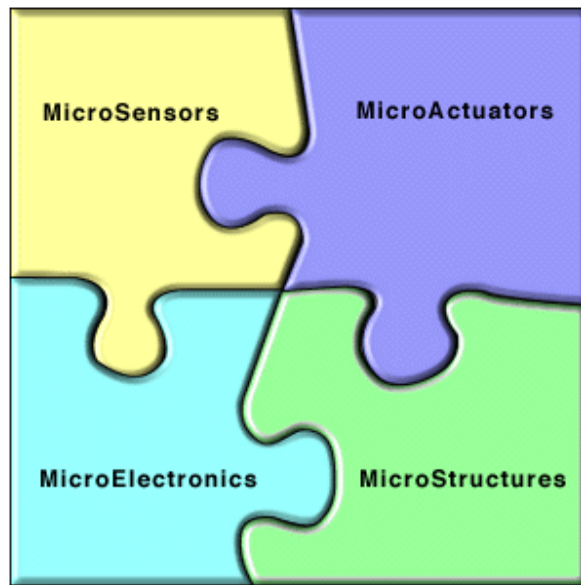


Figure 1 Components of MEMS

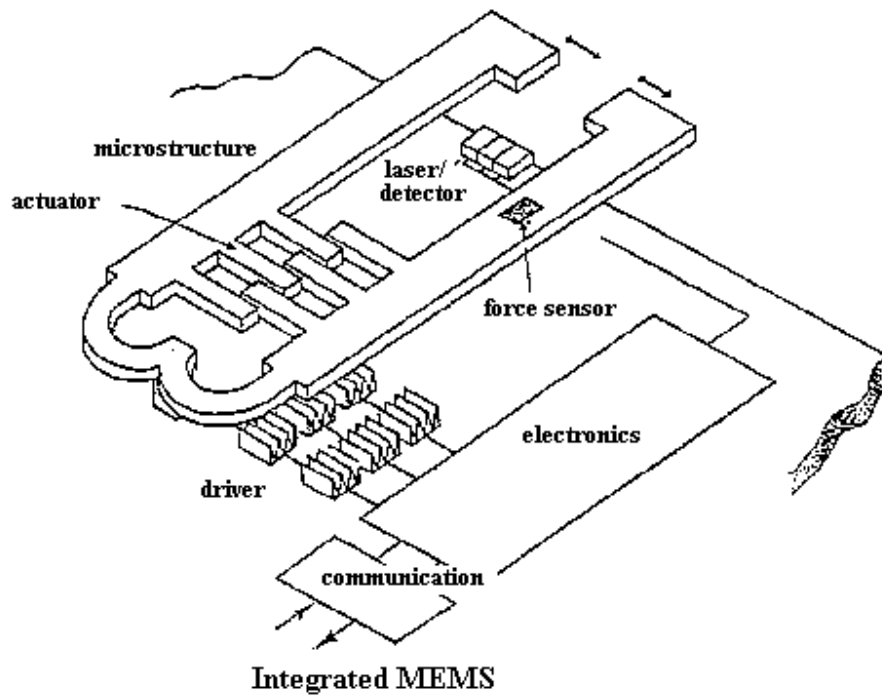
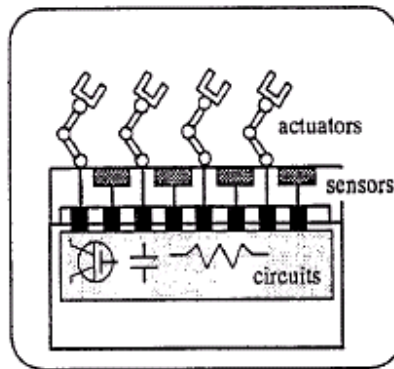


Figure 2 An example of smart module component of sensors, actuators and circuits.

Usually sensors and actuators must be located on the surface of microsystem because they have physical interaction with the environment. On the contrary, electronics must be protected in the system. This requirement leads to the concept of multilayered construction of microsystems as schematically shown in Fig. 3.



**Figure 3 Multilayer integration process of sensors, actuators and circuits.**

MEMS fall under the field of Smart Structures. Smart structures are those which incorporate actuators and sensors that are highly integrated into the structure and have structural functionality, as well as highly integrated control logic, signal conditioning and power amplification electronics.

The term MEMS was coined around 1987, when a series of three workshops on microdynamics and MEMS was held in July 1987 at Salt Lake City, Utah; in November 1987 at Hyannis, Massachusetts; and in January 1988 at Princeton, New Jersey, ushering in a new era of microdevices. The field of solid-state transducers has traditionally been application driven and technology limited, and has emerged as an interdisciplinary field which involves many areas of science and engineering. MEMS is expected to follow a similar trend.

Fig. 4 schematically represents a room that is equipped with microsystems to maintain amenity. Illumination, temperature, humidity, air flow and sounds are controlled by microsystems embedded in the walls. A microsystem for this purpose detects conditions in the room using its temperature sensor, humidity sensor, air-flow sensor, infrared sensor and

microphone. Electronic circuits in the system determine the appropriate response based on sensor signals and information from neighboring microsystems. The effectors of the system, such as a heater, a ventilator, a lamp and a speaker, which all are miniaturized and arrayed, can adjust the conditions to achieve maximum amenity. The total system will probably have adaptive capability to trim its performance in accordance with the owner's preference and habits.

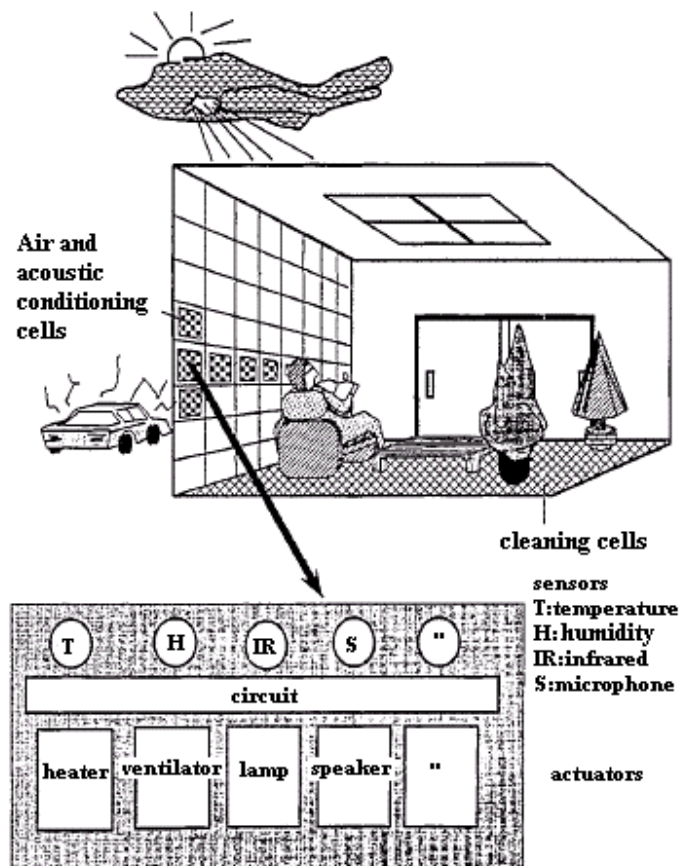


Figure 4 Schematic representation of a room in which smart cells are integrated on the walls and floor to maintain maximum amenity.

## 1.2 Advantages of MEMS

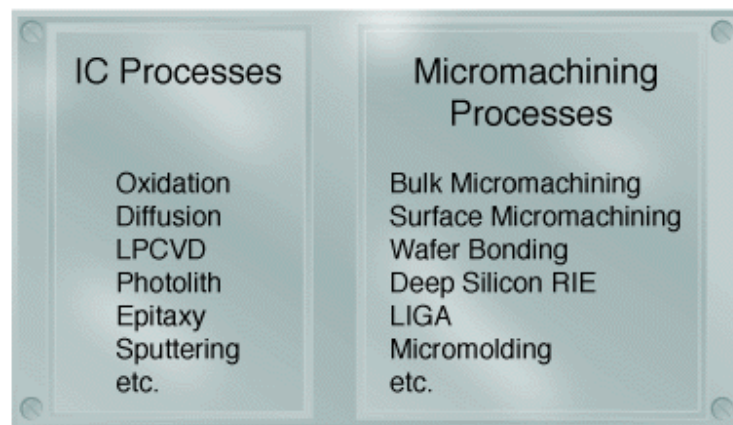
MEMS is not about making things out of silicon, even though silicon possesses excellent materials properties making it an attractive choice for many high-performance

mechanical applications. Instead, MEMS is a manufacturing technology; a new way of making complex electromechanical systems using batch fabrication techniques similar to the way integrated circuits are made and making these electromechanical elements along with electronics. This new manufacturing technology has several distinct advantages. First, MEMS is an extremely diverse technology that potentially could significantly impact every category of commercial and military products. Already, MEMS is used for everything ranging from in-dwelling blood pressure monitoring to active suspension systems for automobiles. The nature of MEMS technology and its diversity of useful applications make it potentially a far more pervasive technology than even integrated circuit microchips. Second, MEMS blurs the distinction between complex mechanical systems and integrated circuit electronics. MEMS technology allows these complex electromechanical systems to be manufactured using batch fabrication techniques allowing the cost and reliability of the sensors and actuators to be put into parity with that of integrated circuits. Interestingly, even though the performance of MEMS devices and systems is expected to be superior to macroscale components and systems, the price is predicted to be much lower.

**MICROMACHINING PROCESSES**

Micromechanical devices and systems are inherently smaller, lighter, faster, and usually more precise than their macroscopic counterparts. However, development of micromechanical systems requires appropriate fabrication technologies which enable the definition of small geometries; precise dimensional control; design flexibility; interfacing with control electronics; repeatability, reliability, and high yield; and low-cost per device.

MEMS devices are manufactured using batch fabrication techniques, similar to ICs, unprecedented levels of functionality, reliability, and sophistication can be placed on a small silicon chip at a relatively low cost. There are few MEMS Processes as follows



**Figure 5 MEMS Processes**

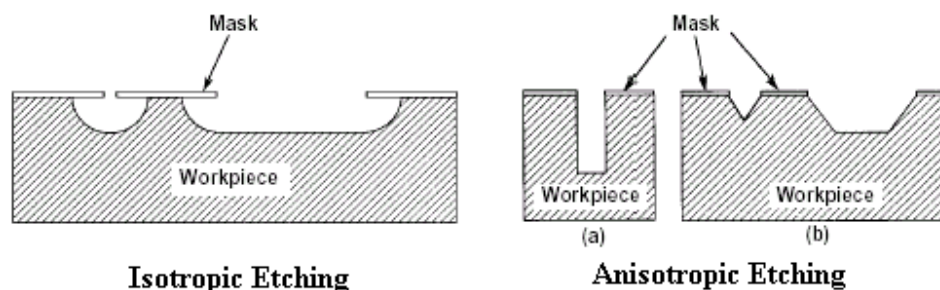
Microfabrication has so far been the primary enabling technology for the development of MEMS. Microfabrication provides a powerful tool for batch processing and miniaturization of mechanical systems into a dimensional domain not accessible by conventional (machining) techniques. Furthermore, microfabrication provides an opportunity for integration of mechanical systems with electronics to develop high-performance closed-loop-controlled MEMS. Here is brief discussion about some of these micromachining processes.

## 2.1 Bulk Micromachining

Bulk micromachining is a micromachining process, by removing a part of substrate itself. Bulk Micromachining makes micromechanical devices by etching deeply into the silicon wafer or other substrates. There are several ways to etch the silicon wafer. In general, there are two classes of etching processes, wet etching and dry etching. In the following, there is brief discussion on the most popular technologies for wet and dry etching.

### 2.1.1 Wet etching

This is the simplest etching technology. All it requires is a container with a liquid solution that will dissolve the material in question. Unfortunately, there are complications since usually a mask is desired to selectively etch the material. One must find a mask that will not dissolve or at least etches much slower than the material to be patterned. Secondly, some single crystal materials, such as silicon, exhibit anisotropic etching in certain chemicals. Anisotropic etching uses etchants like KOH that etch different crystallographic directions at different rates (Fig.6). Certain crystallographic planes etch extremely slowly, and are called stop planes. Anisotropic etching usually produces Vee grooves, pyramids, and channels into the surface of the silicon wafer. Isotropic etching etches all directions in the silicon wafer with nearly the same rate, and produces rounded depressions on the surface of the wafer that usually resemble hemispheres and cylinders.



**Figure 6 Difference between isotropic and anisotropic etching**

### 2.1.2 Dry Etching

The dry etching technology can split in three separate classes called reactive ion etching (RIE), sputter etching, and vapor phase etching.

- In RIE, the substrate is placed inside a reactor in which several gases are introduced. Plasma is struck in the gas mixture using an RF power source, breaking the gas molecules into ions. The ions are accelerated towards, and react at, the surface of the material being etched, forming another gaseous material (Fig. 7).
- Sputter etching is essentially RIE without reactive ions. The systems used are very similar in principle to sputtering deposition systems. The big difference is that substrate is now subjected to the ion bombardment instead of the material target used in sputter deposition.
- Vapor phase etching is another dry etching method, which can be done with simpler equipment than what RIE requires. In this process the wafer to be etched is placed inside a chamber, in which one or more gases are introduced. The material to be etched is dissolved at the surface in a chemical reaction with the gas molecules. The two most common vapor phase etching technologies are silicon dioxide etching using hydrogen fluoride (HF) and silicon etching using xenon difluoride (XeF<sub>2</sub>), both of which are isotropic in nature.

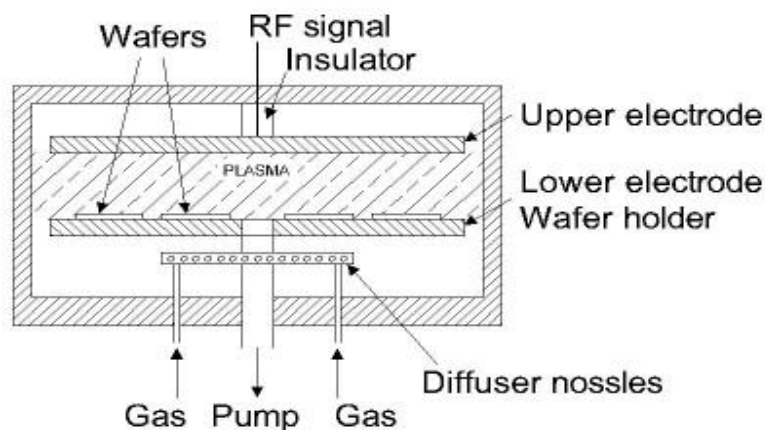
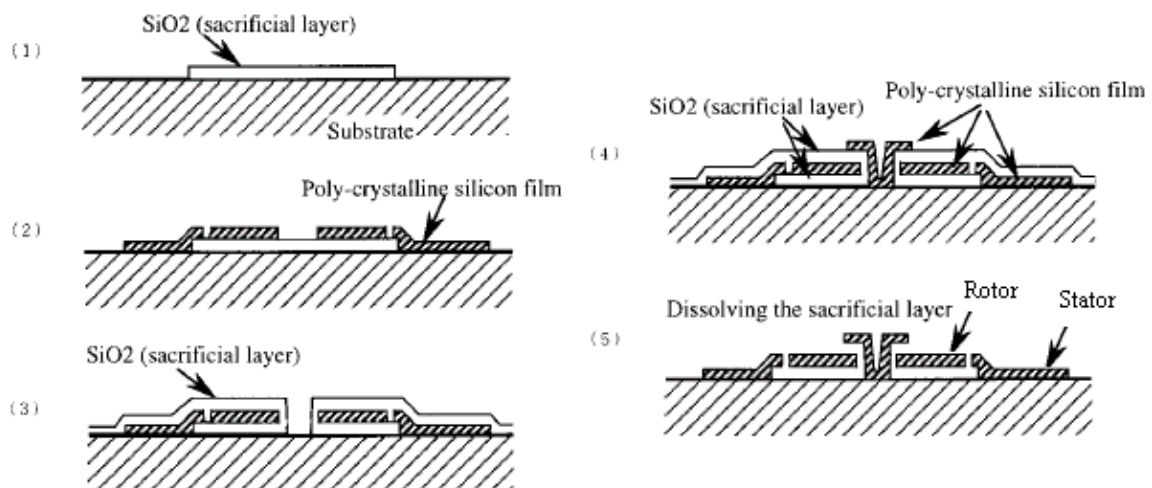


Figure 7 Typical parallel-plate reactive ion etching system

## 2.2 Surface Micromachining

The surface micromachining technology makes thin micromechanical devices on the surface of a silicon wafer. Large numbers of devices can be inexpensively made, and this technology integrates well with electronics. On the surface of a silicon wafer, thin layers of structural and sacrificial material are deposited and patterned. At the end of the processing the sacrificial material is removed, and completely assembled micro mechanical devices remain.

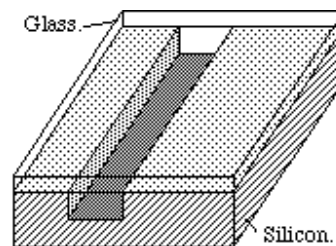
Fig. 8 shows the fabrication process of an electrostatic micromotor. The structural material poly-crystalline silicon thin film and the gap-creating material silicon oxide film are laminated alternately while being patterned by photolithography and etched. The stator and the shaft are fixed to the substrate; however, the rotor must be rotated freely with respect to the substrate. For the particular purpose, the surface of the rotor is covered entirely with the laminated silicon oxide film in the fabrication process. Finally the whole structure is submerged in the etching solution (hydrofluoric acid solution) that selectively dissolves silicon oxide film only. As a result, the rotor is completely released from the substrate to become freely to rotate.



**Figure 8 Fabrication process steps of electrostatic micromotor**

## 2.3 Wafer Bonding

There are a number of different methods available for bonding micromachined silicon wafers together, or to other substrates, to form larger more complex devices. A method of bonding silicon to glass that appears to be gaining in popularity is anodic bonding (electrostatic bonding). The silicon wafer and glass substrate are brought together and heated to a high temperature. A large electric field is applied across the join, which causes an extremely strong bond to form between the two materials. Fig. 9 shows a glass plate bonded over a channel etched into a silicon wafer, forming a pipe through which fluid can flow.



**Figure 9 Typical example of wafer bonding**

It is also possible to bond silicon wafers directly together using gentle pressure, under water (direct silicon bonding). Other bonding methods include using an adhesive layer, such as a glass, or photoresist. Whilst anodic bonding and direct silicon bonding form very strong joints they suffer from some disadvantages, including the requirement that the surfaces to be joined are very flat and clean. Wafer bonding techniques can potentially be combined with some of the basic micromachined structures to form the valves, pumps, etc, of a microfluid handling system.

## 2.4 Deep Reactive ion Etching (DRIE)

A special subclass of RIE which continues to grow rapidly in popularity is deep RIE (DRIE). In this process, etch depths of hundreds of microns can be achieved with almost

vertical sidewalls. The primary technology is based on the so-called "Bosch process", named after the German company Robert Bosch which filed the original patent, where two different gas compositions are alternated in the reactor. The first gas composition creates a polymer on the surface of the substrate, and the second gas composition etches the substrate. The polymer is immediately sputtered away by the physical part of the etching, but only on the horizontal surfaces and not the sidewalls. Since the polymer only dissolves very slowly in the chemical part of the etching, it builds up on the sidewalls and protects them from etching. As a result, etching aspect ratios of 50 to 1 can be achieved. The process can easily be used to etch completely through a silicon substrate, and etch rates are 3-4 times higher than wet etching.

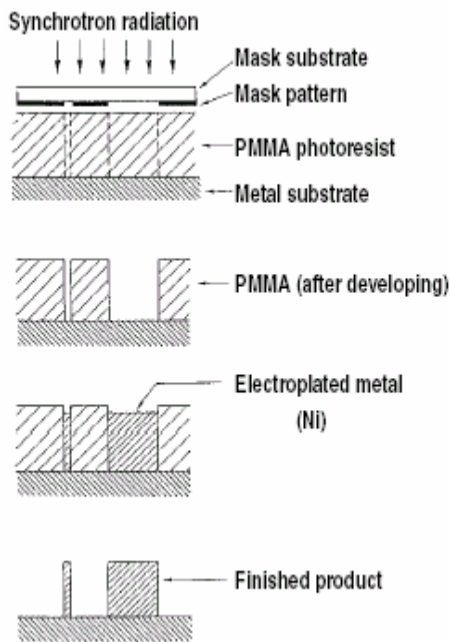
## **2.5 LIGA**

The LIGA process was developed by Karlsruhe Research Center, Germany, in 1986. LIGA stands for the three processes mentioned below, using initials of German words.

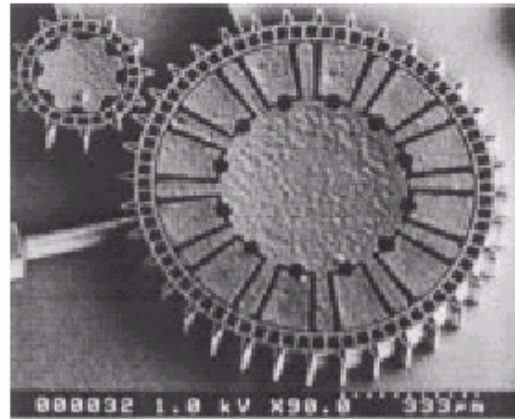
- i. Cavity formation by lithography (Lithografie in German)
- ii. Molding of cavity by metal electroplating (Galvanoformung in German)
- iii. Reproduction of metal mold shape in resin by injection molding (Abformung in German)

Fig. 10 illustrates the cross-sectional view of steps (1) and (2) in the LIGA process above. This process features the use of synchrotron radiation (SOR) in place of ordinary UV light. With SOR used, exposure of the 2-D mask pattern is deeply and accurately made in PMMA-system photoresist with a thickness of several millimeters. By developing this pattern, a cavity with an aspect ratio in excess of 100 is formed.

A metal structure as shown in Fig. 11 can be processed by electroplating the inside of the cavity and reproducing the shape. The structure in this phase can be directly put into practical use.



**Figure 10 Cross-sectional view of the LIGA Process**



**Figure 11 Micromotor Structure made of Ni by the LIGA process (Courtesy of Prof. S. Suglyama)**

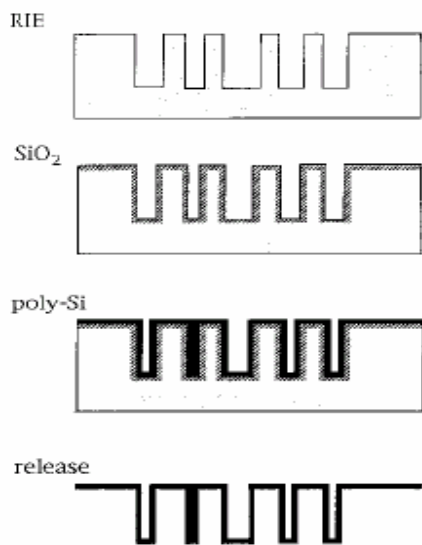
## 2.6 Micromolding

Micromolding is the technology to transfer microscopic shapes, which are fabricated by the methods discussed previously, in other materials. These technologies feature two outstanding effects as follows:

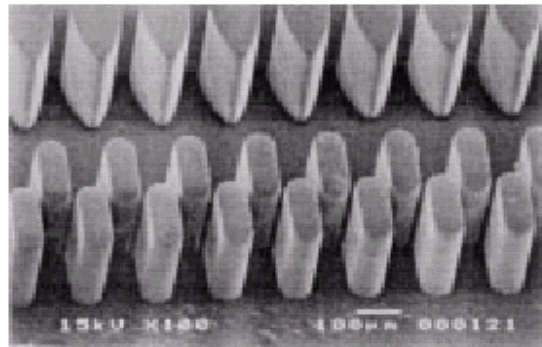
- (1) The mass production of microscopic parts is possible.
- (2) Micromachining using various types of materials including silicon is possible.

Fig. 12 shows the cross sectional view of the fabrication process of a honeycomb type film structure. A film structure is separated after processing a silicon single crystal substrate with a large aspect ratio by RIE, laminating a sacrificial layer such as a silicon dioxide film and structure material such as polycrystalline silicon film in order over the substrate surface entirely, including inner surface of recesses, and finally etching away the sacrificial layer selectively. Through this procedure, a honeycomb structure with a thickness of 100  $\mu\text{m}$  is

produced with a film with a thickness of 1 to 2  $\mu\text{m}$ . By performing injection molding of plastics (Fig. 13) with the structure of a die, and reproducing the shape with electroplating further applied, or using the structure for ceramic molding, the structure can be applied to various types of materials.



**Figure 12** Typical example of micromolding



**Figure 13** Example of molded plastic part made by using the LIGA process (Courtesy of Brother industries, Ltd.)

# MICROSENSORS AND MICROACTUATORS

Microsensors and microactuators broaden the scope of micromachines for the development of MEMS. Now a day many devices are equipped with sensors and actuators to enhance their functionality.

## 3.1 Microsensor

As the term "microelectromechanical systems" suggests, MEMS technology relates most directly and has the greatest impact on sensors for mechanical variables. A *sensor* is a device that converts one physical or chemical quantity to an electrical one, for processing by the microsystem. Deformation of a piezoelectric crystal under an applied electric field is one example.

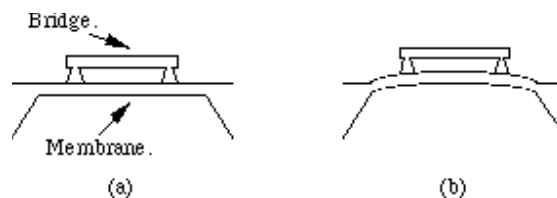
### 3.1.1 Mechanical Sensor

Two different types of mechanical sensors will be discussed here.

- The first uses physical mechanisms to directly sense the parameter of interest (e.g. distance, strain). This type of sensors include:-
  - a) Piezoresistors: -The change in resistance of a material with applied strain is termed the piezoresistive effect.
  - b) Piezoelectric sensors: -When a force is applied to a piezoelectric material, a charge is induced on the surface which is proportional to the applied force.
  - c) Capacitive sensors: -For two parallel conducting plates, separated by an insulating material, the capacitance between the plates is given by equation 1; where  $A$  is the area of the plates,  $d$  the distance between them, and  $\epsilon$  is a constant depending on the material between the plates.

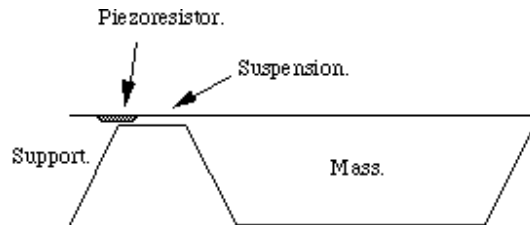
$$C = \epsilon A / d \quad \text{(Equation 1)}$$

- d) Optical sensors: -Silicon is a reflective material, as are other materials used in semiconductor device fabrication (e.g. aluminum). Thus optical means may be used to sense displacement or deformation of microengineered beams, membranes, etc.
- e) Resonant sensors: -These are based on micromachined beams or bridges which are driven to oscillate at their resonant frequency. Figure 10a shows a bridge, driven to resonance, on a thin membrane. The resonant frequency of the bridge is related to the force applied to it (between anchor points), its length, thickness, width, its mass, and the modulus of elasticity of the material from which it has been fabricated. If the membrane that the bridge is mounted on is deformed (Fig. 14), for instance there is greater pressure on one side than the other, then the force applied to the bridge changes, and hence the resonant frequency changes. Alternatively, a resonant device may be used as a biosensor, by coating it with a material that binds to the substance of interest. As more of the substance binds to the device, its mass will be increased, again altering the resonant frequency



**Figure 14 A typical resonant sensor**

- The second type uses microstructures to enable the mechanical sensors to detect parameters of interest that cannot be measured directly with the first type of sensor (e.g. acceleration).
  - a) Accelerometers: -Microengineered acceleration sensors, accelerometers, consist of a mass suspended from thin beams. As the device is accelerated, a force is developed which bends the suspending beams. Piezoresistors situated in the device where the beams meet the support (where strain is greatest) can be used to detect acceleration (Fig. 15).



**Figure 15 A typical Accelerometer**

- b) Pressure sensors: -Microengineered pressure sensors are usually based around thin membranes. On one side is an evacuated cavity and the other side is exposed to the pressure to be measured. The deformation of the membrane is usually monitored using piezoresistors, or capacitive techniques.

### 3.1.2 Thermal Sensor

There are a number of different types of thermal (temperature) sensors. Two of the commonest types are thermocouples and thermoresistors (thermistors).

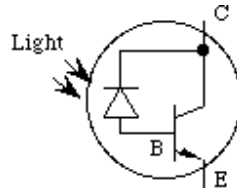
- Thermocouples: -When two dissimilar metals (e.g. copper and iron) are brought together in a circuit, and the junctions are held at different temperatures, then a small voltage is generated and an electrical current flows between them.
- Thermistors: -The electrical resistivity of metals varies with temperature. Above -200degC, the resistivity varies almost linearly with temperature.

### 3.1.3 Radiation sensors

There are a variety of radiation sensors for different types of radiation, including nuclear radiation as well as visible light, infrared and ultraviolet. Only a couple of the commonest will be considered here: the photodiode and phototransistor, charge coupled devices (CCDs), and pyroelectric sensors.

- Photodiodes: -The simplest photodiode is a reverse biased p-n (diode) junction. When no light falls on the device only a small amount of current flows (the dark current). When light falls on the device, additional carriers are generated, and more current flows.

- Phototransistors: -The phototransistor is essentially a transistor with the base current supplied by the current produced by illumination of the base-collector junction; it can be considered to be similar to a photodiode supplying the base current to a transistor (Fig. 16). Normal transistor action amplifies the small base current.



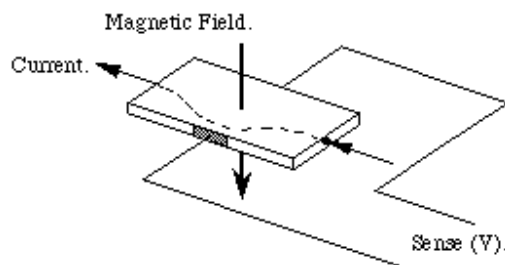
**Figure 16 A Phototransistor**

- Pyroelectric sensors: -These devices operate on the pyroelectric effect in polarised crystals (e.g. zinc oxide). These crystals have a built in electrical polarisation level which changes with the amount of incident thermal energy.

### 3.1.4 Magnetic sensors

There are many ways of sensing magnetic fields. Many measurements can be made, however, using Hall effect sensors. These are very common, and are outlined below.

A Hall effect sensor is shown diagrammatically in Fig. 17. The sensor consists of a conducting material, usually a semiconductor, and a current is passed between two contacts on opposite sides of the device. Two sensing contacts are placed on two other sides of the device, opposite each other, perpendicular to the current flow. A magnetic field perpendicular to the plane of the contacts is causes a deviation in the current flow across the device. This in turn is detected as a potential difference between the two sensing contacts.



**Figure 17 A Hall effect Sensor**

## 3.2 Microactuators

An *actuator* is a device which converts an electrical quantity into a physical or chemical one. They are also required to produce the mechanical output required of particular microsystems: this may be moving micromirrors to scan laser beams, or switch them from one fibre to another; to drive cutting tools for microsurgical applications; to drive micropumps and valves for microanalysis or microfluidic systems; or these may even be microelectrode devices to stimulate nervous tissue in neural prosthesis applications.

### 3.2.1 Electrostatic actuators

When the plates of the capacitor move towards each other, the work done by the attractive force between them can be computed as the change in  $U$  (energy stored) with distance ( $x$ ). The force can be computed by equation 2.

$$F_x = V^2 \partial C / \partial x / 2 \quad (\text{Equation 2})$$

Note that only attractive forces can be generated in this instance. Also, to generate large forces (which will do the useful work of the device), a large change of capacitance with distance is required. This has led to the development of electrostatic comb drives (Fig. 18).

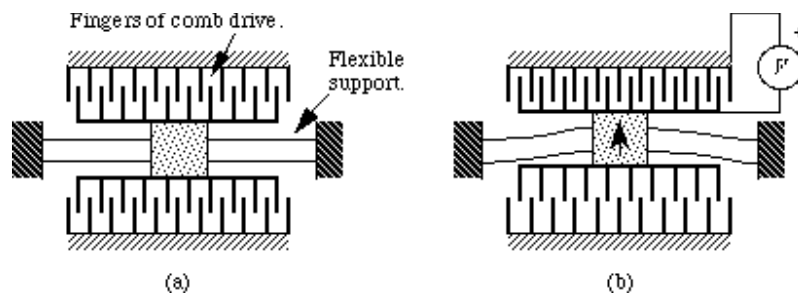
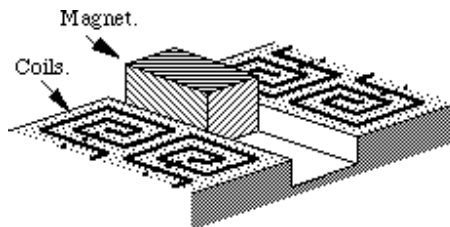


Figure 18 An Electrostatic Comb drive

### 3.2.2 Magnetic actuators

Microstructures are often fabricated by electroplating techniques, using nickel. This is particularly common with LIGA. Nickel is a (weakly) ferromagnetic material, so lends itself to use in magnetic microactuators. An example of a magnetic microactuator is the linear

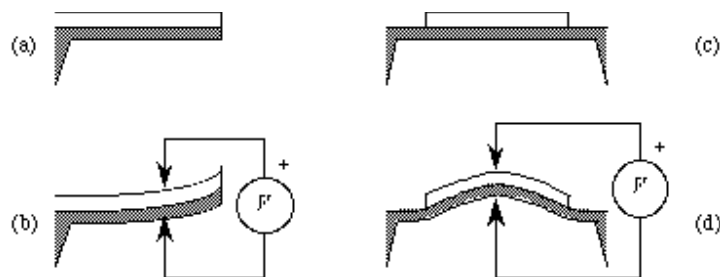
motor shown in figure 19. The magnet resting in the channel is levitated and driven back and forth by switching current into the various coils either side of the channel at the appropriate time.



**Figure 19 A Magnetic Linear Motor**

### 3.2.3 Piezoelectric actuators

The piezoelectric effect mentioned previously for use in force sensors also works in reverse. If a voltage is applied across a film of piezoelectric material, a force is generated. Examples of how this may be used are given in figure 20. In figure 20a, a layer of piezoelectric material is deposited on a beam. When a voltage is applied, the stress generated causes the beam to bend (figure 20b).



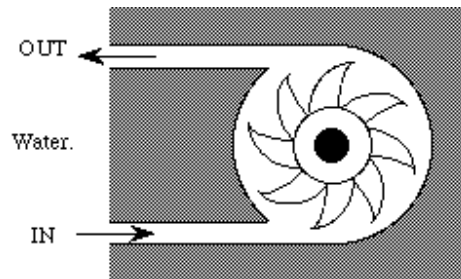
**Figure 20 Actuation by Piezoelectric Effect**

The same principle can be applied to thin silicon membranes (figure 20c). When a voltage is applied, the membrane deforms (figure 20d). This, when combined with microvalves, can be used to pump fluids through a microfluidic system.

### 3.2.4 Hydraulic actuators

Despite problems associated with leaky valves and seals (a problem in many microfluidic systems), hydraulic actuators have considerable potential as quite a lot of power can be delivered from an external source along very narrow diameter tubes. This has

potential in areas such as catheter tip mounted microsurgical tools. LIGA techniques can be used to fabricate turbines (as in figure 21), which can deliver power to cutting tools.

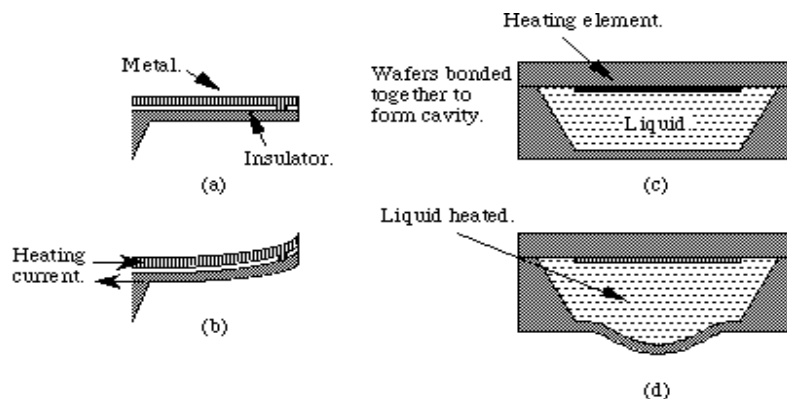


**Figure 21 A Micro Turbine**

### 3.2.5 Thermal actuators

Thermal microactuators are commonly either of the "bimetallic" type, or rely on the expansion of a liquid or gas.

In figure 22a, a beam is machined from one material (e.g. silicon), and a layer of material with a different coefficient of thermal expansivity (e.g. aluminium). When the two are heated, one material expands faster than the other, and the beam bends (figure 22b). Heating may be accomplished by passing a current through the device; heating it electrically. Figure 22c shows a cavity containing a volume of fluid, with a thin membrane as one wall. Current passed through a heating resistor causes the liquid in the cavity to expand, deforming the membrane (figure 22d).



**Figure 22 Thermal Actuators**

**MEMS DEVICES AND APPLICATIONS**

With the advancement of MEMS Technology MEMS based devices have been developed in variety of fields (Fig. 23).

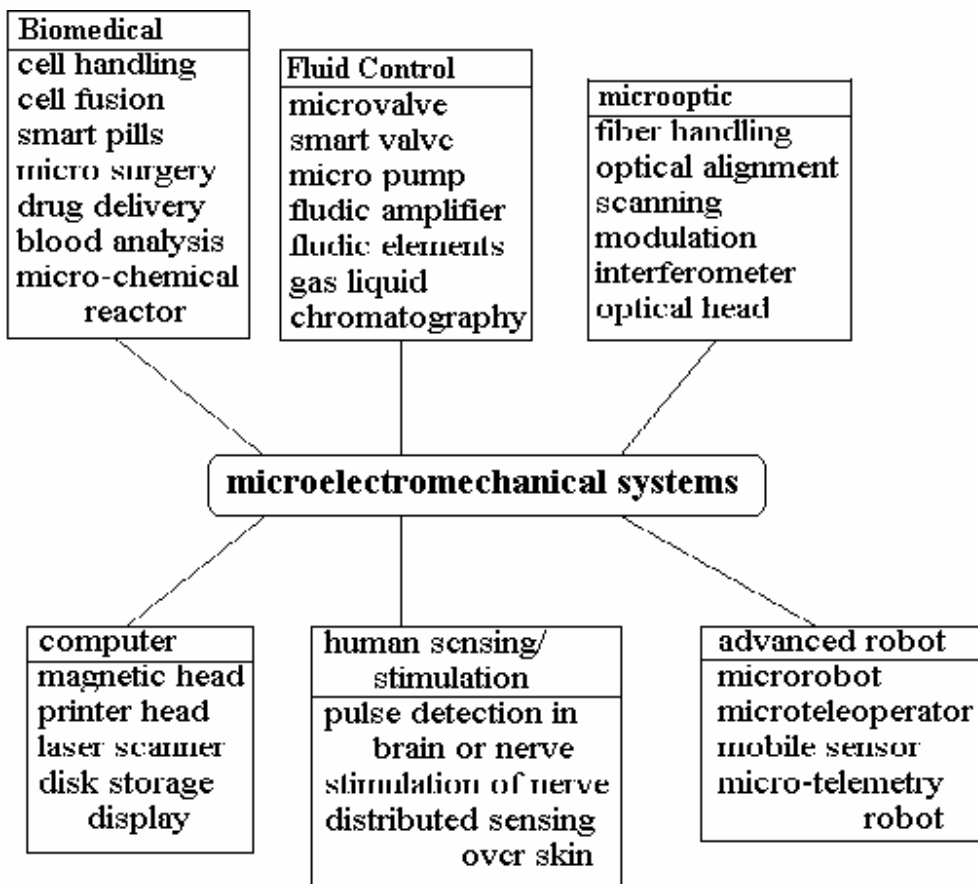
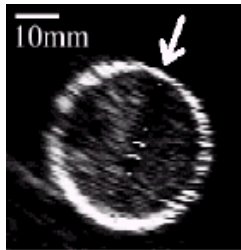


Figure 23 Microelectromechanical Devices in various fields

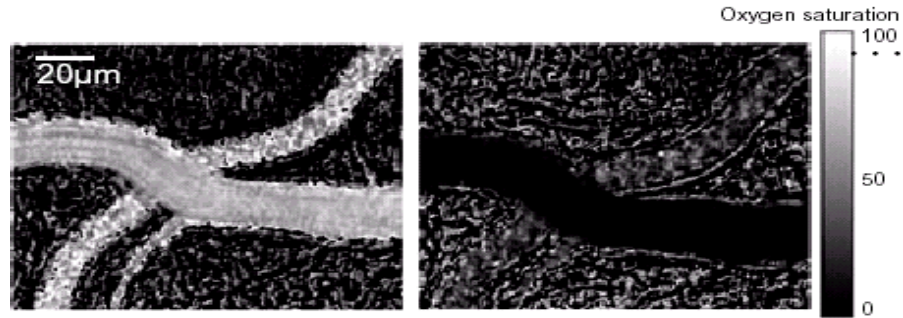
**4.1 Biomedical**

**Drug Delivery System** The surfaces of microcapsules collapse when exposed to ultrasound at their resonance frequency. Research on a physical drug delivery system (DDS)<sup>1</sup> is being conducted using this effect on microcapsules filled with drugs, wherein ultrasound is radiated

from the surface of the body to administer drugs selectively to an affected organ. This technique is advantageous in that capsules can be broken (Fig.24) while simultaneously monitoring the organ and capsule distribution in ultrasonic tomographic images (Fig. 25).



**Figure 24 Using ultrasound beams to break microcapsules in a virtual organ**



**Figure 25 2D images showing oxygen saturation in microvessels of rabbit mesentery (left: saturated state, right: low oxygen state)**

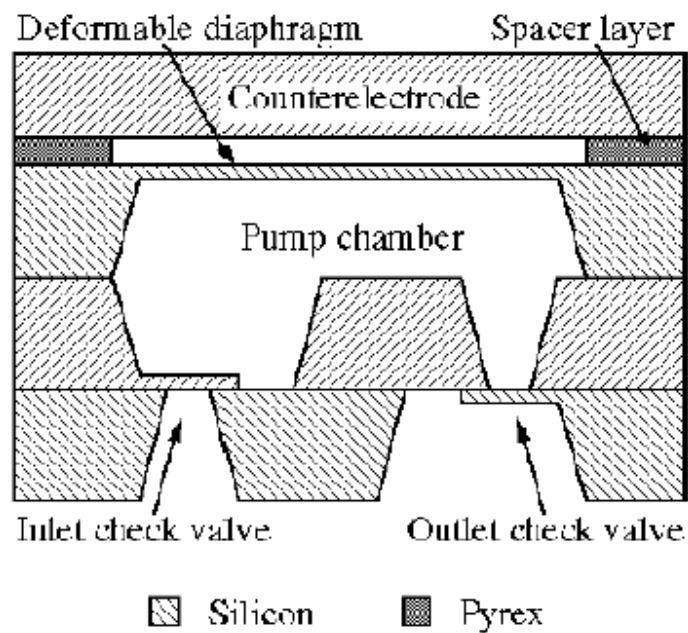
## 4.2 Automobile

**Manifold Absolute Pressure Sensor (MAP)** For the problem of gasoline crisis the fundamental solution that the automotive industry developed was the incorporation of tight control of the stoichiometric ratio between air and fuel. The critical component was the manifold pressure sensor. The first such sensor was developed by gulton in 1974 based on variable reluctance. It was however too expensive for the automotive taste. The next solution was the piezoresistive pressure sensor was developed by Honeywell for General Motors. The total 1995 market for MAP is about 25 million/year. It means that many cars offer better fuel economy while reducing the pollution, providing a better environment for all of us, thanks to a small silicon pressure sensor.

## 4.3 Fluid Control

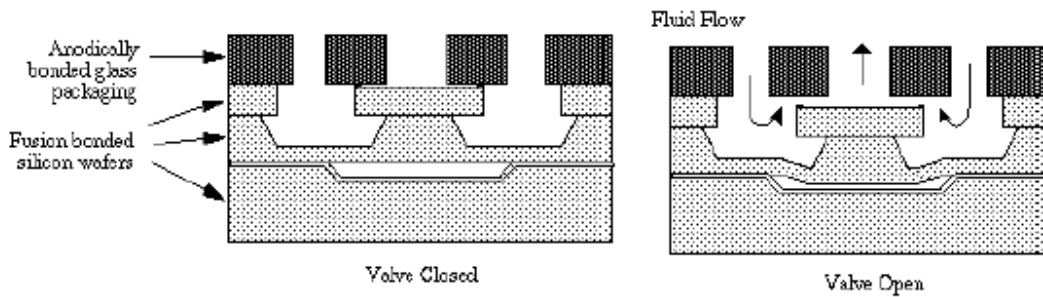
**(a)Micro-Pump** Another application of microactuator technology is in the development of micropumps. Such micropumps are of interest, for example, in developing chemical analysis

and drug delivery microsystems. The micropump in Fig. 26 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 micromachined holes. When a voltage is applied to the counter electrode, the diaphragm deflects up, 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 described, the square diaphragm is 4x4 mm<sup>2</sup> and 25 μm thick; the actuator gap is 4 μm. 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.



**Figure 26 Schematic drawing of an electrostatic micropump**

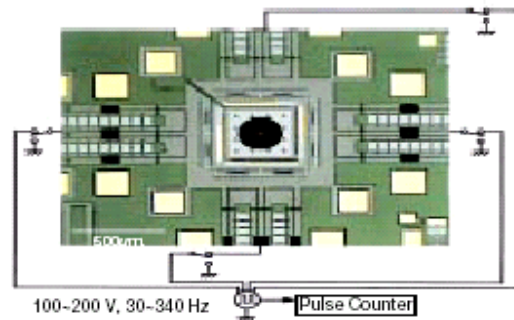
**(b)Micro-valve** A pressure-balanced electrostatically-actuated microvalve was reported by Huff et al. Several fusion bonded silicon layers were combined to form a valve suitable for controlling high-pressure fluid flow. The device is shown in Figure 27.



**Figure 27 Electrostatically-actuated microvalve**

## 4.4 Computer

**Micro-lens Two-Dimensional Laser Scanner** Fig.28 shows an optical transmission scanner employing the XY movement of a micro lens. Unlike the mirror type scanner, the lens movement and scanning angle of the light are linear. Further, the lens can be maintained at a desirable position. Four polysilicon scratch drive actuators are employed to drive the lens. The lens position (scanning angle) is controlled through the counting of voltage pulses.



**Figure 28 Two-Dimensional micro-lens laser scanner**

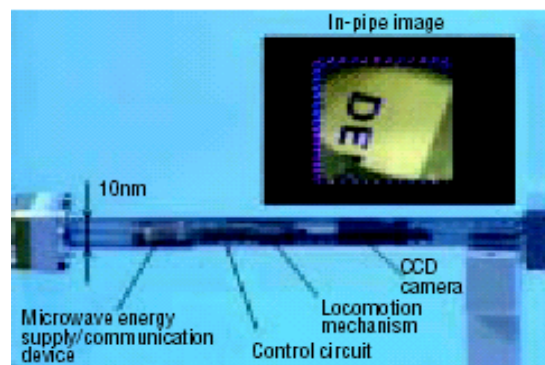
## 4.5 Advanced robot

**In Pipe micro inspection machine** DENSO CORP. has recently completed wireless micromachine for inspection on inner surface of tubes capable of traveling through and

inspecting the inside of complex pipes at power plants and other facilities (Fig. 29). The micro inspection machine is 9.5 mm in diameter, 66 mm long, and weighs 7.3 g. Its total power consumption is about 650 mW. Toshiba was in charge of the mirror rotating mechanism and CCD camera, while Sanyo Electric developed the photovoltaic devices. DENSO was responsible for all remaining components and integration of the entire system. This prototype can move at about 10 mm/sec in a pipe having a diameter of 10 mm, while wirelessly transmitting images from the inside of the pipe to an external host. The microrobot receives energy wirelessly from external light and microwaves. Control is performed by wirelessly transmitting control commands from a remote location. Fig. 30 is a photo showing the completed microrobot operating in a pipe. The photo in the upper right is an in-pipe image transmitted wirelessly from the microrobot. The images are updated at a rate of 2.2 frames/sec.



**Figure 29 Overall view of the in-pipe inspection microrobot**

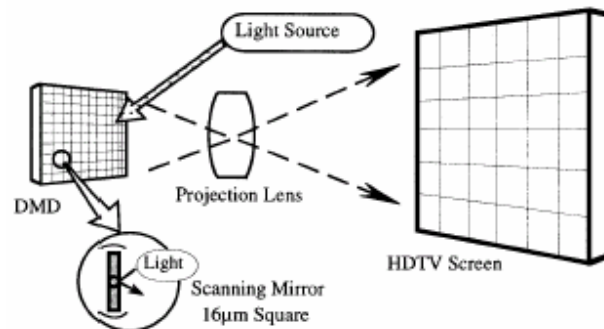


**Figure 30 Wireless controlled in-pipe locomotion and inspection**

## 4.6 Micro-optic

**Digital light processing device** The digital light processing (DLP) device developed by Texas Instruments Inc., U.S.A., is another example of a successful project of surface micromachining. Figure 31 shows the principle of a video projector using the DLP device. About one million micro reflecting mirrors are laid over the surface of the DLP device. The mirrors are supported respectively with spring structures which swing the mirrors for a range of  $\pm 10^\circ$  in angle.

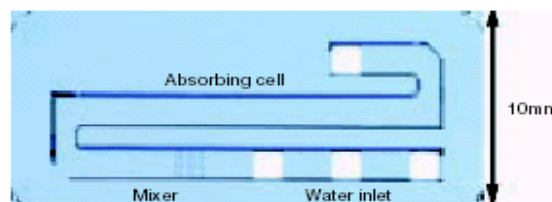
The mirrors and springs are made of a thin aluminum film, while the sacrificial layer is polymer substance. The mirrors swing as they are driven electrostatically. The motion of each mirror is individually controlled by the transistor formed on the silicon substrate. The light from the source is reflected on the surface of the device to be projected onto the wall. This application has already been widely accepted as one type of video projector system, along with liquid crystal devices.



**Figure 31 Principal of the video projection system using digital micro-mirror device**

## 4.7 Miscellaneous

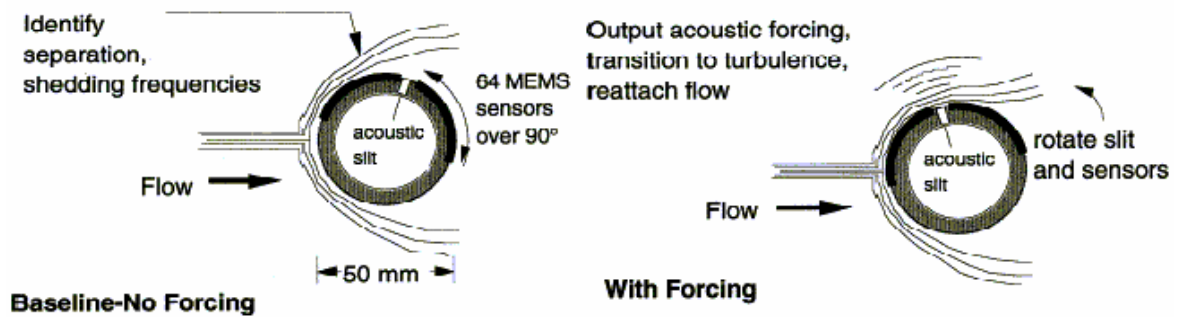
**(a)Water quality monitor** Silicon micromachining technology is applied to the development of a small sized water quality monitor the size of an A4 sheet of paper (1/100 the conventional volume). This device contributes to human safety and health management by automatically measuring residual chlorine and the like in water pipes for general households that have extremely limited installation space. The primary feature of this device is that it employs microfluid channels produced by silicon anisotropic wet etching (Fig.32).



**Figure 32 Microfluid circuit for a small sized water quality monitor**

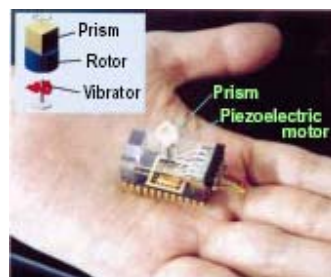
**(b)Active turbulence transitioning** As shown in Fig. 33 state of the art MEMS hot film sensors mounted on the cylinder perimeter will be used to evaluate classic flow phenomena

such as stagnation, separation and the vortex shedding. This data will provide the necessary information to properly tune and locate internal acoustic forcing. Acoustic disturbances aimed at the separation region from a thin span wise slit on the cylinder, will then be amplified by the shear layer instability to accelerate the transition to turbulence.



**Figure 33 Flow sensing and control with surface mounted MEMS sensors and acoustic forcing**

**(c)Micro piezoelectric motor** In the micro piezoelectric motor used in this exhibit (Fig. 34), there are three vibrators (0.1 mm thickness) and a piezoelectric device (PZT) is attached to the back of them. When a voltage is applied to the piezoelectric device, the expansion and contraction of the piezoelectric device is converted to up and down movements of the vibrator, and these up and down movements are converted to rotor rotation movements. Very low voltages (several volts) are applied and practical rotations ranging from several tens to several hundreds of rpm's have been achieved.



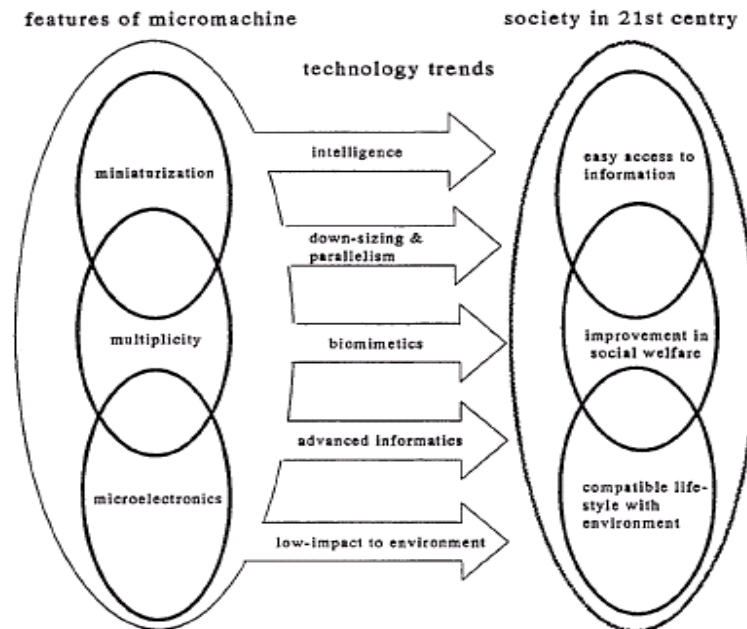
**Figure 34 Micro Piezoelectric Motor**

**FUTURE PROSPECTS**

Although the small size of the mechanical components of the system is very distinctive feature of this emerging technology, it has other may be more attractive features. The three characteristic features are:

- Miniaturization
- Multiplicity
- Microelectronics

Miniaturization is clearly essential. However the mere miniaturization of macroscopic machines is not possible because of scaling effect. Multiplicity is the key to successful microsystem. The integration of microelectronics is essential for moving microelements to cooperate with each other and to perform a given task.

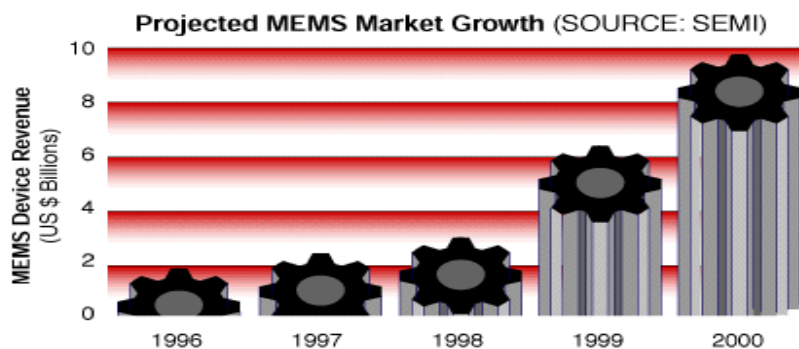


**Figure 35 The microsystem will contribute to the society in 21<sup>st</sup> century because of its three features**

## 5.1 The Opportunity of MEMS Technology

MEMS is destined to become a hallmark 21<sup>st</sup>-century manufacturing technology with numerous and diverse applications having a dramatic impact on everything from aerospace technology to biotechnology. The MEMS technologies now being forged in R&D labs will generate new technological capabilities for society, tremendous economic growth through countless commercial opportunities, many of new products, and thousands of high-paying, high-quality jobs. As breakthrough technology allowing unparalleled synergy between hitherto unrelated fields of endeavor such as biology and microelectronics, MEMS is forecasted to have a commercial and defense market growth similar to its parent IC technology.

A market research by Semiconductor Equipment and Materials International (SEMI), the largest trade organization for the semiconductor industry, projected that the MEMS device industry would grow from 1996's current level of \$1.93 billion to nearly \$10 billion annually (see figure below) by the year 2000 (note: last year's sales were \$1.0 billion). Several other market research studies had projected even higher growth. However, these market figures on MEMS components sales are not the whole story. An additional annual sales of nearly \$100 billion by the end of this decade in new or improved industrial and medical systems are projected through the use of MEMS devices. The application areas considered in these studies have been typically restricted to pressure sensors, inertial sensors, fluid regulation and control, optical switching, analytical instruments, and mass data storage. Since MEMS is a nascent and synergistic technology, many new applications will emerge, expanding the markets beyond that which is currently identified or known.



**TABLE 1 Projected growth of MEMS Market.**

<b>SPC MEMS market survey (DARPA sponsored)</b>	<b>YEAR</b>	<b>SENSING</b>	<b>NON-SENSING</b>
	2003	1.8-3.6 B	5-8 B
<b>Janusz Bryzek (Sensors and Actuators, 1996)</b>	<b>YEAR</b>	<b>TOTAL MEMS</b>	<b>NON-SENSING</b>
	1995	1.45 B	0.05 B
	2005	6.7 B	3.4 B

While MEMS manufacturing leverages heavily from IC manufacturing, the principal users of MEMS are expected not to be limited to the traditional electronics or computer companies. Instead many of the companies to benefit from MEMS will be system integrators and commercial or defense product manufacturers who make automobiles, scientific analytical instruments, consumer goods, medical devices, aerospace navigational systems, and similar products.

## **5.2 Challenges Ahead**

- The accessibility of companies, both small and large, to MEMS fabrication facilities needs to be increased. Currently, most companies who wish to explore the potential of MEMS technology have very limited options for getting devices prototyped or manufactured. It is believed that many of the largest beneficiaries of MEMS technology will be firms that have no capability or core competency in microfabrication technology and access by these companies is critically important to their successful utilization. A mechanism allowing these organizations to have responsive and affordable access to MEMS fabrication resources for prototyping and manufacturing is essential.
- Advanced simulation and modeling tools for MEMS design are urgently needed. Presently, most MEMS devices are modeled using weak analytical tools resulting in a relatively inaccurate prediction of performance behavior. As a result, the MEMS

design process is usually performed in a trial-and-error fashion requiring several iterations before the performance requirements of a given device are finally satisfied. This non-ideal design methodology combined with the length of time and high cost associated with MEMS prototyping results in a very inefficient and ineffective scenario for commercial product development. The availability of suitable design tools combined with computer networks to provide access to high performance workstations and local or remote supercomputer capability can radically alter this situation.

- The packaging of MEMS devices and systems needs to improve considerably from its current primitive state. MEMS packaging presents unique challenges compared to IC packaging due to the diversity of MEMS devices and the requirement that many of these devices are in continuous and intimate contact with their environment. Presently, nearly all MEMS development efforts must develop a new and specialized package each time a new device is designed. Consequently, most companies find that packaging is the single most expensive and time consuming task in their overall MEMS product development program. As with the actual components themselves, numerical modeling and simulation tools for MEMS packaging are virtually non-existent. Approaches which allow designers to select from a catalog of existing standardized packages for a new MEMS device without compromising performance would be beneficial.
- MEMS device design must be separated from the complexities of the fabrication sequence. Currently, the designer of a MEMS device requires a high level of fabrication knowledge in order to embody a successful design. Further, the development of even the most mundane MEMS device frequently requires a dedicated research effort directed at formulating a suitable fabrication sequence. An interface which separates design from fabrication allowing the designer to use process-independent design tools and methodologies will reduce the amount of time and effort required to successfully realize MEMS devices. This will permit more manufacturable designs, done correct the first time or with fewer iterations to become routine. Since extensive knowledge of fabrication will no longer be a prerequisite before beginning design activities, more designers will be able to participate in design

activities and this will result in increased levels of innovation and creativity. Further, an interface separating design from fabrication will enable higher levels of integration without increasing development time or costs. To be of most utility, the interface should allow designers to have ability and know the manufacturing implications of their designs at design time and fabrication specialists to be able to provide the needed functions to aid designers.

- Quality control standards for MEMS technologies are needed. Frequently, the quality of many MEMS devices fabricated at either academic or commercial facilities is low. Part of the problem is that the technology is so new that the fabricators do not yet know how to define quality, much less measure it.
- The output of well-trained MEMS engineers and scientists from the nation's universities needs to increase. The present output from the nation's universities of technical persons trained in MEMS technology is much smaller than the number required to support the projected growth of MEMS industry. Traditionally, the training of MEMS engineers and scientists has entailed a graduate education at one of a few research universities with the student working under the direction of an experienced faculty member to design, fabricate, and test some hopefully new and unique type of MEMS device. A graduate education in MEMS technology is very costly and comparatively time-consuming. A new methodology to increase the number of MEMS engineers and scientists while lowering the cost and improving the quality of their education is needed.