SATHYABAMA
INSTITUTE OF SCIENCE AND TECHNOLOGY
(DEEMED TO BE UNIVERSITY)
Accredited “A” Grade by NAAC | 12B Status by UGC | Approved by AICTE
www.sathyabama.ac.in

SCHOOL OF BIO & CHEMICAL ENGINEERING

DEPARTMENT OF BIOMEDICAL ENGINEERING

UNIT – I - MEMS in Healthcare – SBMA7007

MEMS AND MICROSYSTEMS- GENERAL PRINCIPLES:

The term MEMS refers to a collection of microsensors and actuators which can sense its environment and have the ability to react to changes in that environment with the use of a microcircuit control. They include, in addition to the conventional microelectronics packaging, integrating antenna structures for command signals into micro electromechanical structures for desired sensing and actuating functions. The system also may need micropower supply, micro relay and microsignal processing units. Microcomponents make the system faster, more reliable, cheaper and capable of incorporating more complex functions.

In the beginning of the 1990s, MEMS emerged with the aid of the development of integrated circuit (IC) fabrication processes, where sensors, actuators and control functions are co-fabricated in silicon. Since then, remarkable research progresses have been achieved in MEMS under strong capital promotions from both government and industry. In addition to the commercialization of some less-integrated MEMS devices, such as micro accelerometers, inkjet printer heads, micro mirrors for projection, etc., the concepts and feasibility of more complex MEMS devices have been proposed and demonstrated for the applications in such varied fields as microfluidics, aerospace, biomedicine, chemical analysis, wireless communications, data storage, display, optics, etc. Some branches of MEMS, such as micro-opto-electromechanical systems (MOEMS), micro total analysis systems (μTAS), etc., have attracted a great deal of research interest since their potential application market. As of the end of the 1990s, most MEMS devices with various sensing or actuating mechanisms were fabricated using silicon bulk micromachining, surface micromachining and LIGA processes. Three dimensional micro fabrication processes incorporating more materials were presented for MEMS recently when some specific application requirements (e.g. biomedical devices) and micro actuators with higher output power were called for in MEMS

Micromachining has become the fundamental technology for the fabrication of microelectromechanical devices and, in particular, miniaturized sensors and actuators. Silicon micromachining is the most mature of the micromachining technologies and it allows for the fabrication of MEMS that have dimensions in the submillimeter range. It refers to fashioning microscopic mechanical parts out of silicon substrate or on a silicon substrate, making the structures three dimensional and bringing new principles to the designers. Employing materials such as crystalline silicon, polycrystalline silicon and silicon nitride, etc., a variety of mechanical microstructures including beams, diaphragms, grooves, orifices, springs, gears, suspensions and a great diversity of other complex mechanical structures has been conceived

The basic MEMS utilize a diaphragm-based, a microbridge-based or a cantilever-based structure. Special processing steps commonly known as micromachining are needed to fabricate these membranes, cantilever beams, resonant structures, etc. For a given application, it may be necessary to have integrated MEMS employing one or more of the basic structures. These three structures provide some feasible designs for microsensors and actuators that eventually perform the desired task in most smart structures. However, the main issues with respect to implementing these structures are the choice of materials that are to be used in fabricating these devices and the micromachining technology that may be utilized. To address the first issue, we note that in all of the three structures proposed the sensing and actuation occur as a result of exciting a piezoelectric layer by the application of an electric field. This excitation brings about sensing and actuation in the form of expansion in the diaphragm, or in the free-standing beam in the microbridge structure, or in the cantilever beam.

ADVANTAGES OF MEMS:

1) Very small size, mass, volume
2) Very low power consumption
3) Low cost
4) Easy to integrate into systems or modify
5) Small thermal constant
6) Can be highly resistant to vibration, shock and radiation
7) Batch fabricated in large arrays
8) Improved thermal expansion tolerance
9) Parallelism

MATERIALS FOR BIO-MEMS AND THEIR PROPERTIES:

Bio-MEMS is an abbreviation for biomedical (or biological) microelectromechanical systems. Bio-MEMS have considerable overlap, and is sometimes considered synonymous, with lab-on-a-chip (LOC) and micro total analysis systems (µTAS). Bio-MEMS is typically more focused on mechanical parts and micro fabrication technologies made suitable for biological applications. On the other hand, lab-on-a-chip is concerned with miniaturization and integration of laboratory processes and experiments into single (often microfluidic) chips. A broad definition for bio-MEMS can be used to refer to the science and technology of operating at the microscale for biological and biomedical applications, which may or may not include any electronic or mechanical functions. The interdisciplinary nature of bio-MEMS combines material sciences, clinical sciences, medicine, surgery, electrical engineering, mechanical engineering, optical engineering, chemical engineering, and biomedical engineering. Some of its major applications include genomics, proteomics, molecular diagnostics, point-of-care diagnostics, tissue engineering, single cell analysis and implantable microdevices.

Materials:

(1) Silicon and glass

Conventional micromachining techniques such as wet etching, dry etching, deep reactive ion etching, sputtering, anodic bonding, and fusion bonding have been used in bio-MEMS to make flow channels, flow sensors, chemical detectors, separation capillaries, mixers, filters, pumps and valves. However, there are some drawbacks to using silicon-based devices in biomedical applications such as their high cost and bio incompatibility. Due to being single-use only, larger than their MEMS counterparts, and the requirement of clean room facilities, high material and processing costs make silicon-based bio-MEMS less economically attractive. ‘’In vivo’’, silicon-based bio-MEMS can be readily functionalized to minimize protein adsorption, but the brittleness of silicon remains a major issue.

(2) Plastics and polymers

Using plastics and polymers in bio-MEMS is attractive because they can be easily fabricated, compatible with micromachining and rapid prototyping methods, as well as have low cost. Many polymers are also optically transparent and can be integrated into systems that use optical detection techniques such as fluorescence, UV/Vis absorbance, or Raman method. Moreover, many polymers are biologically compatible, chemically inert to solvents, and electrically insulating for applications where strong electrical fields are necessary such as electrophoretic separation. Surface chemistry of polymers can also be modified for specific applications. Specifically, the surface of PDMSs can be ion-irradiated with elements such as magnesium, tantalum, and iron to decrease surface hydrophobicity, allowing for better cell adhesion in ‘’in vivo’’ applications. The most common polymers used in bio-MEMS include PMMA, PDMS, OSTEmer and SU-8.

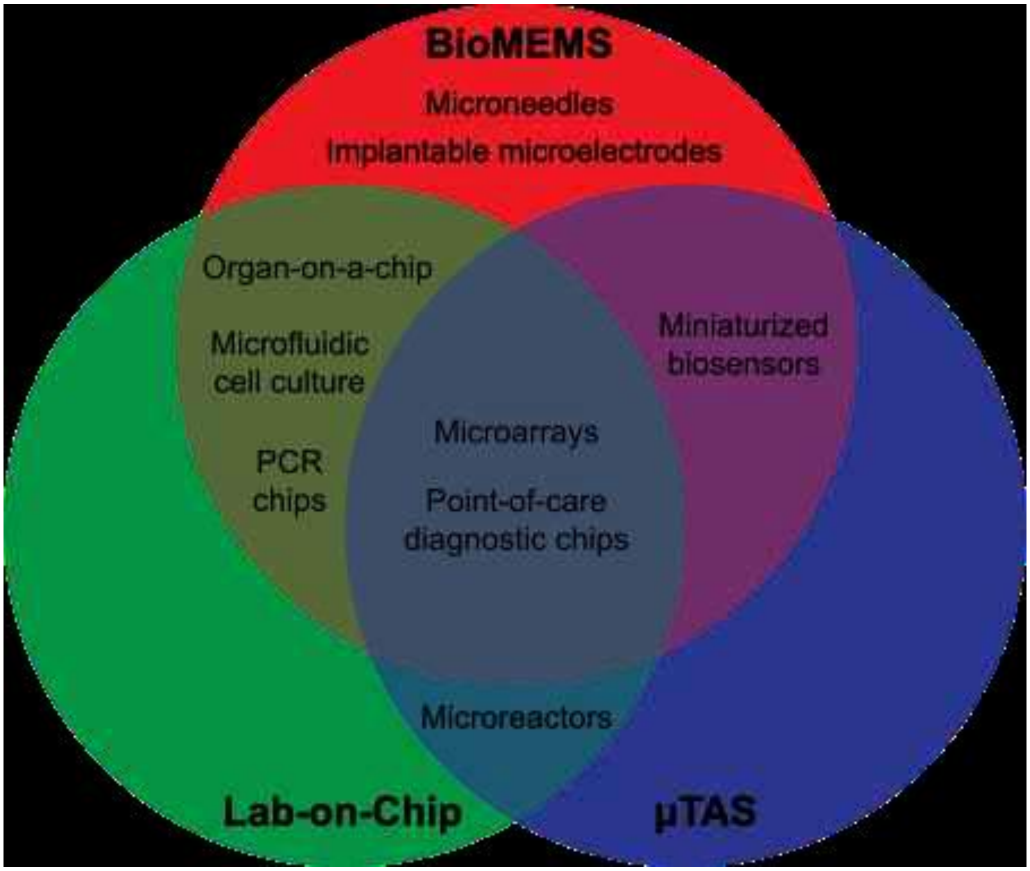


Fig-1: A Venn diagram outlining and contrasting some aspects of the fields of BIOMEMS, lab-on-a-chip, uTAS.

(3) Biological materials:

Microscale manipulation and patterning of biological materials such as proteins, cells and tissues have been used in the development of cell-based arrays, microarrays, micro fabrication based tissue engineering, and artificial organs. Biological micropatterning can be used for high-throughput single cell analysis, precise control of cellular microenvironment, as well as controlled integration of cells into appropriate multi-cellular architectures to recapitulate in vivo conditions. Photolithography, micro contact printing, selective microfluidic delivery, and self-assembled monolayers are some methods used to pattern biological molecules onto surfaces. Cell micropatterning can be done using microcontact patterning of extracellular matrix proteins, cellular electrophoresis, optical tweezer arrays, electrophoresis, and electrochemically active surfaces.

(4) Paper:

Paper microfluidics (sometimes called lab on paper) is the use of paper substrates in micro fabrication to manipulate fluid flow for different applications. Paper microfluidics have been applied in paper electrophoresis and immunoassays, the most notable being the commercialized pregnancy test, ClearBlue. Advantages of using paper for microfluidics and electrophoresis in bio-MEMS include its low cost, biodegradability, and natural wicking action. A severe disadvantage of paper-based microfluidics is the dependency of the rate of wicking on environmental conditions such as temperature and relative humidity. Paper-based analytical devices are particularly attractive for point-of-care diagnostics in developing countries for both the low material cost and emphasis on colorimetric assays which allow medical professionals to easily interpret the results by eye. Compared to traditional microfluidic channels, paper micro channels are accessible for sample introduction (especially forensic-style samples such as body fluids and soil), as well as its natural filtering properties that exclude cell debris, dirt, and other impurities in samples. Paper-based replicas have demonstrated the same effectiveness in performing common microfluidic operations such as hydrodynamic focusing, size-based molecular extraction, micro-mixing, and dilution; the common 96- and 384-well micro plates for automated liquid handling and analysis have been reproduced through photolithography on paper to achieve a slimmer profile and lower material cost while maintaining compatibility with conventional micro plate readers. Techniques for micro patterning paper include photolithography, laser cutting, ink jet printing, plasma treatment, and wax patterning.

TECHNOLOGY INVOLVED IN MEMS-FABRICATION TECHNIQUES:

Silicon micromachining has been a key factor for the vast progress of MEMS. Silicon micromachining refers to fashioning microscopic mechanical parts out of a silicon substrate or on a silicon substrate. Silicon micromachining comprises of two technologies: bulk micromachining, in which structures are etched into silicon substrate, and surface micromachining, in which the micromechanical layers are formed from layers and films deposited on the surface.

Bulk micromachining and surface micromachining are the two major micromachining processes of silicon; silicon wafer bonding is usually necessary for silicon microfabrication. LIGA and three dimensional (3D) microfabrications have been used for high-aspect ratio and 3D microstructures fabrication for MEMS.

BULK MICROMACHINING:

Bulk micromachining technique was developed in 1960s and allows the selective removal of significant amounts of silicon from a substrate to form membranes on one side of a wafer, a variety of trenches, holes, or other structures (Figure shown). The bulk micromachining technique can be divided into wet etching and dry etching of silicon according to the phase of etchants. Liquid etchants, almost exclusively relying on aqueous chemicals, are referred to as wet etching, while vapor and plasma etchants are referred to as dry etching.

Bulk micromachining is the most mature of the two silicon micromachining technologies. It emerged in the early 1960s and has been used since then in the fabrication of different microstructures. It is utilized in the manufacturing of the majority of commercial devices – almost all pressure sensors and silicon valves and 90% of silicon accelerometers. The term bulk micromachining comes from the fact that this type of micromachining is used to realize micromechanical structures within the bulk of a single-crystal silicon wafer by selectively removing (‘etching’) wafer material. The microstructures fabricated using bulk micromachining may cover the thickness range from submicron to full wafer thickness (200 to 500 μm) and the lateral size range from submicron to the lateral dimensions of a full wafer.

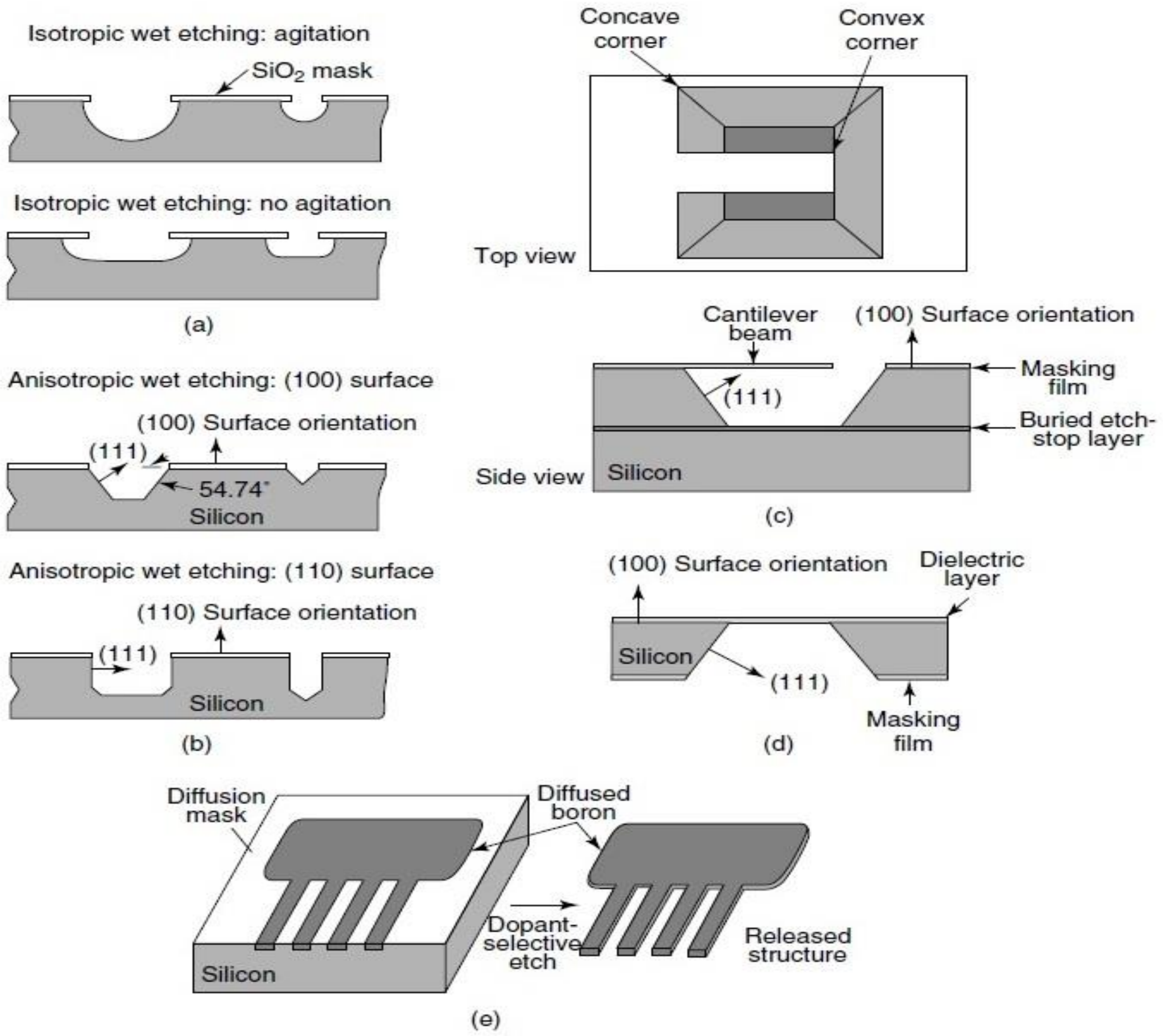


Fig-2: Bulk silicon micromachining: (a) isotropic etching; (b) anisotropic etching; (c) anisotropic etching with buried etch-stop layer; (d) dielectric membrane released by back-side bulk etching; (e) dopant dependent wet etching.

For etching such thick silicon substrate, anisotropic wet etchants such as solutions of potassium hydroxide (KOH), ethylenediamine pyrocatechol (EDP), tetramethylammonium hydroxide (TMAH) and hydrazine-water are used. These etchants have different etch rates in different crystal orientations of the silicon. Wet etching in most case is done from the back side of the wafer while the plasma-etching is being applied to the front side. In recent years, a vertical-walled bulk micromachining technique known as SCREAM (single-crystal reactive etching and metallization), which is a combination of anisotropic and isotropic plasma etching, is used. The etch process can be made selective by the use of dopants (heavily doped regions etch slowly), or may even be halted electrochemically (e.g. etching stops upon encountering a region of different polarity in a biased p–n junction). A region at which wet etching tends to slow down or diminish is called an ‘etch-stop’. There are several ways in which an etch-stop region can be created; doping-selective etching (DSE) and bias-dependent DSE. Wet etching occurs by dipping substrate into an etching bath or spraying it with etchants which may be acid or alkaline. Wet etching can either be isotropic etching or anisotropic etching depending on the structure of the materials or the etchants used. If the material is amorphous or polycrystalline, wet etching is always isotropic etching (Figure a). During isotropic etching (etchants used are acid solution), resist is always undercut, meaning the deep etching is not practical for MEMS. Single-crystal silicon can be anisotropically etched. The etching features are determined by the etching speed, which is dependent on the crystal’s orientation. The etching slows down significantly at the (111) planes of silicon, relative to other planes. With the chosen wafers with different crystal orientation, different buck machined features can be achieved (Figures b and c). Most common etchants used for anisotropic etching of silicon include alkali hydroxide etchants (KOH, NaOH, etc.), ammonium-based solutions {NH4OH,TMAH [(CH3)4NOH], etc.} and EDP (ethylene diamine pyrocatechol, and water). By combining anisotropic etching with boron implantation (P+ etch-stop), and electrochemical etch-stop technique, varied silicon microstructures can be bulk machined.

Dry etching occurs through chemical or physical interaction between the ions in the gas and the atoms of the substrate. Nonplasma, isotropic dry etching can be possible using xenon difluoride or a mixture of interhalogen gases and provides very high selectivity for aluminum, silicon dioxide, silicon nitride, photoresist, etc. The most common dry etching of bulk silicon are plasma etching and reactive ion etching (RIE) etching, where the external energy in the form of RF powder drives chemical reactions in low-pressure reaction chambers. A wide variety of chlorofluorocarbon gases, sulfur hexafluoride, bromine compounds and oxygen are commonly used as reactants. The anisotropic dry etching processes are widely used in MEMS because of the geometry flexibility and less chemical contamination than in wet etching sometimes.

With bulk-micromachined silicon microstructures, the wafer-bonding technique is necessary for the assembled MEMS devices. Surface micromachining, however, can be used to build the monolithic MEMS devices.

SURFACE MICROMACHINING:

Surface micromachining does not shape the bulk silicon but instead builds structures on the surface of the silicon by depositing thin films of ‘sacrificial layers’ and ‘structural layers’ and by removing eventually the sacrificial layers to release the mechanical structures (figure shown below)

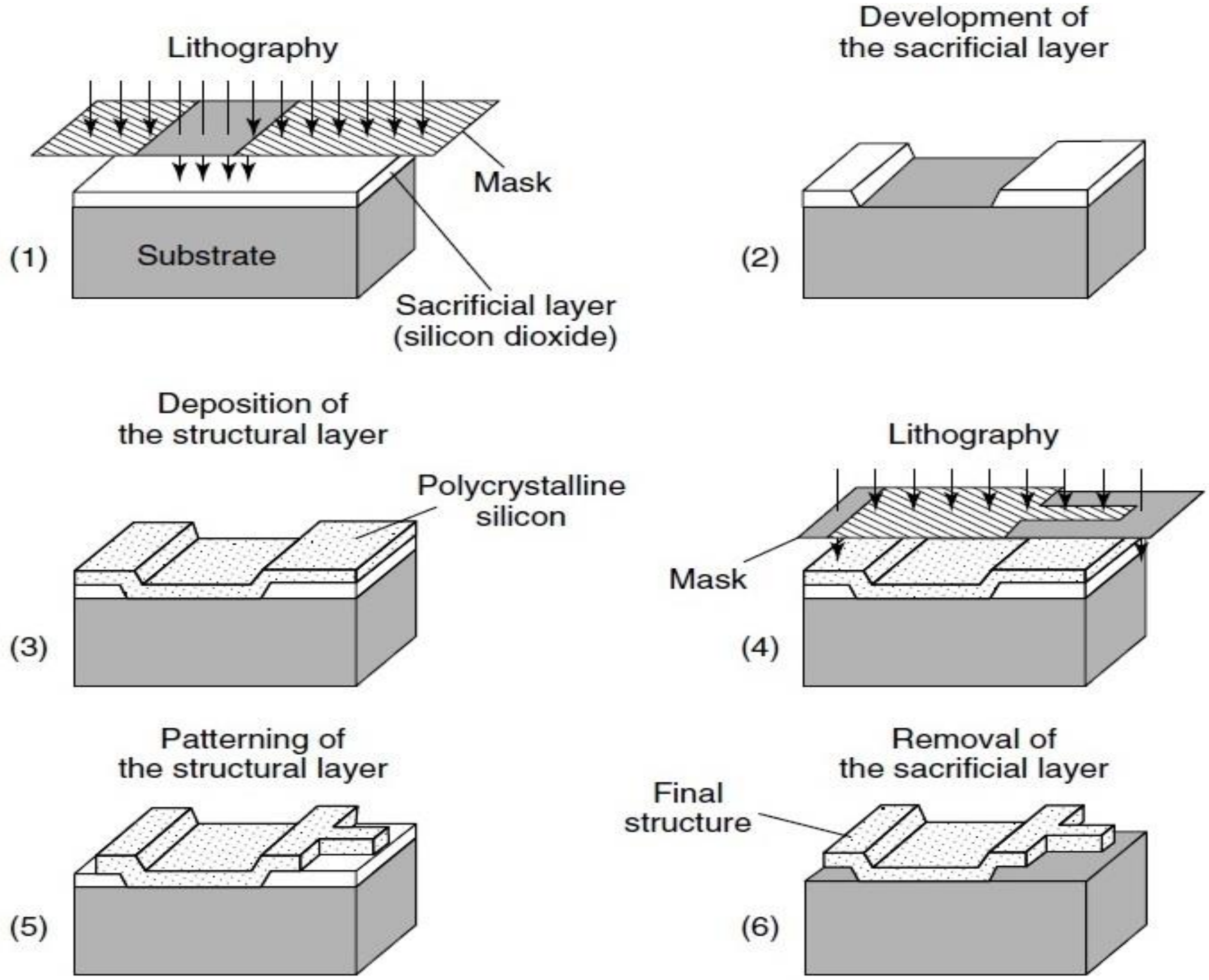


Fig-3: Processing steps of typical surface micromachining

The dimensions of these surface micromachined structures can be several orders of magnitude smaller than bulk-micromachined structures. The prime advantage of surface-micromachined structures is their easy integration with IC components, since the wafer is also the working for IC elements. It should be noted that as miniaturization in immensely increased by surface micromachining, the small mass structure involved may be insufficient for a number of mechanical sensing and actuation applications. Surface micromachining requires a compatible set of structural materials, sacrificial materials and chemical etchants. The structural materials must possess the physical and chemical properties that are suitable for the desired application. In addition, they must have satisfactory mechanical properties; e.g. high yield and fracture stresses, minimal creep and fatigue and good wear resistance. The sacrificial materials must have good mechanical properties to avoid device failure during fabrication. These properties include good adhesion and low residual stresses in order to eliminate device failure by delamination and/or cracking. The etchants to remove the sacrificial materials must have excellent etch selectivity and they must be able to etch off the sacrificial materials without affecting the structural ones. In addition the etchants must have proper viscosity and surface tension characteristics. The common IC compatible materials used in surface micromachining are: (1) polysilicon/Silicon dioxide; low-pressure chemical vapor deposition (LPCVD) deposited polysilicon as the structural material and LPCVD deposited oxide as the sacrificial material.

The oxide is readily dissolved in HF solution without the polysilicon being affected. Together with this material system, silicon nitride is often used for electrical insulation. (2) Polyimide/aluminum; in this case polyimide is the structural material and aluminum is the sacrificial material. Acid-based etchants are used to dissolve the aluminum sacrificial layer. (3) Silicon nitride/polysilicon; silicon nitride is used as the structural material, whereas polysilicon is the sacrificial material. For this material system, silicon anisotropic etchants such as KOH and EDP are used to dissolve polysilicon. (4) Tungsten/silicon dioxide; CVD deposited tungsten is used as the structural material with oxide as the sacrificial material. HF solution is used to remove the sacrificial oxide. Other IC-compatible materials such as silicon carbide, diamond-like carbon, zinc oxide, gold, etc. are also used.

Surface micromachining could also be performed using dry etching methods. Plasma etching of the silicon substrate with SF6/O2-based and CF4/H2-based gas mixtures is advantageous since high selectivities for photoresist, silicon dioxide and aluminum masks can be achieved. However, when using plasma etching, a large undercut of the mask is observed. This is due to the isotropic fluorine atom etching of silicon which is known to be high compared with the vertical etch induced by ion bombardment. In contrast, reactive ion etching of poly-Si using a chlorine/fluorine gas combination produces virtually no undercut and almost vertical etch profiles when using photoresist as a masking material. Thus, rectangular silicon patterns which are up to 30mm deep can be formed using chlorine/fluorine plasmas out of polysilicon films and the silicon wafer surface. Silicon microstructures fabricated by surface micromachining are usually planar structures (or are two dimensional). Other techniques involving the use of thin-film structural materials released by the removal of an underlying sacrificial layer have helped to extend conventional surface micromachining into the third dimension. By connecting polysilicon plates to the substrate and to each other with hinges, 3D micromechanical structures can be assembled after release. Another approach to 3D structures used the conformal deposition of polysilicon and sacrificial oxide films to fill deep trenches previously etched in the silicon substrate.

LITHOGRAPHY:

Lithography (from Ancient Greek , lithos, meaning 'stone', and graphein, meaning 'to write') is a method of printing originally based on the immiscibility of oil and water. The printing is from a stone (lithographic limestone) or a metal plate with a smooth surface. Lithography can be used to print text or artwork onto paper or other suitable material.

Lithography in the MEMS context is typically the transfer of a pattern to a photosensitive material by selective exposure to a radiation source such as light. A photosensitive material is a material that experiences a change in its physical properties when exposed to a radiation source. If we selectively expose a photosensitive material to radiation (e.g. by masking some of the radiation) the pattern of the radiation on the material is transferred to the material exposed, as the properties of the exposed and unexposed regions differs (as shown in figure 4).

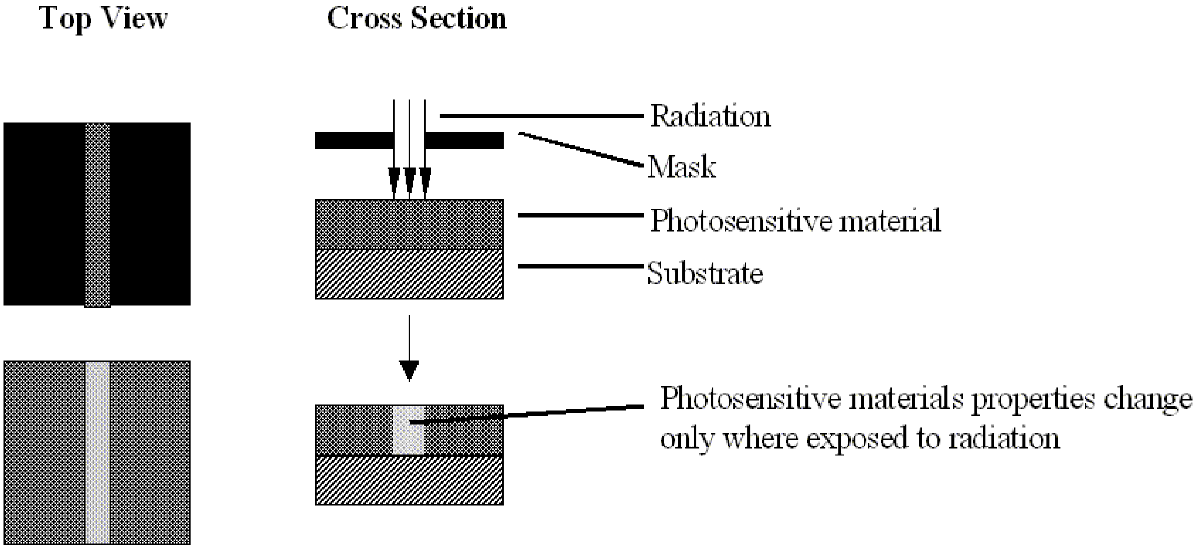


Fig-4: Transfer of a pattern to a photosensitive material.

In lithography for micromachining, the photosensitive material used is typically a photoresist (also called resist, other photosensitive polymers are also used). When resist is exposed to a radiation source of a specific a wavelength, the chemical resistance of the resist to developer solution changes. If the resist is placed in a developer solution after selective exposure to a light source, it will etch away one of the two regions (exposed or unexposed). If the exposed material is etched away by the developer and the unexposed region is resilient, the material is considered to be a positive resist (shown in figure 5a). If the exposed material is resilient to the developer and the unexposed region is etched away, it is considered to be a negative resist (shown in figure 5b).

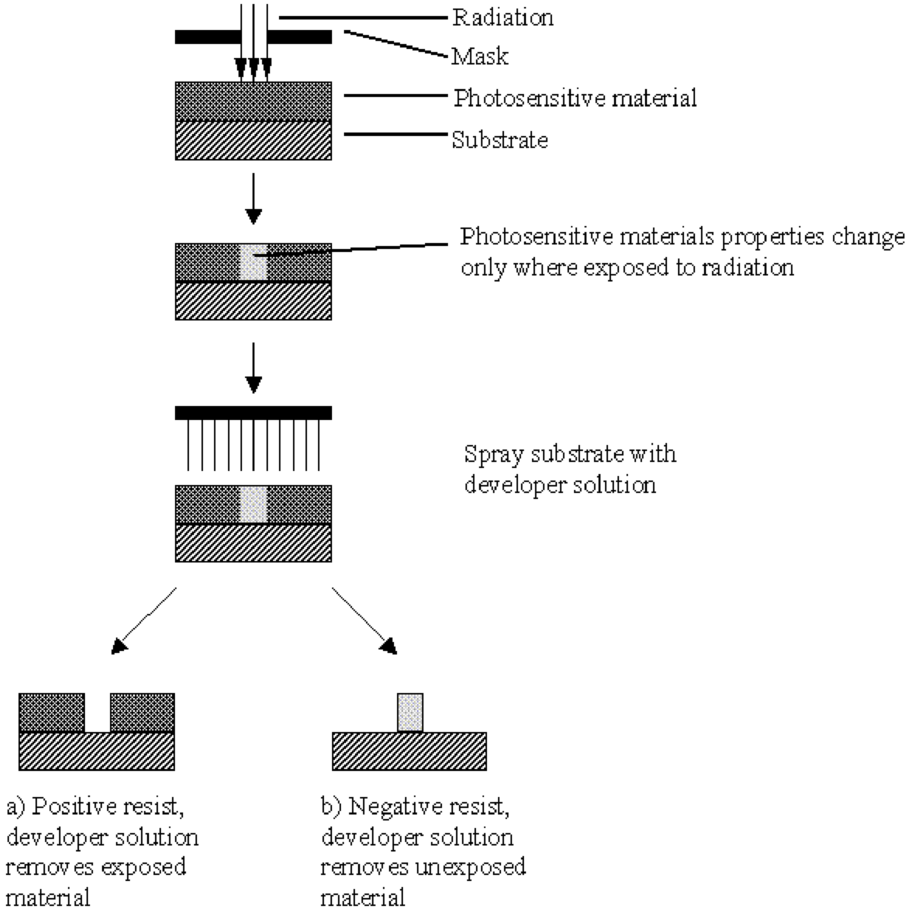


Fig-5: a) Pattern definition in positive resist, b) Pattern definition in negative resist.

Lithography is the principal mechanism for pattern definition in micromachining. Photosensitive compounds are primarily organic, and do not encompass the spectrum of materials properties of interest to micro-machinists. However, as the technique is capable of producing fine features in an economic fashion, a photosensitive layer is often used as a temporary mask when etching an underlying layer, so that the pattern may be transferred to the underlying layer (shown in figure 6a). Photoresist may also be used as a template for patterning material deposited after lithography (shown in figure 6b). The resist is subsequently etched away, and the material deposited on the resist is "lifted off".

The deposition template (lift-off) approach for transferring a pattern from resist to another layer is less common than using the resist pattern as an etch mask. The reason for this is that resist is incompatible with most MEMS deposition processes, usually because it cannot withstand high temperatures and may act as a source of contamination.

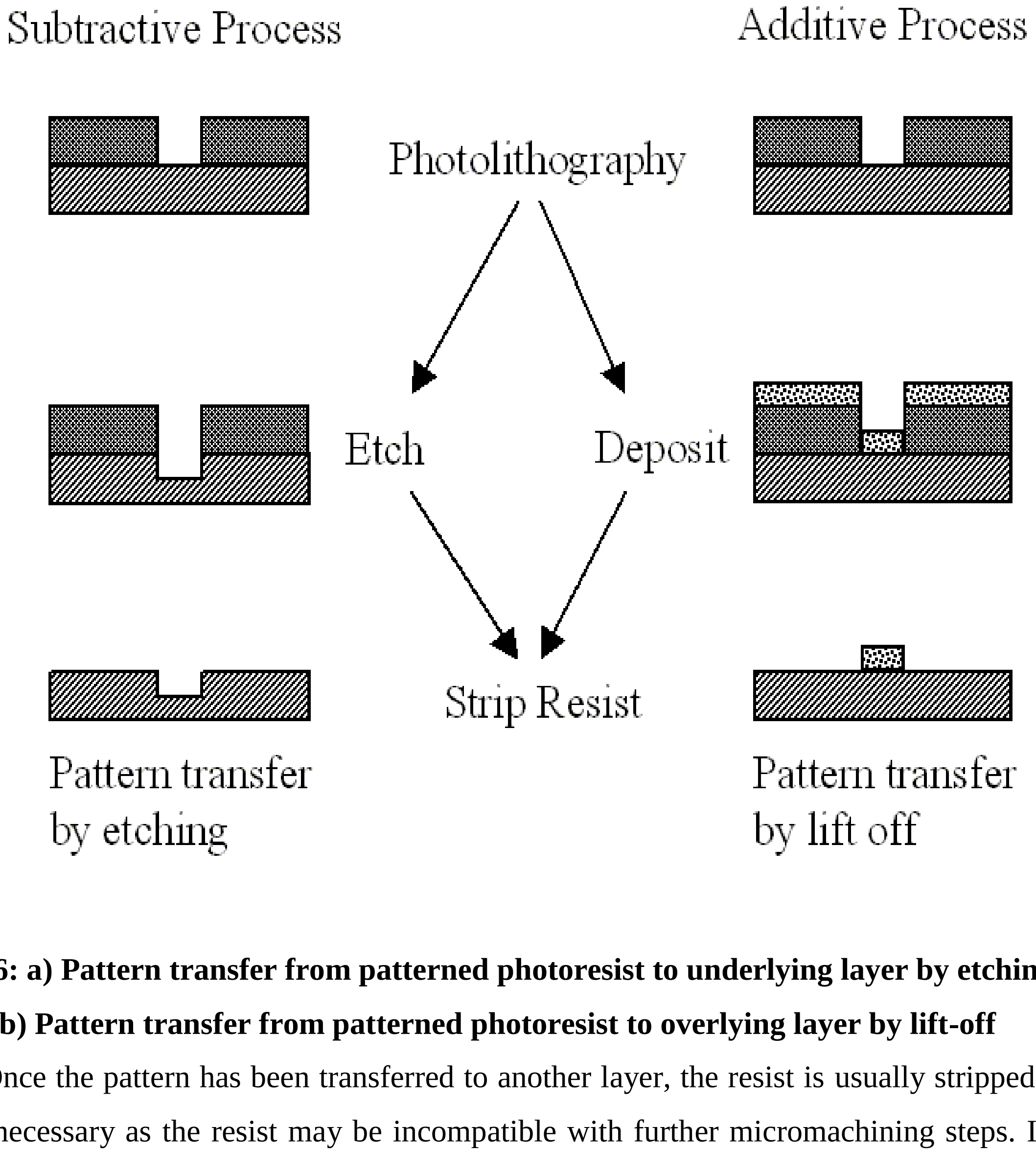


Fig-6: a) Pattern transfer from patterned photoresist to underlying layer by etching

b) Pattern transfer from patterned photoresist to overlying layer by lift-off

Once the pattern has been transferred to another layer, the resist is usually stripped. This is often necessary as the resist may be incompatible with further micromachining steps. It also makes the topography more dramatic, which may hamper further lithography steps.

PHOTOLITHOGRAPHY:

Photolithography, also called optical lithography or UV lithography, is a process used in micro fabrication to pattern parts on a thin film or the bulk of a substrate (also called a wafer). It uses light to transfer a geometric pattern from a photo mask (also called an optical mask) to a photosensitive (that is, light-sensitive) chemical photoresist on the substrate. A series of chemical treatments then either etches the exposure pattern into the material or enables deposition of a new material in the desired pattern upon the material underneath the photoresist. In complex integrated circuits, a CMOS wafer may go through the photolithographic cycle as many as 50 times.

Photolithography shares some fundamental principles with photography in that the pattern in the photoresist etching is created by exposing it to light, either directly (without using a mask) or with a projected image using a photomask. This procedure is comparable to a high precision version of the method used to make printed circuit boards. Subsequent stages in the process have more in common with etching than with lithographic printing. This method can create extremely small patterns, down to a few tens of nanometers in size. It provides precise control of the shape and size of the objects it creates and can create patterns over an entire surface cost-effectively. Its main disadvantages are that it requires a flat substrate to start with, it is not very effective at creating shapes that are not flat, and it can require extremely clean operating conditions. Photolithography is the standard method of printed circuit board (PCB) and microprocessor fabrication. Directed self-assembly is being evaluated as an alternative to photolithography.

The set up of photo lithography is given below. Here light beam is focuses on a condenser lens. A condenser is an optical lens which renders a divergent beam from a point source into a parallel or converging beam to illuminate an object. Condensers are an essential part of any imaging device, such as microscopes, enlargers, slide projectors, and telescopes.

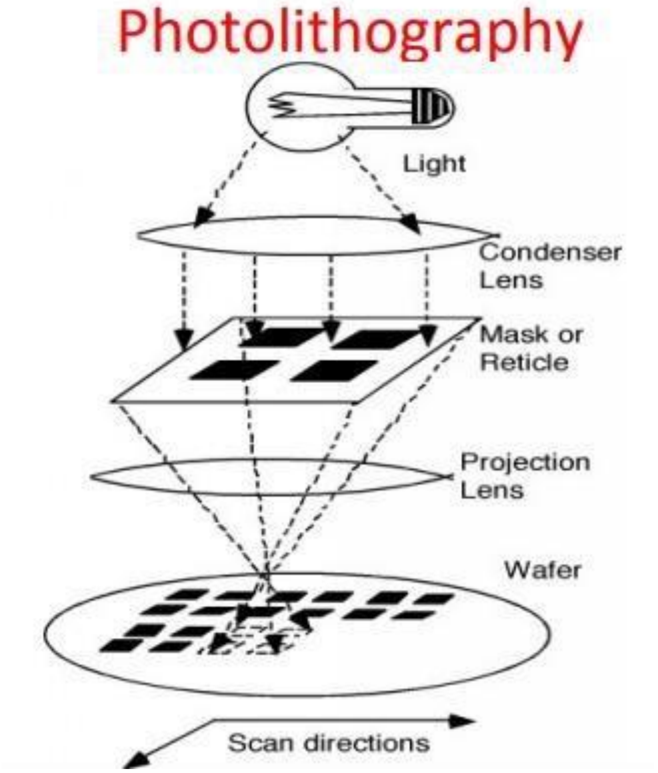


Fig-7: Photolithography setup

The term Photomask (sometimes abbreviated to Mask) is used to mean any type of glass plate with a pattern etched into an opaque surface. A Reticle is a special type of photomask where the data for only part of the final exposed area is present.

A Reticle is loaded into a Stepper or Scanner system where multiple exposures are made to cover the full patterned area. Most modern reticles have the features scaled up by 5X or 4X of the final image size and the features will be reduced in scale as the Reticle is exposed. Other scale factors such as 2X, 2.5X and 10X are also possible. The light passes over this section and moves towards the projection lens. A projection lens is the part of a projector that magnifies an image and casts it onto a screen. These lenses typically feature multiple lens elements and come in two main types: zoom and fixed focus. The pattern is finally transferred to the wafer placed at the last.

ETCHING:

In order to form a functional MEMS structure on a substrate, it is necessary to etch (remove or take away) the thin films previously deposited and/or the substrate itself. In general, there are two classes of etching processes:

1. Wet etching where the material is dissolved when immersed in a chemical solution
2. Dry etching where the material is sputtered or dissolved using reactive ions or a vapor phase etchant

In the following, popular technologies for wet and dry etching are discussed.

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 in contrast to isotropic etching means different etch rates in different directions in the material. The classic example of this is the <111> crystal plane sidewalls that appear when etching a hole in a <100> silicon wafer in a chemical such as potassium hydroxide (KOH). The result is a pyramid shaped hole instead of a hole with rounded sidewalls with a isotropic etchant.

When to use wet etching?

This is a simple technology, which will give good results if you can find the combination of etchant and mask material to suit your application. Wet etching works very well for etching thin films on substrates, and can also be used to etch the substrate itself. The problem with substrate etching is that isotropic processes will cause undercutting of the mask layer by the same distance as the etch depth. Anisotropic processes allow the etching to stop on certain crystal planes in the substrate, but still results in a loss of space, since these planes cannot be vertical to the surface when etching holes or cavities. If this is a limitation for you, you should consider dry etching of the substrate instead. However, keep in mind that the cost per wafer will be 1-2 orders of magnitude higher to perform the dry etching

If we are making very small features in thin films (comparable to the film thickness), we may also encounter problems with isotropic wet etching, since the undercutting will be at least equal to the film thickness. With dry etching it is possible etch almost straight down without undercutting, which provides much higher resolution.

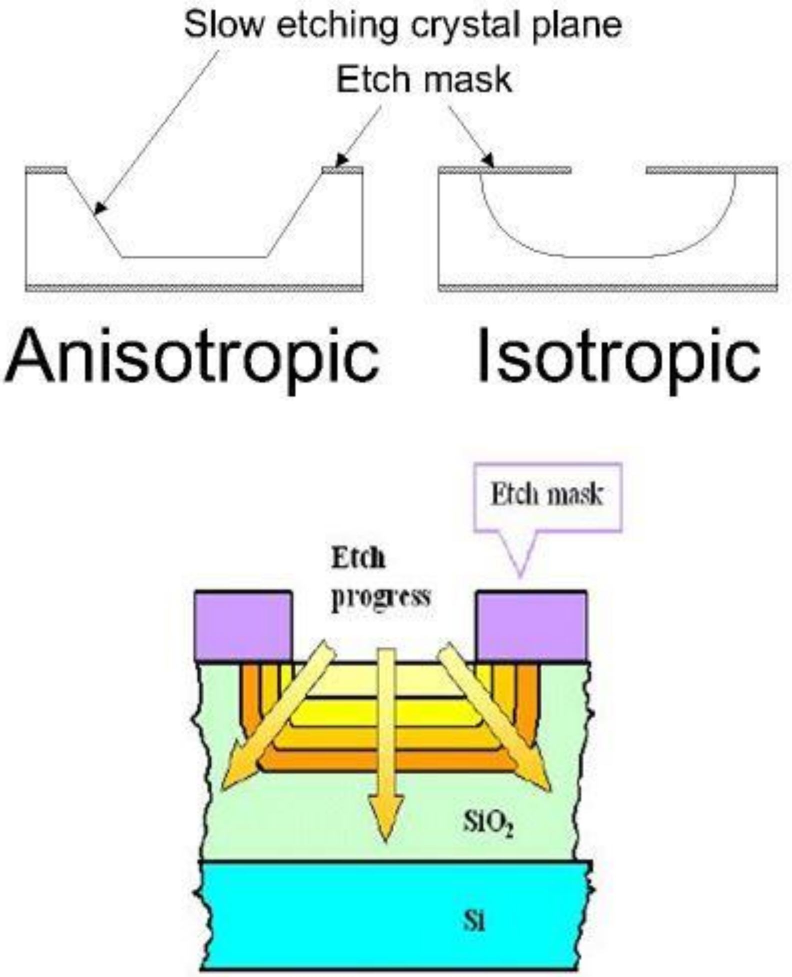


Fig-8: Difference between anisotropic and isotropic wet etching.

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. A plasma is struck in the gas mixture using an RF power source, breaking the gas molecules into ions. The ions are accelerated towards, and reacts at, the surface of the material being etched, forming another gaseous material. This is known as the chemical part of reactive ion etching. There is also a physical part which is similar in nature to the sputtering deposition process. If the ions have high enough energy, they can knock atoms out of the material to be etched without a chemical reaction. It is a very complex task to develop dry etch processes that balance chemical and physical etching, since there are many parameters to adjust. By changing the balance it is possible to influence the anisotropy of the etching, since the chemical part is isotropic and the physical part highly anisotropic the combination can form sidewalls that have shapes from rounded to vertical.

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.

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 diflouride (XeF_2), both of which are isotropic in nature. Usually, care must be taken in the design of a vapor phase process to not have bi-products form in the chemical reaction that condense on the surface and interfere with the etching process.

When required to use dry etching?

The first thing to be noted about this technology is that it is expensive to run compared to wet etching. If you are concerned with feature resolution in thin film structures or you need vertical sidewalls for deep etchings in the substrate, you have to consider dry etching. If you are concerned about the price of your process and device, you may want to minimize the use of dry etching. The IC industry has long since adopted dry etching to achieve small features, but in many cases feature size is not as critical in MEMS. Dry etching is an enabling technology, which comes at a sometimes high cost.

PLASMA ETCHING:

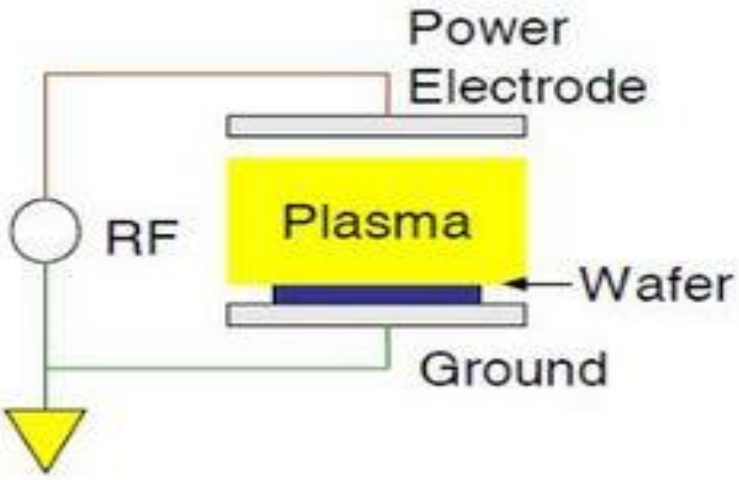


Fig-9: Plasma Etching.

- Substrate (wafer) is on ground electrode
- Ions bombard on the wafer (Substrate) and etch away the required. This is done using a power electrode

DEEP REACTIVE ION ETCHING (DRIE):

- In DRIE, the substrate is placed inside a reactor, and several gases are introduced.

- Uses high density plasma to alternately etch and deposit etch resistant polymer on sidewalls.

Chemical part : A plasma is struck in the gas mixture which breaks the gas molecules into ions. The ions accelerate towards, and react with the surface of the material being etched, forming another gaseous material.

Physical part : if the ions have high enough energy, they can knock atoms out of the material to be etched without a chemical reaction.

Major techniques are :-

- Cryogenic process
- Bosch process

Cryogenic process: This procedure is done at low temperature considering that the material (substrate) is isotropic in nature. However, ions continuous to bombard upward facing surface and etch them away. This process produces trenches with highly vertical side walls.

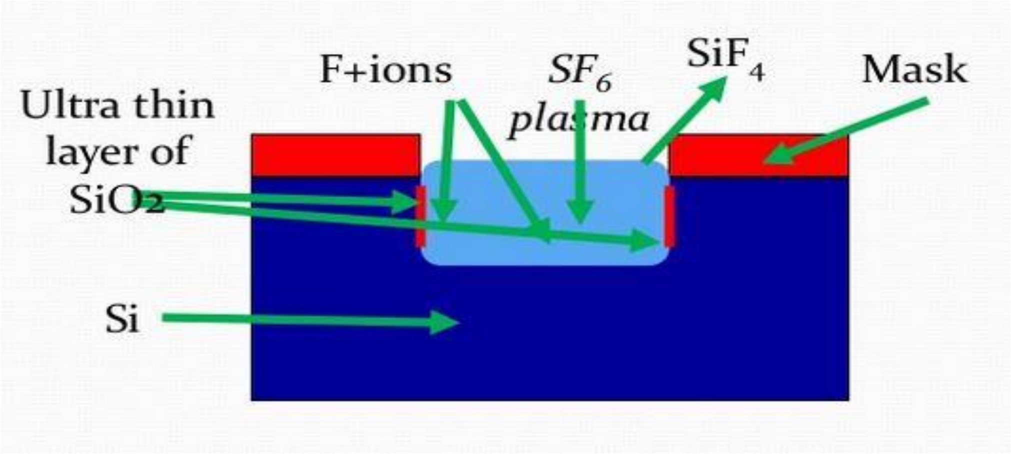


Fig-10: Cryogenic Etching process

Bosch process:

1) It’s a high aspect ratio plasma etching process
2) This process is consisted of the cyclic isotropic etching and fluorocarbon-based protection film deposition
3) The SF_6 plasma cycle etches silicon, and the C_4F_8 plasma cycle creates a protection layer.
4) Its also known as pulse (or) time multiplexed etching. It oscillates repeatedly between two modes to achieve nearly vertical structure.

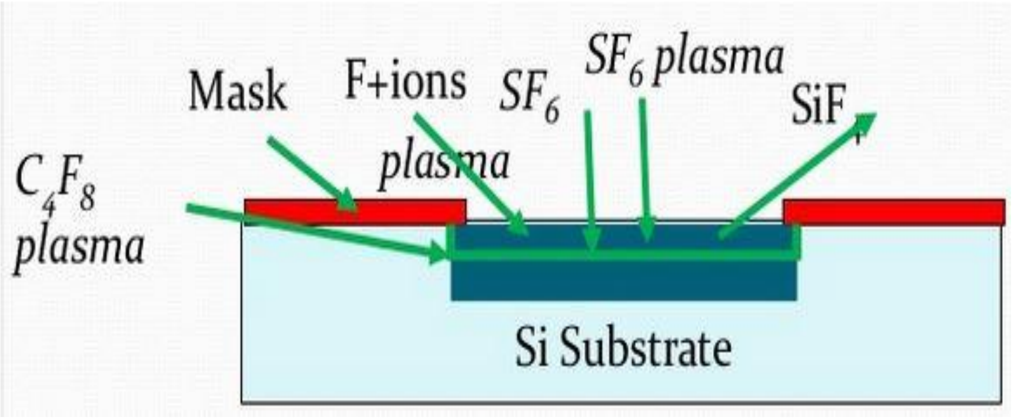


Fig-11: Bosch Process of etching.

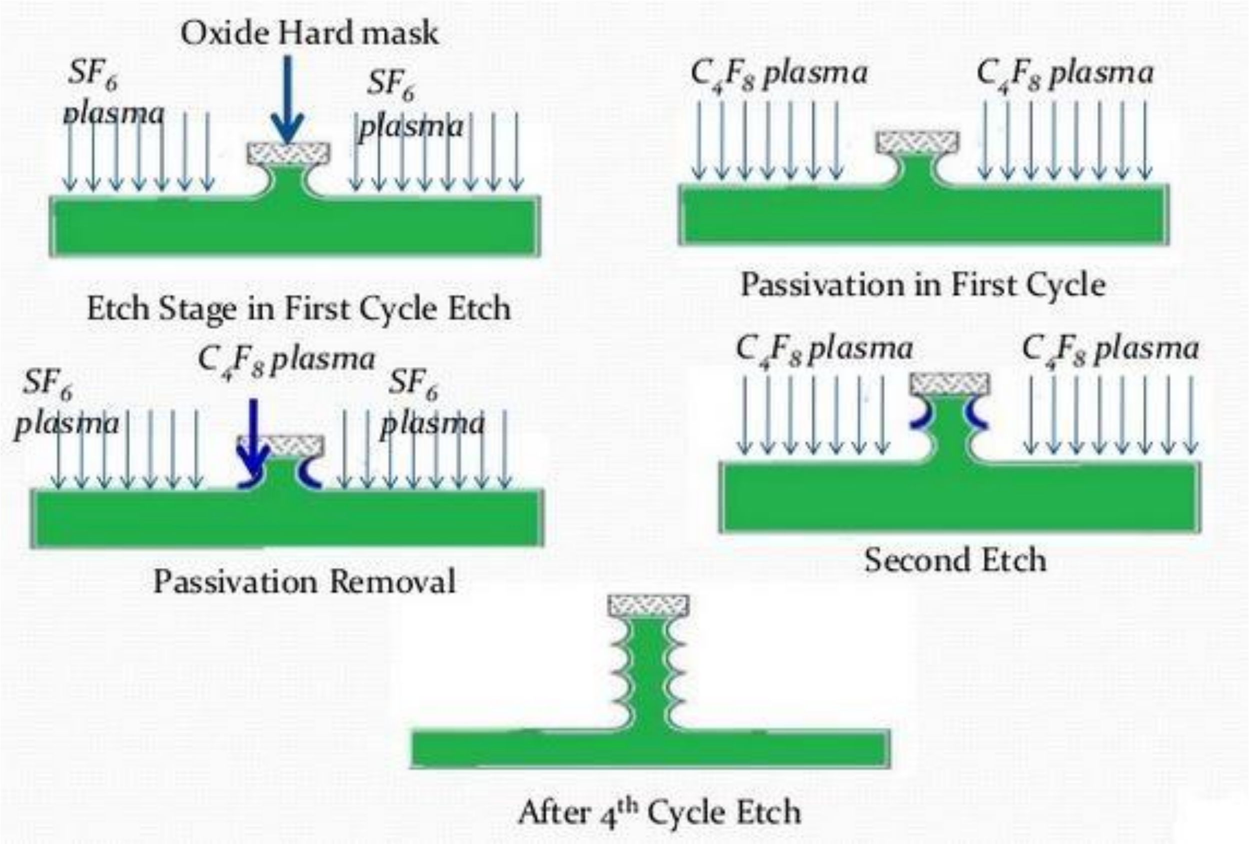


Fig-12: Steps involved in Bosch Process.

ION IMPLANTATION:

Ion Implantation is an alternative to deposition-diffusion and is used to produce a shallow surface region of dopant atoms deposited into a silicon wafer. This technology has made significant roads into diffusion technology in several areas. In this process a beam of impurity ions is accelerated to kinetic energies in the range of several tens of kV(kilo volts) and is directed to the surface of the silicon. As the impurity atoms enter the crystal, they give up their energy to the lattice in collisions and finally come to rest at some average penetration depth, called the projected range expressed in micro meters. Depending on the impurity and its implantation energy, the range in a given semiconductor may vary from a few hundred angstroms to about 1micro meter. Typical distribution of impurity along the projected range is approximately Gaussian. By performing several implantations at different energies, it is possible to synthesize a desired impurity distribution, for example a uniformly doped region.

Block diagram of the Ion Implantation technique is shown below:

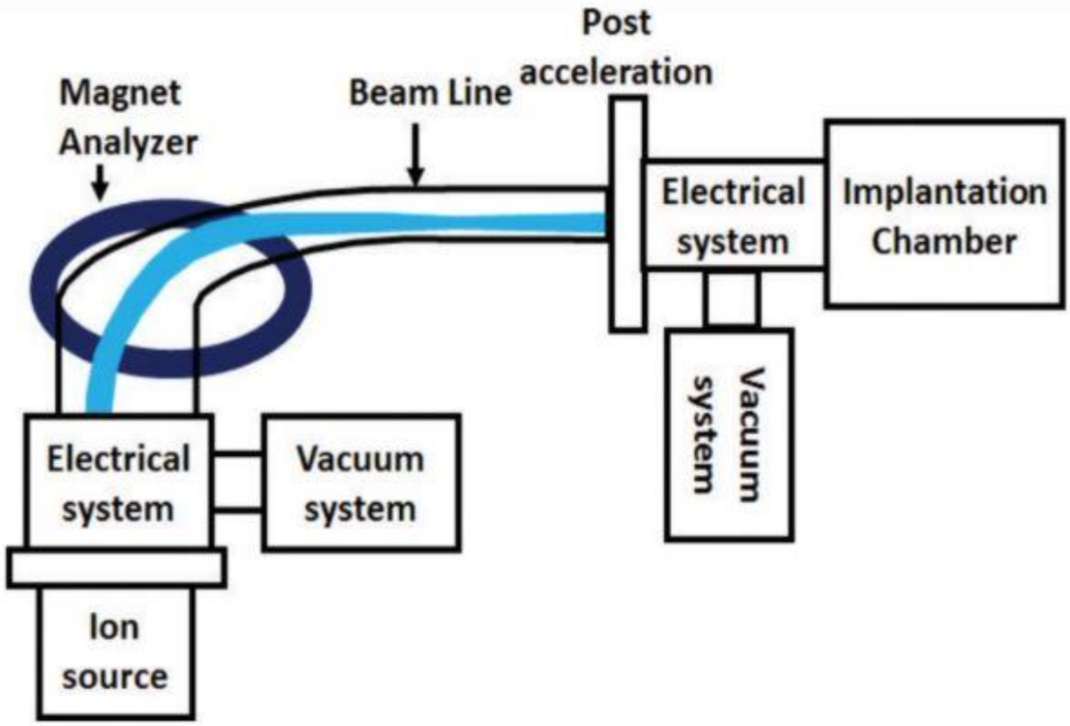


Fig-13: Block diagram of Ion Implantation technique.

A typical ion-implantation system is shown in the figure below.

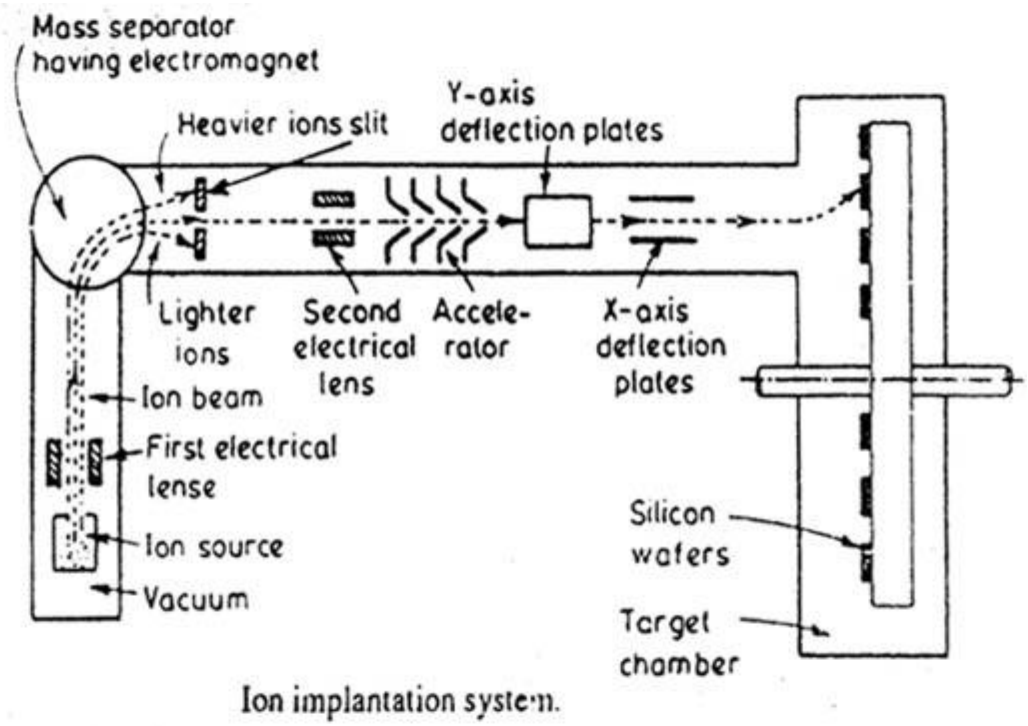


Fig-14: Ion Implantation Technique.

A gas containing the desired impurity is ionized within the ion source. The ions are generated and repelled from their source in a diverging beam that is focussed before if passes through a mass separator that directs only the ions of the desired species through a narrow aperture. A second lens focuses this resolved beam which then passes through an accelerator that brings the ions to their required energy before they strike the target and become implanted in the exposed areas of the silicon wafers. The accelerating voltages may be from 20 kV to as much as 250 kV. In some ion implanters, the mass separation occurs after the ions are accelerated to high energy. Because the ion beam is small, means are provided for scanning it uniformly across the wafers. For this purpose the focused ion beam is scanned electrostatically over the surface of the wafer in the target chamber.

Repetitive scanning in a raster pattern provides exceptionally uniform doping of the wafer surface. The target chamber commonly includes automatic wafer handling facilities to speed up the process of implanting many wafers per hour.

Properties of Ion Implantation:

The depth of penetration of any particular type of ion will increase with increasing accelerating voltage. The penetration depth will generally be in the range of 0.1 to 1.0 micro meters.

Annealing after Implantation

After the ions have been implanted they are lodged principally in interstitial positions in the silicon crystal structure, and the surface region into which the implantation has taken place will be heavily damaged by the impact of the high-energy ions. The disarray of silicon atoms in the surface region is often to the extent that this region is no longer crystalline in structure, but rather amorphous. To restore this surface region back to a well-ordered crystalline state and to allow the implanted ions to go into substitutional sites in the crystal structure, the wafer must be subjected to an annealing process. The annealing process usually involves the heating of the wafers to some elevated temperature often in the range of 1000°C for a suitable length of time such as 30 minutes.

Laser beam and electron-beam annealing are also employed. In such annealing techniques only the surface region of the wafer is heated and re-crystallized. An ion implantation process is often followed by a conventional-type drive-in diffusion, in which case the annealing process will occur as part of the drive-in diffusion.

Ion implantation is a substantially more expensive process than conventional deposition diffusion, both in terms of the cost of the equipment and the throughput, it does, however, offer following advantages.

Advantages of Ion Implantation:

Ion implantation provides much more precise control over the density of dopants deposited into the wafer, and hence the sheet resistance. This is possible because both the accelerating voltage and the ion beam current are electrically controlled outside of the apparatus in which the implants occur. Also since the beam current can be measured accurately during implantation, a precise quantity of impurity can be introduced. Tins control over doping level, along with the uniformity of the implant over the wafer surface, make ion implantation attractive for the IC fabrication, since this causes significant improvement in the quality of an IC.

Due to precise control over doping concentration, it is possible to have very low values of dosage so that very large values of sheet resistance can be obtained. These high sheet resistance values are useful for obtaining large-value resistors for ICs. Very low-dosage, low-energy implantations are also used for the adjustment of the threshold voltage of MOSFET's and other applications.

An obvious advantage of implantation is that it can be done at relatively low temperatures, this means that doped layers can be implanted without disturbing previously diffused regions. This means a lesser tendency for lateral spreading.

Importance of Ion Implantation for VLSI (Very Large Scale Integrated) Technology:

Ion implantation is a very popular process for VLSI because it provides more precise control of dopants (as compared to diffusion). With the reduction of device sizes to the submicron range, the electrical activation of ion-implanted species relies on a rapid thermal annealing technique, resulting in as little movement of impurity atoms as possible. Thus, diffusion process has become less important than methods for introducing impurity atoms into silicon for forming very shallow junctions, an important feature of VLSI circuits. Ion, implantation permits introduction of the dopant in silicon that is controllable, reproducible and free from undesirable side effects. Over the past few years, ion implantation has been developed into a very powerful tool for IC fabrication. Its attributes of controllability and reproducibility make it a very versatile tool, able to follow the trends to finer-scale devices. Ion implantation continues to find new applications in VLSI technologies.

WAFER BONDING FOR MEMS:

Silicon micromachining has limitations in forming complex 3D microstructures in a monolithic format; multichip structures are then proposed for advanced MEMS, where wafer-to-wafer bonding is critical in the formation. The wafer bonding for MEMS can be categorized into six major types: anodic bonding, intermediate-layer assisted bonding, direct bonding, Plasma enhanced bonding, adhesive bonding and metallic bonding

Anodic bonding:

Anodic bonding is also called field-assisted thermal bonding, electrostatic bonding, etc. Anodic bonding is usually established between a sodium glass and silicon for MEMS. For the anodic bonding, a cathode and an anode are attached to the glass (or silicon with glass thin coating) and silicon wafer, respectively; voltages applied range from 200V to 1000 V. At the same time, the anode is put on a heater providing the bonding temperature around (180 to ∼500)

◦C (Figure shown below). During the bonding, oxygen ions from the glass migrate into the silicon, resulting in the formation of a silicon dioxide layer between silicon wafer and glass wafer and form a strong and hermetic chemical bond. The advantage of anodic bonding for MEMS is that the low temperature used can ensure the metalization layer (aluminum) could withstand this temperature without degradation.

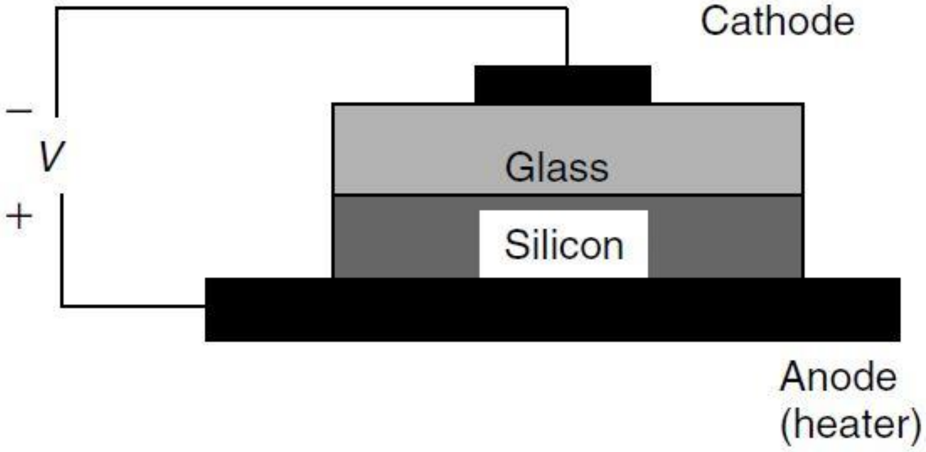


Fig-15: Anodic Bonding.

Intermediate-layer assisted bonding:

This type of bonding for MEMS requires an intermediate layer, which can be metal, polymer, solders, glasses, etc., to fulfill the bonding between wafers. One of the earliest wafer bonding – eutectic bonding – utilized gold as the intermediate layer for Si–Si bonding for pressure sensors .The Au–Si eutectic bonding takes place at 363 ◦C, well below the critical temperature of the metallized aluminium layer. But the stress generated during bonding was found to be significant and introduced sensor drift. Polymers as an intermediate layer for bonding prevail at very low temperature, reasonable high strength, no metal ion presence and low stress because of the elastic property of polymers, etc. Usually, UV photoresists such as polyimide, AZ-4000, SU-8, polymethylmethacrylate (PMMA), and other UV-curable cross-linked polymers. The disadvantage is that the bonded device with polymer may not hold the hermetic sealing performance owing to the relatively high permittivity of polymers. Glasses with low melting temperature as the intermediate layer for the bonding is also demonstrated, where a layer of glass frit is usually deposited on the silicon wafer.

The flatness of the deposited frit layer is critical to obtaining uniform, strong, low-stress bonding. The screen printing of glass frit was used for pressure sensor bonding and exhibits good performance.

Direct bonding:

Direct bonding is also called silicon fusion bonding, which is used for silicon–silicon bonding. Direct bonding is based on a chemical reaction between OH groups present at the surface of native silicon or grown oxides covering the wafers. The direct bonding usually follows three steps: surface preparation, contacting and thermal annealing.

The surface preparation step involves cleaning the surfaces of the two wafers to form a hydrate surface. The wafer surface should be mirror smooth, the roughness should be no greater than 10A˚, and the bow of a 4-inch wafer should be less than 5 micron to achieve the necessary flatness. Following this preparation, the wafers are aligned and contacted in a cleanroom environment by gently pressing the two wafers at the surface central point. The surface attraction of the two hydrated surfaces then brings the intimate contact over the entire wafer surfaces. The final step in direct bonding is to anneal the bonding from room temperature to 1200 ◦C. This annealing process increases the bond strength by more than one order of magnitude at temperatures as high as (800 to ∼1200) ◦C. But high-temperature annealing is not allowed for the metallized wafers. The direct bonding prevails in the high-strength bonding, and the devices’ dimensions could be scaled down if direct bonding approaches are taken other than anodic bonding. Some low-temperature direct bonding processes are to be further developed.

Plasma Enhanced Bonding:

Plasma-activated bonding is a derivative, directed to lower processing temperatures for direct bonding with hydrophilic surfaces. The main requirements for lowering temperatures of direct bonding are the use of materials melting at low temperatures and with different coefficients of thermal expansion (CTE).

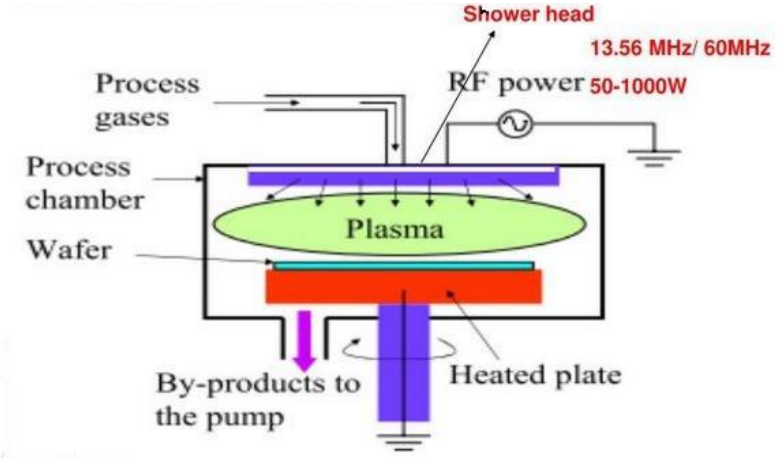


Fig-16: Plasma Enhanced bonding.

Adhesive bonding:

- Adhesive bonding (also referred to as gluing or glue bonding) describes a wafer bonding technique with applying an intermediate layer to connect substrates of different types of materials.

The procedure enables bonding temperatures from 1000 °C down to room temperature. The most important process parameters for achieving a high bonding strength are:

- adhesive material
- coating thickness
- bonding temperature
- processing time
- chamber pressure
- tool pressure

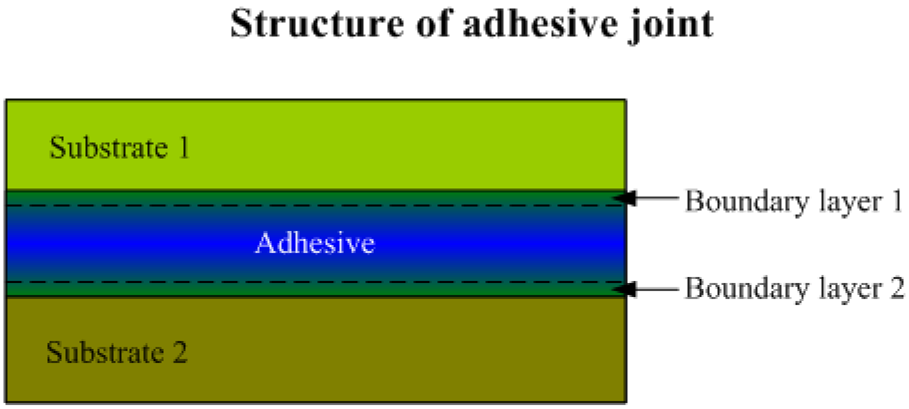


Fig-17: Adhesive bonding

Metallic Bonding:

'Metallic bond' is a term used to describe the collective sharing of a sea of valence electrons between several positively charged metal ions. Metallic bonding is a type of chemical bonding and is responsible for several characteristic properties of metals such as their shiny lustre, their malleability, and their conductivities for heat and electricity. Both metallic and covalent bonding can be observed in some metal samples. For example, covalently bonded gallium atoms tend to form crystal structures that are held together via metallic bonds. The mercurous ion also exhibits metallic and covalent bonding.

The factors that affect the strength of a metallic bond include:

- Total number of delocalized electrons.
- Magnitude of positive charge held by the metal cation.
- Ionic radius of the cation.

An illustration describing the way electrons are delocalized over a rigid lattice of metal ions in a metallic bond is provided below.

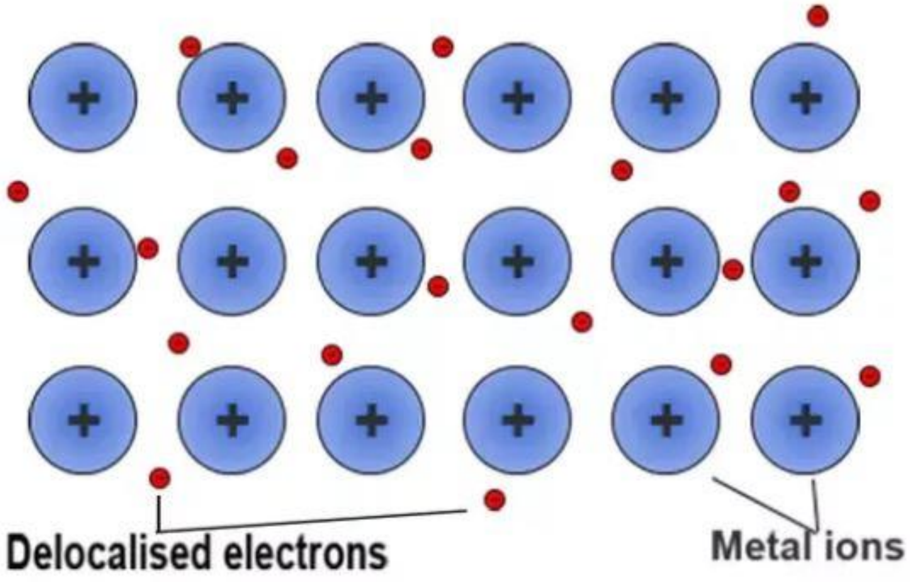


Fig-18: Arrangement of **electrons are delocalized over a rigid lattice of metal ions in a metallic bond**

Properties Attributed by Metallic Bonding:

1) Electrical Conductivity:

When a potential difference is introduced to the metal, the delocalized electrons start moving towards the positive charge. This is the reason why metals are generally good conductors of electric current.

2) Thermal Conductivity:

The thermal conductivity of a material is a measure of its ability to conduct/transfer heat. When one end of a metallic substance is heated, the kinetic energy of the electrons in that area increases. These electrons transfer their kinetic energies to other electrons in the sea via collisions.

The greater the mobility of the electrons, the quicker the transfer of kinetic energy. Due to metallic bonds, the delocalized electrons are highly mobile and they transfer the heat through the metallic substance by colliding with other electrons.

3) Malleability and Ductility:

When an ionic crystal (such a sodium chloride crystal) is beaten with a hammer, it shatters into many smaller pieces. This is because the atoms in the crystals are held together in a rigid lattice that is not easily deformed. The introduction of a force (from the hammer) causes the crystal structure to fracture, resulting in the shattering of the crystal.

In the case of metals, the sea of electrons in the metallic bond enables the deformation of the lattice. Therefore, when metals are beaten with a hammer, the rigid lattice is deformed and not fractured. This is why metals can be beaten into thin sheets. Since these lattices do not fracture easily, metals are said to be highly ductile.

4) Metallic Luster:

When light is incident on a metallic surface, the energy of the photon is absorbed by the sea of electrons that constitute the metallic bond. The absorption of energy excites the electrons, increasing their energy levels. These excited electrons quickly return to their ground states, emitting light in the process. This emission of light due to the de-excitation of electrons attributes a shiny metallic lustre to the metal.

5) High Melting and Boiling Points:

As a result of powerful metallic bonding, the attractive force between the metal atoms is quite strong. In order to overcome this force of attraction, a great deal of energy is required. This is the reason why metals tend to have high melting and boiling points. The exceptions to this include zinc, cadmium, and mercury

The metallic bond can retain its strength even when the metal is in its melt state. For example, gallium melts at 29.76^{o}C but boils only at 2400^{o}C. Therefore, molten gallium is a nonvolatile liquid.

CHEMICAL VAPOUR DEPOSITION (CVD):

There are three deposition methods that are commonly used to form a thin film on a substrate. These methods are all based on chemical vapor deposition (CVD) and are:

- Atmospheric-pressure chemical vapor deposition (APCVD)
- Low-pressure chemical vapor deposition (LPCVD)
- Plasma-enhanced chemical vapor deposition (PECVD)

The latter method is an energy-enhanced CVD method. The appropriate method from among these three deposition methods is based on the substrate temperature, the deposition rate and film uniformity, the morphology, the electrical and mechanical properties and the chemical composition of the dielectric films.

A schematic diagram of a typical CVD system is shown in Figure except that different gases are used at the gas inlet. Figures 19 (a) and 19 (b) show, respectively, a LPCVD and PECVD reactor.

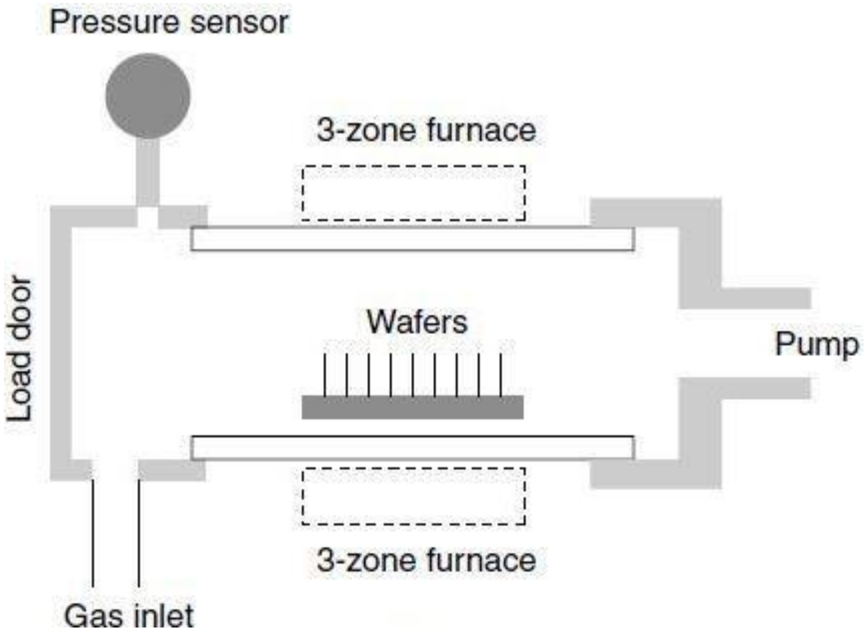


Fig-19: (a) Typical layout of low-pressure chemical vapor deposition reactor

In Figure 19 (a), the quartz tube is heated by a three-zone furnace, and gas is introduced at one end of the reactor (gas inlet) and pumped out at the opposite end (pump). The substrate wafers are held vertically in a slotted quartz boat. The type of LPCVD reactor shown in Figure 19 (a) is a hot-wall LPCVD reactor where the quartz tube wall is hot because it is adjacent to the furnace, in contrast to cold-wall LPCVD, such as the horizontal epitaxial reactor, that uses radio frequency (RF) heating.

Usually, reaction chamber LPCVD process parameters are in the ranges:

- pressure between 0.2 and 2.0 Torr
- gas flow between 1 to 10 $cm^3\ s^{-1}$
- temperatures between (300 and 900)^{0}C

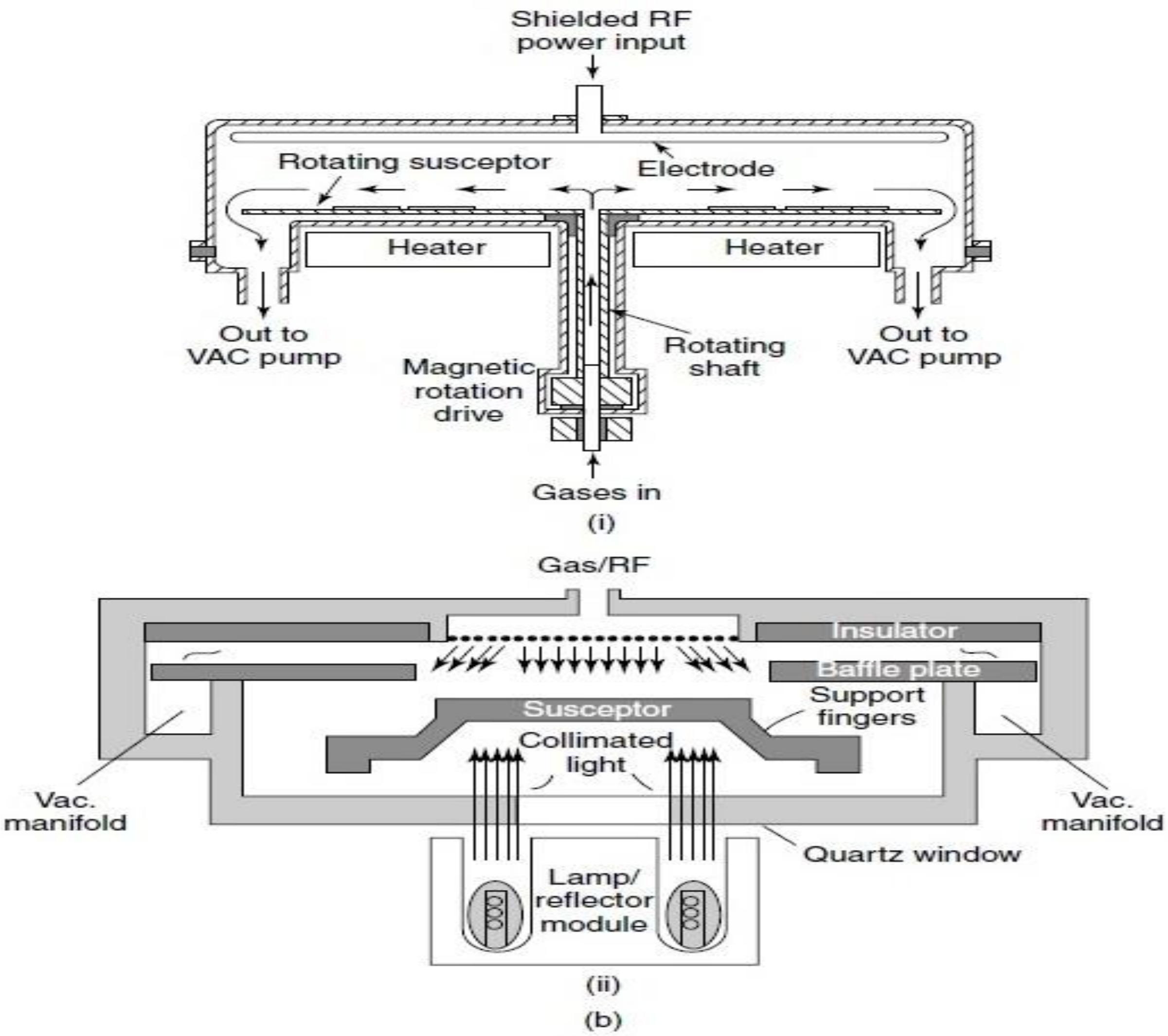


Fig-19: (b) : Two plasma-enhanced chemical vapor deposition reactors

Figure 19 (b) shows a parallel-plate, radial-flow PECVD reactor that comprises a vacuum-sealed cylindrical glass chamber. Two parallel aluminium plates are mounted in the chamber with an RF voltage applied to the upper plate while the lower plate is grounded. The RF voltage causes a plasma discharge between the plates (electrodes). Wafers are placed in the lower electrode, which is heated between 100^0C and 400^0C by resistance heaters. Process gas flows through the discharge from outlets located along the circumference of the lower electrode.

CVD is used extensively in depositing SiO_2, silicon nitride (Si_3N_4) and polysilicon. CVD SiO_2 does not replace thermally grown SiO_2, which has superior electrical and mechanical properties to CVD oxide. However, CVD oxides are used, instead, to complement thermal oxides and in many cases to form oxide layers that are much thicker in relatively very short times than thermal oxides. SiO_2 can be CVD deposited by several methods. It can be deposited from reacting silane and oxygen in an LPCVD reactor a 300^0C to 500^0C where

$$\mathrm{SiH_4 + O_2 \xrightarrow{500\,^\circ C} SiO_2 + 2H_2}$$

It can also be LPCVD deposited by decomposing tetraethylorthosilicate, $Si(OC_2H_5)_4$. The compound, abbreviated to TEOS, is vaporized from a liquid source. Alternatively, dichlorosilane can be used as follows:

$$\mathrm{SiCl_2H_2 + 2H_2O \xrightarrow{900\,^\circ C} SiO_2 + 2H_2 + 2HCl}$$

Likewise, Si_3N_4 can be LPCVD deposited by an intermediate-temperature process or a low-temperature PECVD process. In the LPCVD process, which is the more common process, dichlorosilane and ammonia react according to the reaction.

$$\mathrm{3SiCl_2H_2 + 4NH_3 \xrightarrow{\sim 800\,^\circ C} Si_3N_4 + 6HCl + 6H_2}$$

Polysilicon Film deposition:

Polysilicon is often used as a structural material in MEMS. Polysilicon is also used in MEMS for electrode formation and as a conductor or high-value resistor, depending on its doping level. A low-pressure reactor, such as the one shown in Figure 19 (a), operated at a temperature of between 600^0C and 650^0C, is used to deposit polysilicon by pyrolyzing silane according to the following reaction:

$$\mathrm{SiH_4 \xrightarrow{600\,^\circ C} Si + 2H_2}$$

The most common low-pressure processes used for polysilicon deposition are the ones that operate at pressures between 0.2 and 1.0 Torr using 100% silane. Another process for polysilicon deposition involves a diluted mixture of 20% to 30% silane in nitrogen.

LIGA PROCESS:

MEMS generally require complex microstructures that are thick and three-dimensional. Therefore, many microfabrication technologies have been developed to achieve high-aspect-ratio (height-to-width) and 3D devices. The LIGA process is one of those microfabrications. LIGA is a German acronym for Lithographie, Galvanoformung, Abformung (lithography, galvanoforming, moulding). It was developed by the research Center Karlsruhe in the early 1980s in Germany using X-ray lithography for mask exposure, galvanoforming to form the metallic parts and moulding to produce microparts with plastic, metal, ceramics, or their combinations. A schematic diagram of the LIGA process is shown in Figure below. With the LIGA process, microstructures height can be up to hundreds of microns to millimeter scale, while the lateral resolution is kept at the submicron scale because of the advanced X-ray lithography.

Various materials can be incorporated into the LIGA process, allowing electric, magnetic, piezoelectric, optic and insulating properties in sensors and actuators with a high-aspect ratio, which are not possible to make with the silicon-based processes. Besides, by combining the sacrificial layer technique and LIGA process, advanced MEMS with moveable microstructures can be built. However, the high production cost of LIGA process due to the fact that it is not easy to access X-ray sources limits the application of LIGA. Another disadvantage of the LIGA process relies on that fact that structures fabricated using LIGA are not truly three-dimensional, because the third dimension is always in a straight feature. As we know, complex thick 3D structures are necessary for some advanced MEMS, which means other 3D microfabrication processes need to be developed for MEMS.

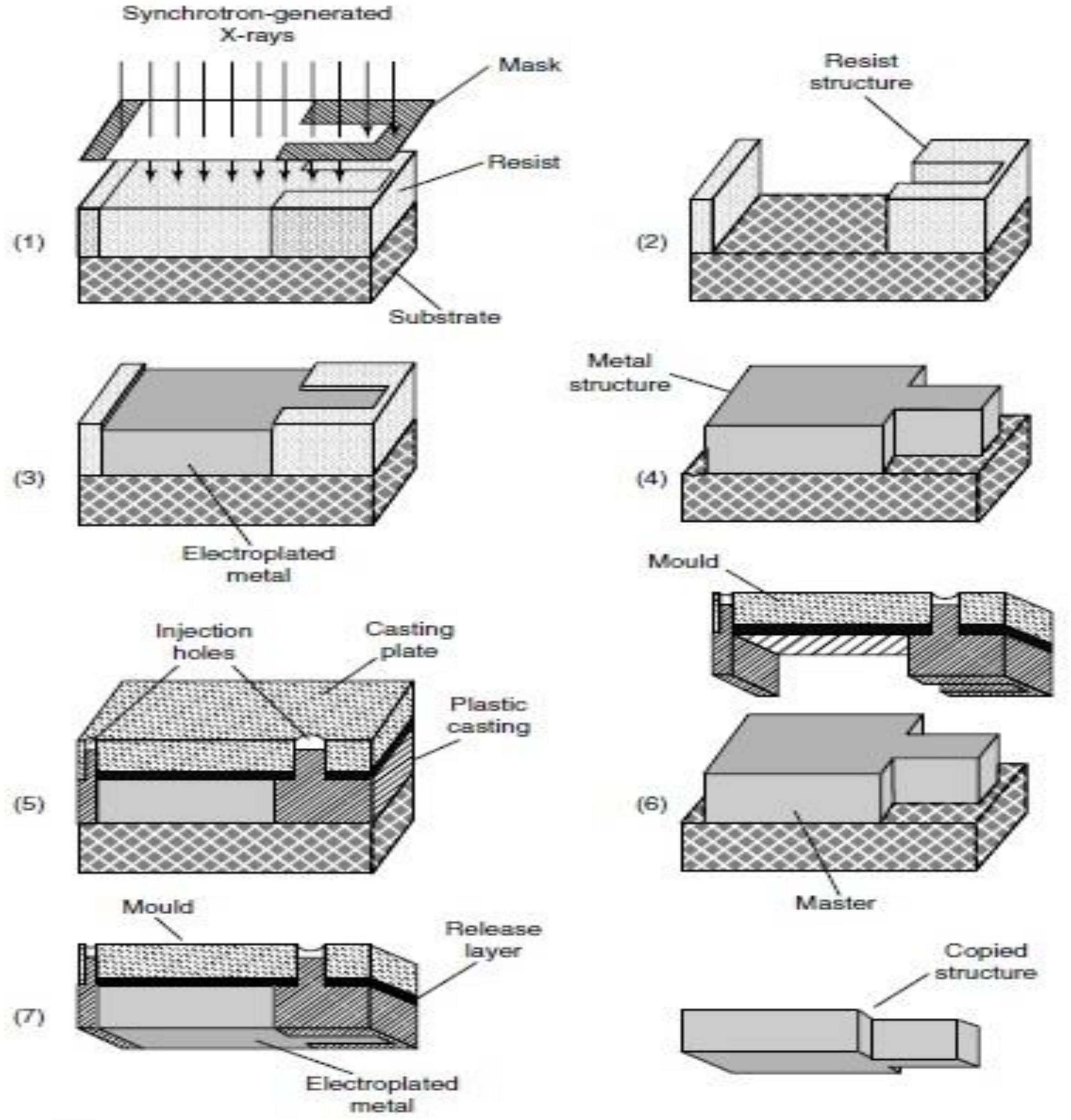


Fig-20: The LIGA Process

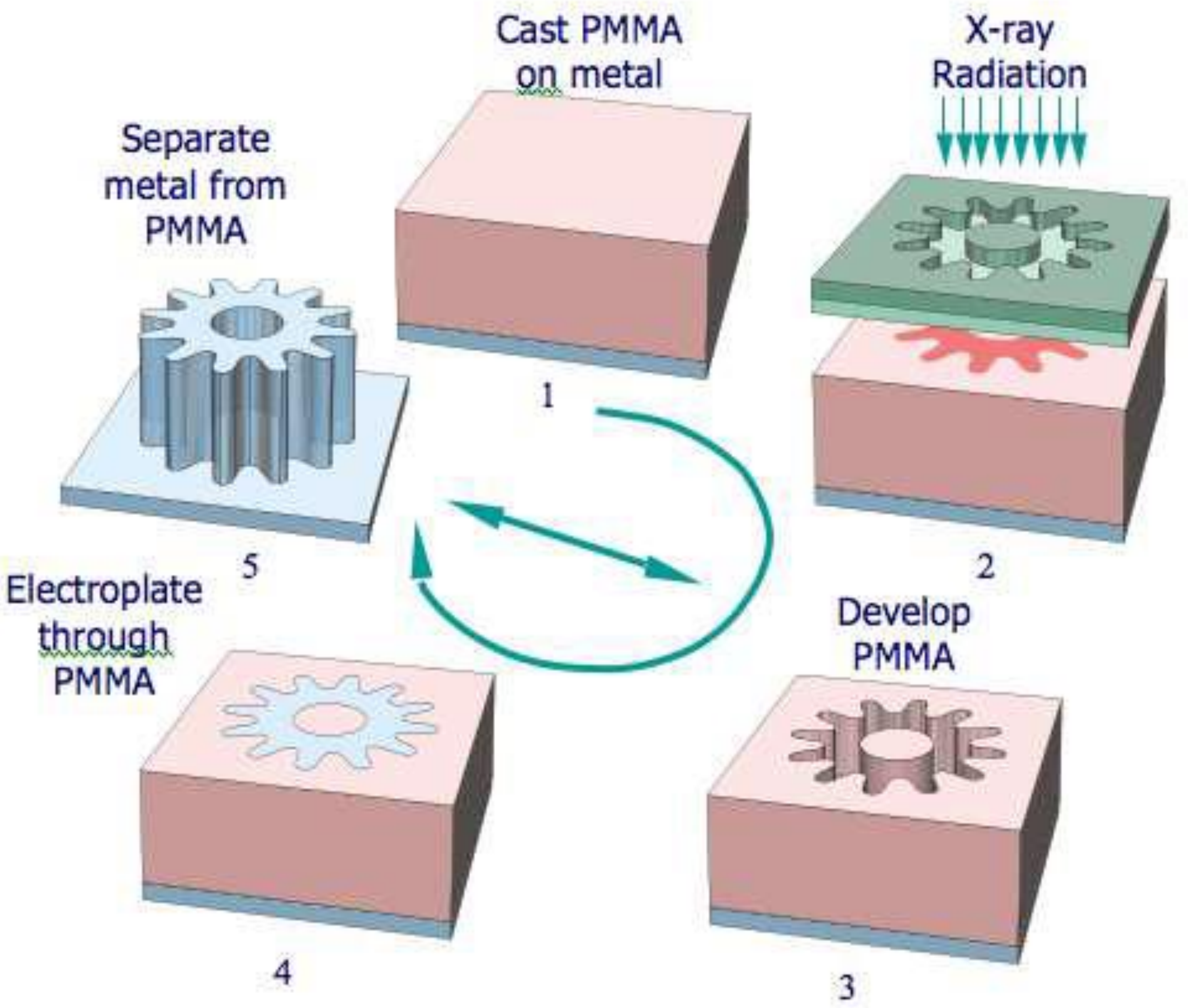


Fig-21: Different view of the LIGA Process

REFERENCES:

1. Tai Ram Hsu, Mems and Microsystems, Design and Manufacture, TMH, 2008.

2. Mohammedhad-el-hak, MEMS Introduction & Fundamentals, CRC Press, 2005.

3. Marc J. Madou, Fundamentals of Microfabrication and Nanotechnology, 3rd Edition, 2011, CRC Press. ISBN
9780849331800

4. Harsingh Nalwa, Encyclopedia of Nanoscience and Nanotechnology, American Scientific Publishers, 2007.

5. Neelina Malsch, Biomedical Nanotechnology. CRC, 2005

6. Richard Booker and Earl Boysen, Nanotechnology for Dummies, John Wiley & Sons, 2011

QUESTION BANK:

1) What are MEMS and Microsystems. Explain in detail their general principle, advantages, disadvantages and applications.?
2) Explain the materials for bio-MEMS and list out their properties.
3) Define Lithography.? What are the steps involved in lithography.?
4) What are dry etching and wet etching.? Explain the procedures in detail.
5) What is Ion implantation. Justify how it is used in fabricating MEMS devices.
6) Define wafer bonding. Illustrate with suitable figures the different types of wafer bonding.
7) What is Bulk Micromachining.? Explain in detail the various procedures involved in bulk micromaching?
8) What is surface micromachining.? Illustrate the procedures with neat sketch.
9) Discuss the chemical vapour deposition techniques.
10) Explain in detail the various steps involved in LIGA process.

SATHYABAMA
INSTITUTE OF SCIENCE AND TECHNOLOGY
(DEEMED TO BE UNIVERSITY)
Accredited "A" Grade by NAAC | 12B Status by UGC | Approved by AICTE
www.sathyabama.ac.in

SCHOOL OF BIO & CHEMICAL ENGINEERING

DEPARTMENT OF BIOMEDICAL ENGINEERING

UNIT – II - MEMS in Healthcare – SBMA7007

INTRODUCTION TO BIOMIMETIC SUBSTRATES:

Biomimetics or biomimicry is the emulation of the models, systems, and elements of nature for the purpose of solving complex human problems. The terms "biomimetics" and "biomimicry" derive from Ancient Greek: *bios*- life, *mimesis*- imitation. Living organisms have evolved well-adapted structures and materials over geological time through natural selection. Biomimetics has given rise to new technologies inspired by biological solutions at macro and nanoscales. Biomimetics is an interdisciplinary field in which principles from engineering, chemistry and biology are applied to the synthesis of materials, synthetic systems or machines that have functions that mimic biological processes.

Fig-1: (a)The tiny hooks on bur fruits (left) inspired Velcro tape (right).

Fig-1: (b) The streamlined design of Shinkansen 500 Series (left) mimics the beak of kingfisher (right) to improve aerodynamics.

Biomimetic cell culture substrates are developed as an alternative to the conventional substrates. They provide necessary biochemical and biophysical cues to the cells from their surrounding environment for their optimal growth, behaviour and physiology. Changes in physiology of cells growing on biomimetic substrate can essentially affect results of in vitro biological experiments such as drug cytotoxicity, nanoparticle internalization or signaling pathways.

MICROSCAFFLODING:

SCAFFOLDING: also called scaffold or staging, is a temporary structure used to support a work crew and materials to aid in the construction, maintenance and repair of buildings, bridges and all other man-made structures. Scaffolds are widely used on site to get access to heights and areas that would be otherwise hard to get.

- Microscaffolds are porous 3D scaffolds with applications in high-throughput screening and cell therapy. Cells grow on, around and into the material, forming micro-islands of adherent cells that are effectively “micro-tissues in solution”.
- Mimetix microscaffolds, made from the same polymer and with the same architecture as the scaffolds in our Mimetix well-plates, also contain iron particles so that they can be physically manipulated using magnets.

Properties:

- Reproducible 3-D culture environment
- Applicable to any cell type
- Movable: from vessels-to-well and well-to-well with magnetism
- Scalable to any assay throughput
- Seamless integration with screening and assay workflows

CELLULAR CO CULTURES:

Cellular Co-Culture is a cell cultivation setup in which two or more different populations of cells are grown with some degree of contact between them. (eg: protein adsorption and cell adhesion). Microfabricated systems provide an excellent platform for the culture of cells, and are an extremely useful tool for the investigation of cellular responses to various stimuli. Advantages offered over traditional methods include cost-effectiveness, controllability, low volume, high resolution, and sensitivity.

- Biocompatible materials such as PMMA or PLGA can be used directly for cell culture
- However, for bio-incompatible materials such as silicon or PDMS, additional steps need to be taken to render these materials more suitable for cell adhesion and maintenance.
-

Few examples of MEMS tool/material used in cell culture:

- X-ray photoelectron Spectroscopy is a surface analysis tool is used to show nitrogen signal as indicator of amine bonds of organic molecules which was significantly higher on bioactive glass.
- Vitronectin & Fibronectin were adsorbed from a fetal bovine serum into a platform of Primaria.
- MEMS materials chemical structure, surface property determine their biocompatibility through protein adsorption and cell adhesion.
- Using CVD (chemical vapour deposition) Si_3N_4 , has the capability for cell culture as NH_2 has got good cell adhesion property.
- PDMS has good gas permeability, excellent adhesion to glass and many substrates.
- PDMS bioreactors were used to cultivate liver cells
- PDMS membrane less than 20µm thick & 5x5µm pores serves as a scaffold for attachment of cells.
- Bovine Aortic Endothelial cells (BAEC) can be cultured using micro-nanogrooved PDMS channels with depth 200nm, 5oonm, 1µm-5µm.
- PDMS microchip monitors catecholamines released from rat cells (PC-12)
- PMMA can be surface modified to introduce amine groups for DNA purification.

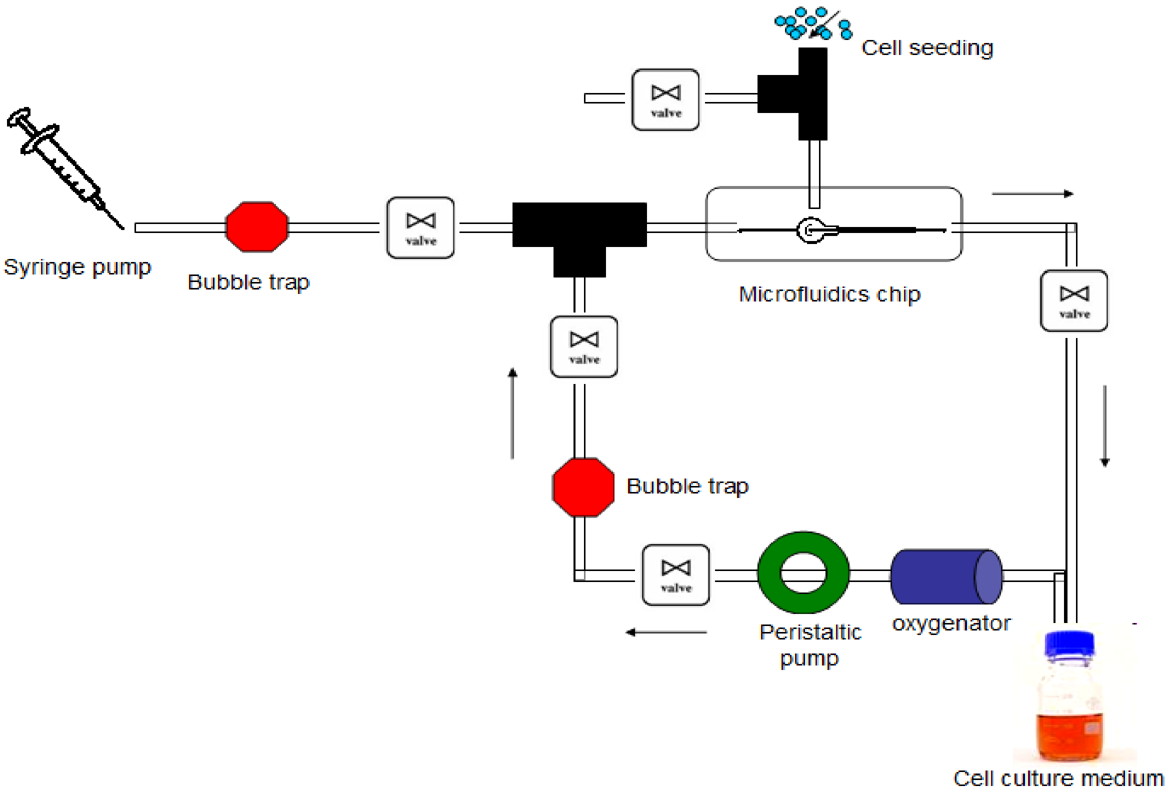


Fig-2: Schematic of prefusion system

MICROSENSORS AND MICROACTUATORS WORKING PRINCIPLE:

MICROSENSORS:

- A sensor element is a device that converts one form of energy into another (e.g., ZnO, a piezoelectric material, which converts mechanical energy into electricity) and provides the user with a usable energy output in response to a specific measurable input.
- Measurands may belong to the radiation, thermal, electrical, chemical, mechanical, or magnetic field domains. The sensor element may be built from plastics, semiconductors, metals, ceramics, etc.
- A microsensor must be in micro scale in dimension.
- A sensor includes a sensor element or an array of sensor elements with physical packaging and external electrical or optical connections. Synonyms for “sensor” are *transducer* and *detector*.
- A sensor system includes the sensor and its assorted signal processing hardware (analog or digital).
- *Transducer* sometimes refers to a sensor system, especially in the process control industry.

- In the case of silicon-based sensors, some additional jargon has developed. A Si sensor element is called a *sensor die*, which refers to a micromachined Si chip.
- It typically sells for $0.10 to $2 as a commodity product, although the price tag can rise to $50 or more for a high-performance structure sold in smaller quantities.

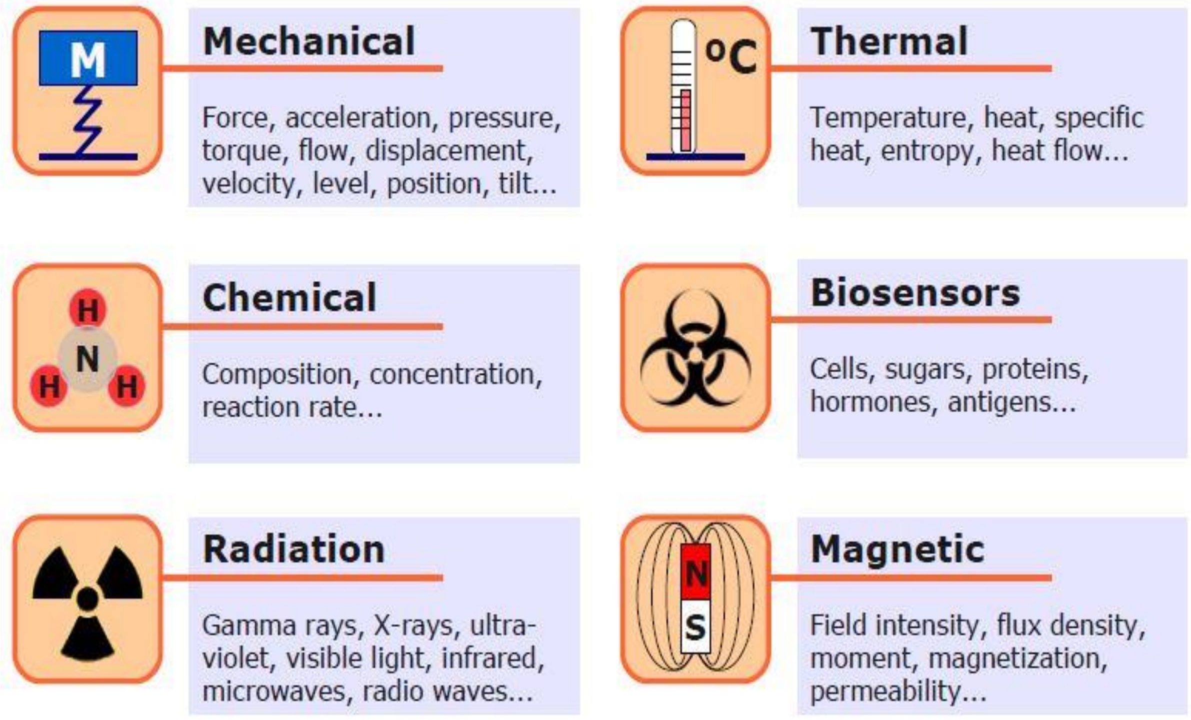


Fig-3: Application of microsensors in different fields of interest

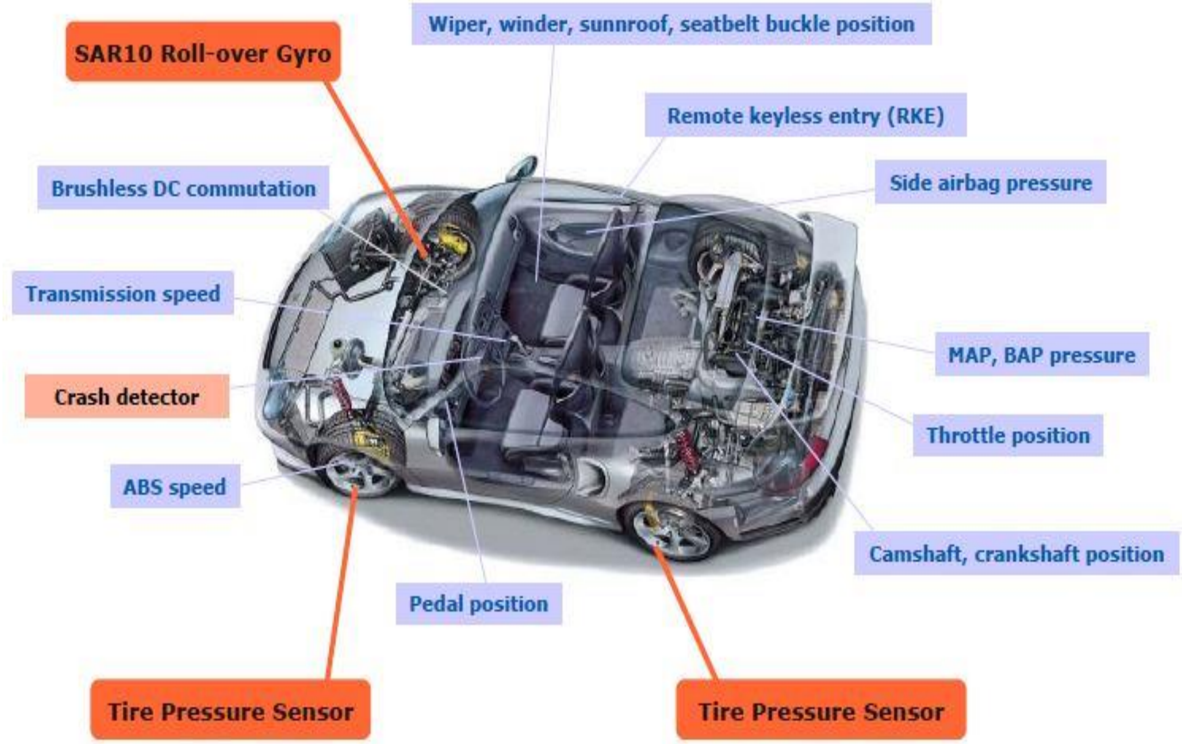


Fig-4: Typical example of microsensors used in cars

Biomedical Applications of Microsensors:

1) Disposable blood pressure sensors (17 million units per year)

2) Intrauterine pressure sensor (1 million units per year)

3) Infusion pump pressure sensor (2,00,000 units per year)

4) Catheter type pressure sensors

5) Lung Capacity meters

6) Kidney dialysis equipment

7) Human care support systems

The silicon sensor die is shown in figure below. It has sensor element that takes input from various process variables like pressure, temperature, viscosity, flow, level, etc. The outputs obtained from the sensor are fed directly to the calibration device and are converted into a suitable form. There is a modulating device which helps in the manipulation of the process variables. The Data conversion element performs the conversion of the obtained process variable from one form to another form while data transmission element transfers the energy from one location to another through bus. It is possible to interface the smart silicon sensor with the module.

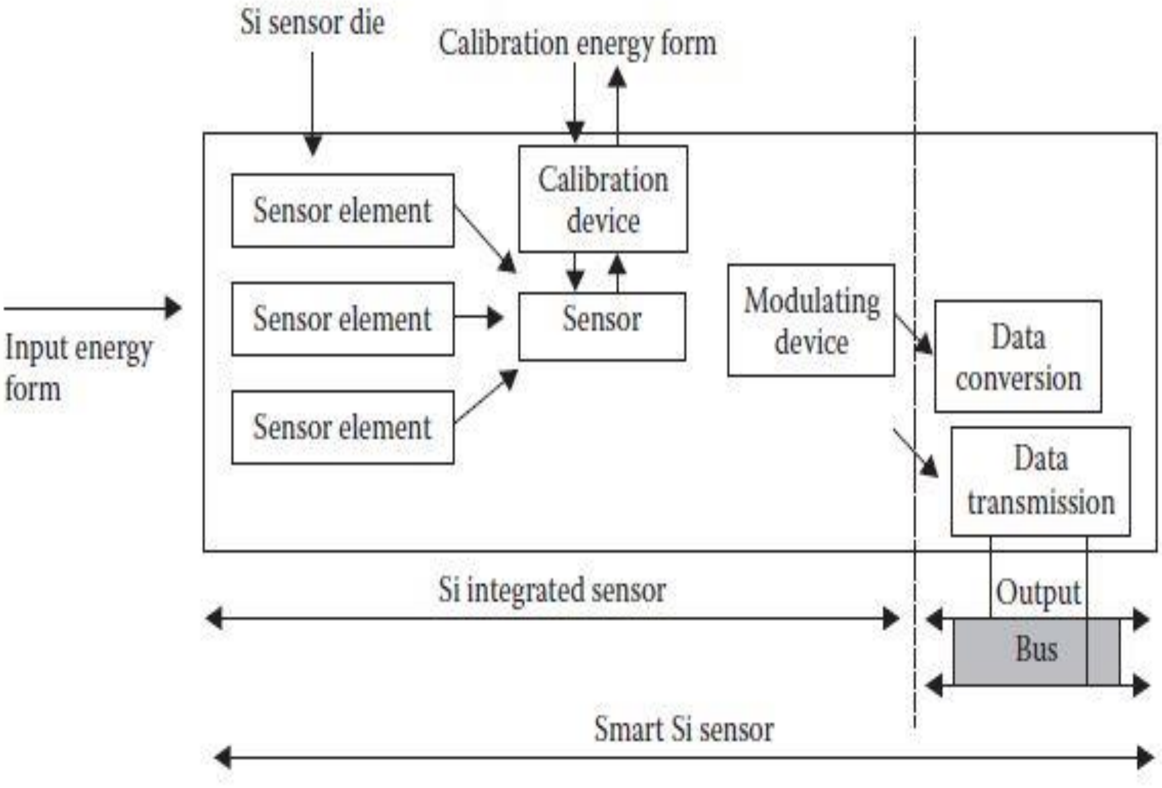


Fig-5: Silicon sensor die

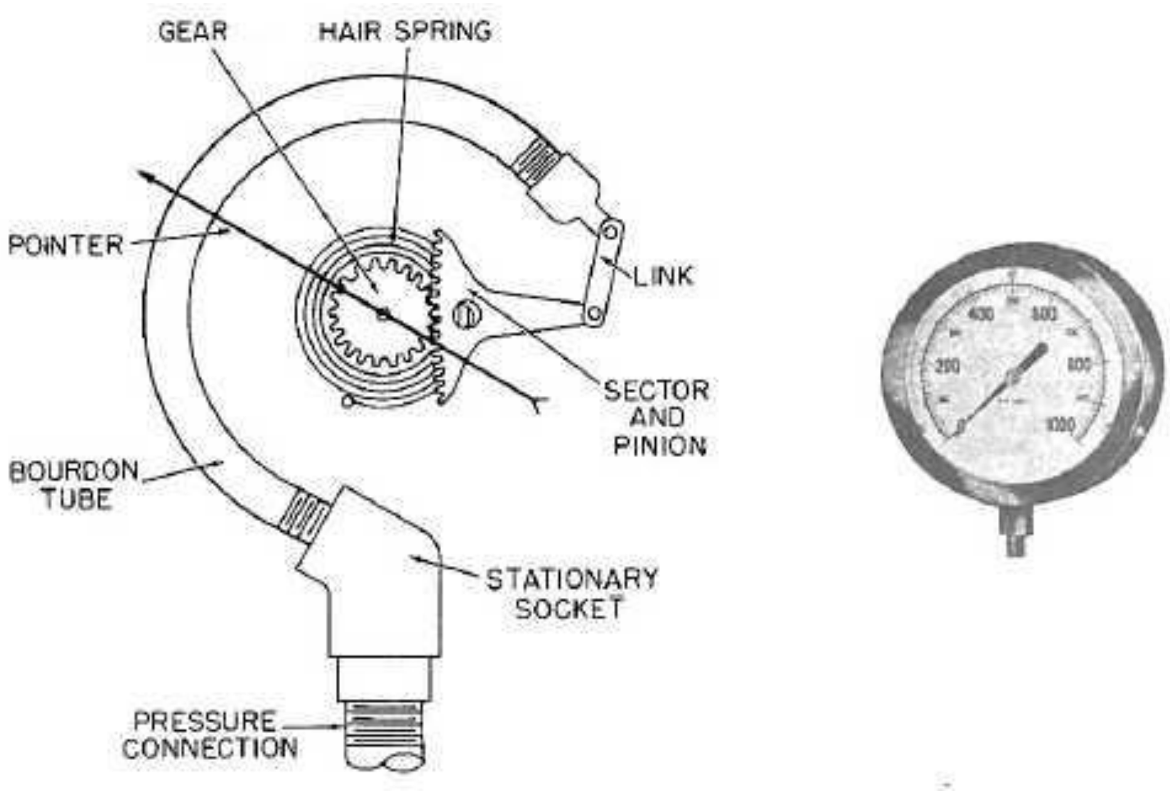
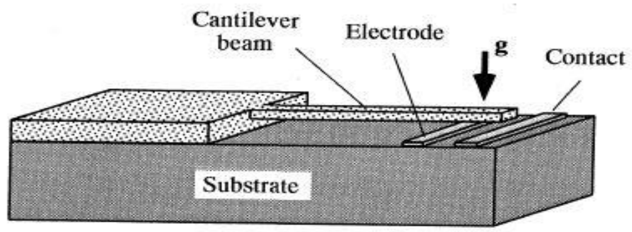


Fig-6: Example measurement system

- At yet a higher level is a *smart silicon sensor*, which is a packaged integrated sensor containing some part of the signal-processing unit to provide performance enhancement for the user.
- Signal processing might include autocalibration, interference reduction, compensation for parasitic effects, offset correction, and self-test.

Example of microsensor:



Cantilever length: 120 - 500 µm
Sensitivity: 0.6 - 100 mV/g
Fabrication: dry etching

- Sensor consists of cantilevers acting as one electrode, an electrode strip and a contact strip
- Sawtooth voltage applied to gradually increase the electrostatic force
- Finally cantilever touches the contact strip
- Acceleration affects the magnitude of the voltage that is required for contact

Fig-7: Capacitive cantilever micro sensor

MICROACTUATORS:

An actuator is a component of a machine that is responsible for moving and controlling a mechanism or system, for example by opening a valve. In simple terms, it is a "mover“. Its main energy source may be an electric current, hydraulic fluid pressure, or pneumatic pressure. When it receives a control signal, an actuator responds by converting the source's energy into mechanical motion. They facilitate a function such as opening a valve, positioning a mirror, moving a plug of liquid, etc.

Since an actuator “acts,” some power is usually needed. The selling price for Si-based actuators in large quantities may range from $5 to $200

Working Principle:

- Microactuators are based on three-dimensional mechanical structures with very small dimensions which are produced with the help of lithographic procedures and non-isotropic etching techniques.
- For an actuator-like displacement the most different principles of force generation are used, such as the bimetal effect, piezo effect, shape memory effect and electrostatic forces.
- Characteristic for microactuators in a more narrow sense is the fact that the mechanism of force generation is integrated monolithically
- Movable structural parts are made up of surface micromachining based on single crystal silicon, techniques like electrical discharge machining (EDM), micro injection molding.

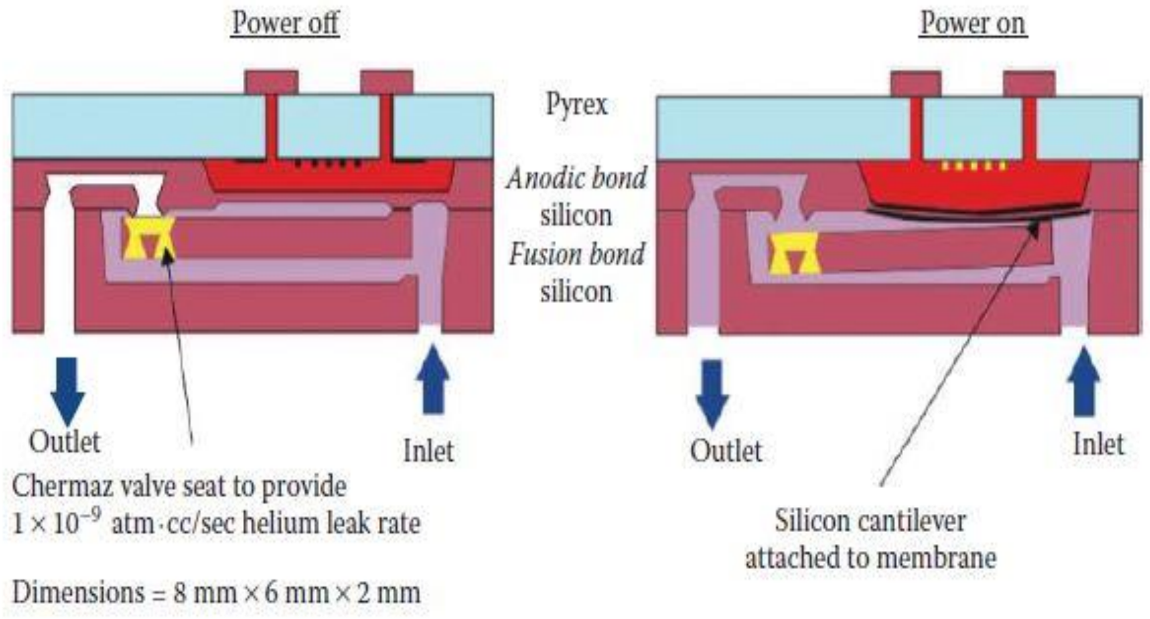


Fig-8: Examples of commercially available actuators. Thermopneumatic valves by Redwood Microsystem s (Fluistor). Normally closed shut-off microvalve featuring a liquid-

filled cavity, which flexes a silicon diaphragm when heated, forcing the valve cover to lift off the valve seat.

EXAMPLE OF MICROACTUATOR- ELECTROMAGNETIC MICRO MOTORS:

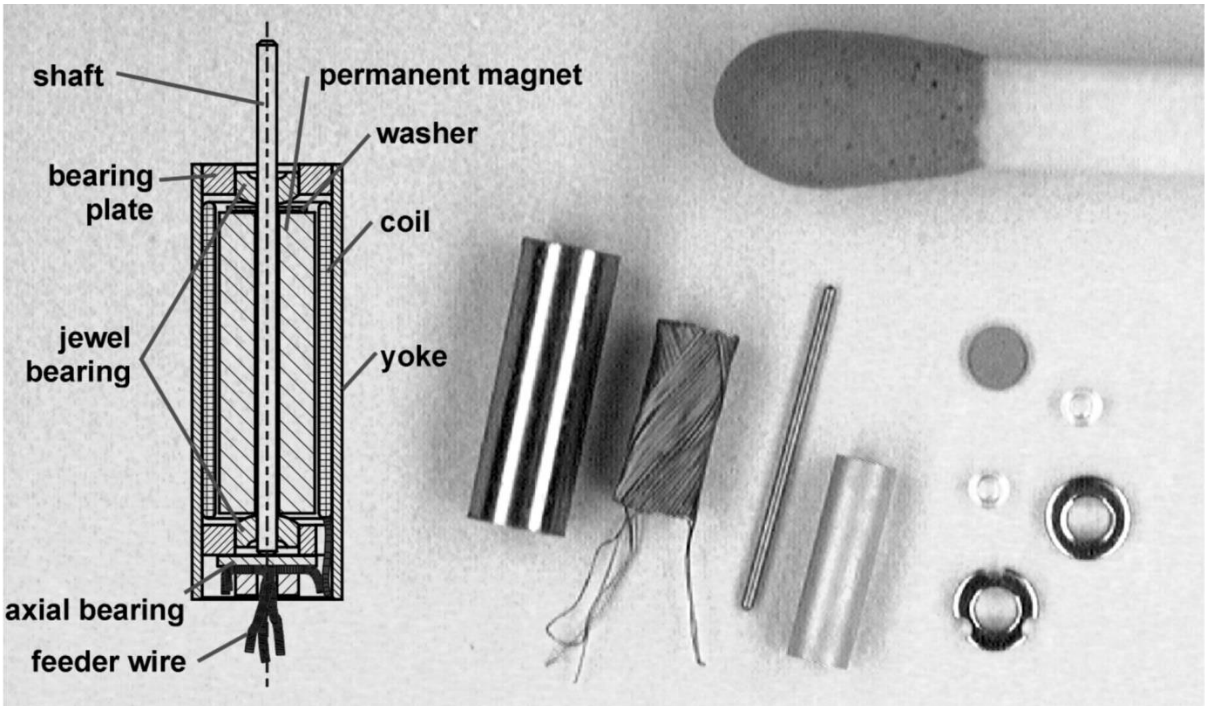


Fig-9: Construction and components of a electromagnetic micromotor

The electromagnetic micromotor has a permanent magnet placed at two sides of the system. It has a bearing plate, shaft, yoke, bearing jewel and axial bearing which are the mechanical components of the electromagnetic micromotor. When current flows in the conductor in the presence of magnetic field, then there is a rotational movement produced in the shaft which is the output obtained across the micromotor.

MICROGRIPPERS:

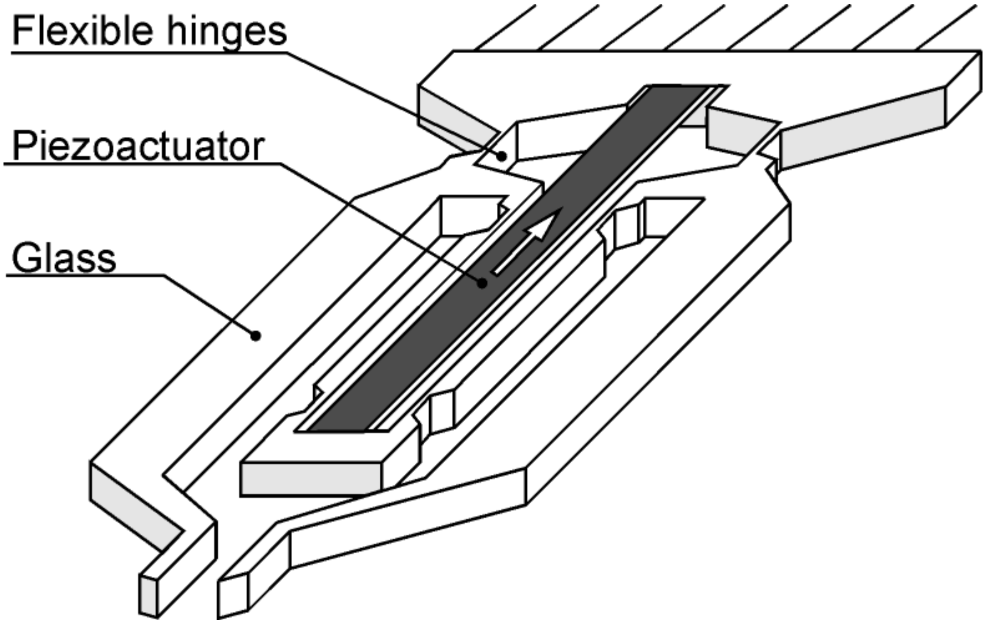


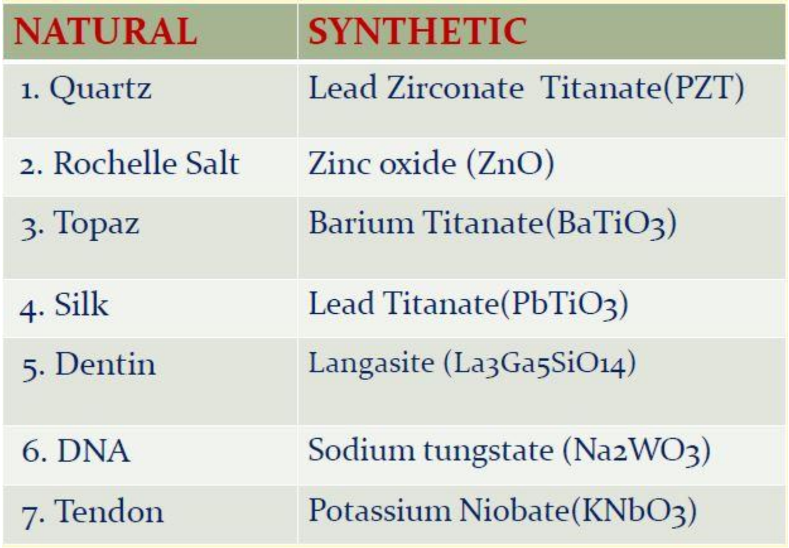
Fig-10: MEMS microgripper

PIEZOELECTRIC CRYSTAL:

- The meaning of the word “piezoelectric” implies “*pressure electricity*”- the generation of electric field by applying pressure.
- Piezoelectricity is observed if a stress is applied to a solid, like by bending , twisting or squeezing it.
- The material exhibiting the direct piezoelectric also exhibit the reverse piezoelectric effect (the internal generation of a mechanical strain resulting from an applied electric field).

Fig-11: Piezoelectric crystal electricity generation

Table-1:Natural & Synthetic material



NATURAL	SYNTHETIC
1. Quartz	Lead Zirconate Titanate(PZT)
2. Rochelle Salt	Zinc oxide (ZnO)
3. Topaz	Barium Titanate($BaTiO_3$)
4. Silk	Lead Titanate($PbTiO_3$)
5. Dentin	Langasite ($La_3Ga_5SiO_{14}$)
6. DNA	Sodium tungstate (Na_2WO_3)
7. Tendon	Potassium Niobate($KNbO_3$)

Working of Piezoelectric:

- Normally, the charges in a piezoelectric crystal are exactly balanced, even if they're not symmetrically arranged .
- The effects of the charges exactly cancel out, leaving no net charge on the crystal faces.(More specifically, the electric dipole moment is zero).
- Now the effect of the charges (their dipole moments) no longer cancel one another out and net positive and negative charges appears on the crystal faces.
- By squeezing the crystal, we have produced a voltage across it's opposite faces– and that's PIEZOELECTRICITY.
- If we squeeze the crystal ,you force the charges out of balance.

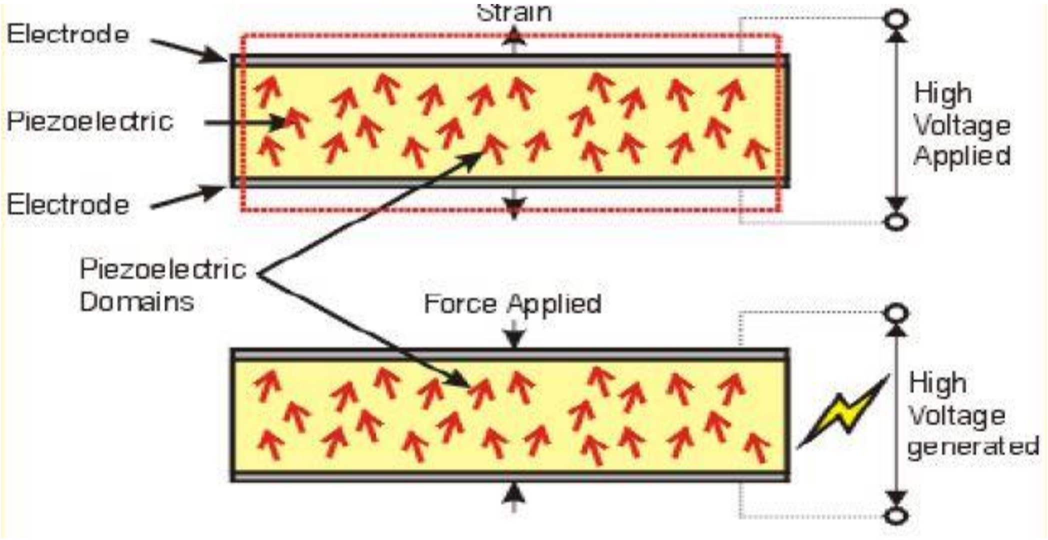


Fig-12: Movement of charges under applied stress

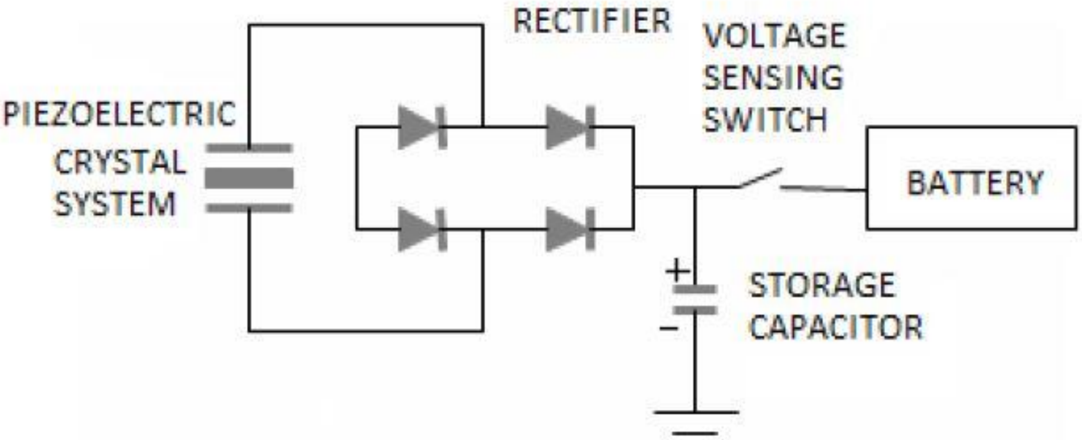


Fig-13: Piezoelectric crystal coupled with rectifier and battery for storing

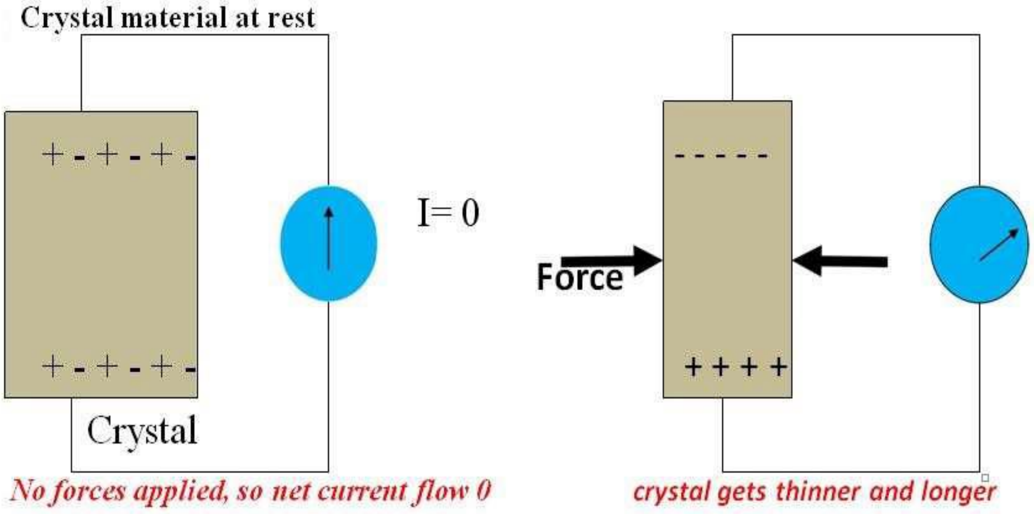


Fig-14: Piezoelectric effect

Applications of Piezoelectric materials:

Sensor:

- -Microphones, Pick-ups
- -Pressure sensor
- -Force sensor
- -Strain gauge

Actuators

- -Loudspeaker

- -Piezoelectric motors
- -Nanopositioning in AFM or STM
- -Acoustic-optical modulators
- -Valves

High voltage and power source

- -Cigarette lighter
- -Energy harvesting
- -AC voltage multiplier

Implementation of Piezoelectricity in practical life:

• **Energy Harvesting**: Vibrations from industrial machinery can also be harvested by piezoelectric materials to charge batteries for backup supplies or to power low-power microprocessors and wireless radios. Piezoelectric elements are also used in the detection and generation of sonar waves.

• **Inkjet printers**: On many inkjet printers, piezoelectric crystals are used to drive the ejection of ink from the inkjet print head towards the paper.

• **Diesel engines**: High-performance common rail diesel engines use piezoelectric fuel injectors, first developed by Robert Bosch , instead of the more common solenoid valve devices.

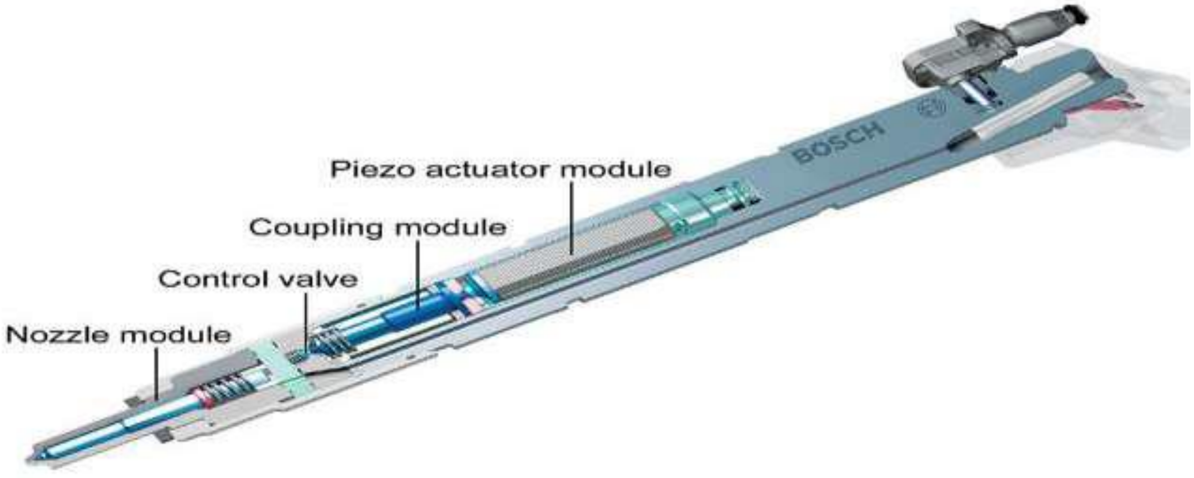
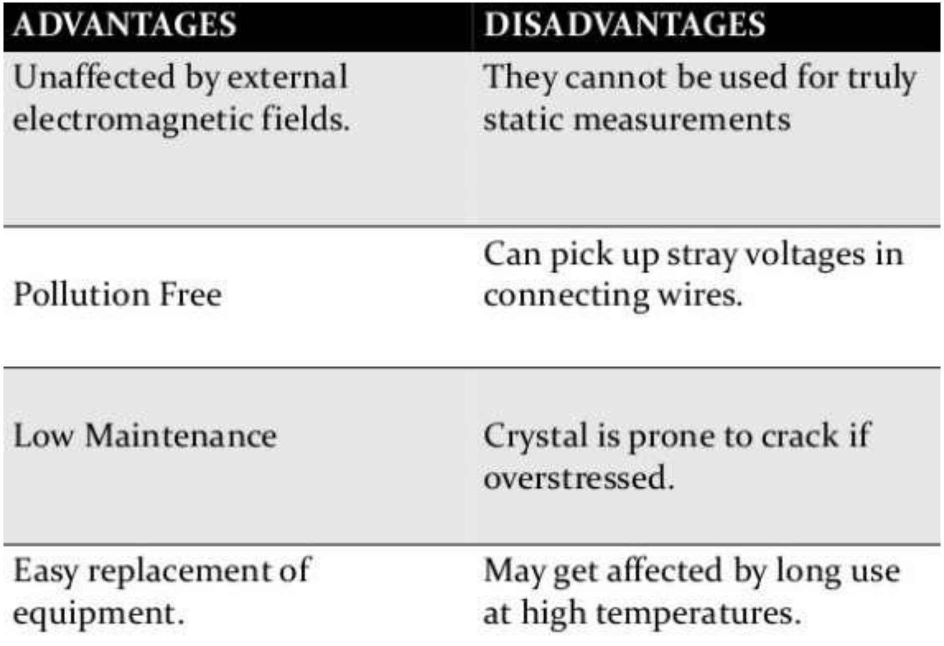


Fig-15: TYPICAL PIEZOELECTRIC INJECTION SYSTEM

Table-2: Advantages and disadvantages of Piezoelectric property materials



ADVANTAGES	DISADVANTAGES
Unaffected by external electromagnetic fields.	They cannot be used for truly static measurements
Pollution Free	Can pick up stray voltages in connecting wires.
Low Maintenance	Crystal is prone to crack if overstressed.
Easy replacement of equipment.	May get affected by long use at high temperatures.

- Piezoelectricity is a revolutionary source for “GREEN ENERGY”
- Flexible piezoelectric materials are attractive for power harvesting applications because of their ability to withstand large amounts of strain.
- Convert the ambient vibration energy surrounding them into electrical energy.
- Electrical energy can then be used to power other devices or stored for later use.

PRESSURE SENSORS:

- Several types of pressure sensor can be built using MEMS techniques.
- Most common: piezoresistive and capacitive.
- In both of these, a flexible layer is created which acts as a diaphragm that deflects under pressure but different methods are used to measure the displacement.

MEMS capacitive pressure sensors

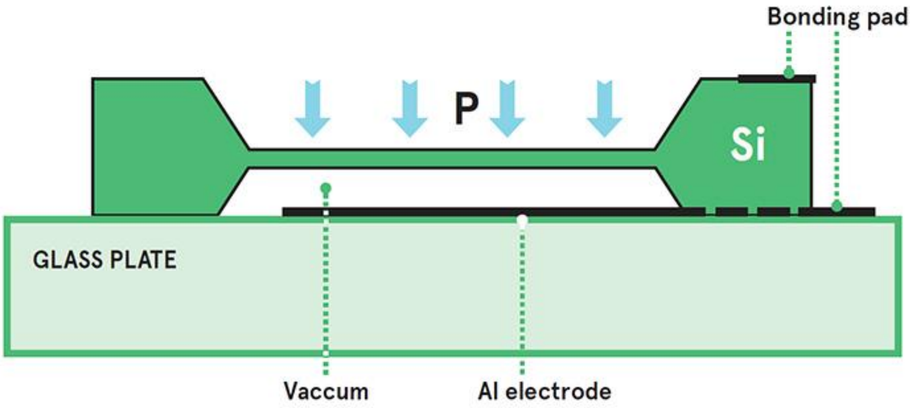


Fig-16: MEMS Capacitive pressure sensor

To create a capacitive sensor, conducting layers are deposited on the diaphragm and the bottom of a cavity to create a capacitor. The capacitance is typically a few picofarads. Capacitive pressure sensors measure pressure by detecting changes in electrical capacitance caused by the movement of a diaphragm. Deformation of the diaphragm changes the spacing between the conductors and hence changes the capacitance.

The change can be measured by including the sensor in a tuned circuit, which changes its frequency with changing pressure.

A capacitor consists of two parallel conducting plates separated by a small gap. The capacitance is defined by:

$$C = \varepsilon_r \varepsilon_0 \frac{A}{d}$$

where:

- ε_r is the dielectric constant of the material between the plates (this is 1 for a vacuum)
- ε_0 is the electric constant (equal to 8.854×10^{-12} F/m),
- A is the area of the plates
- d is the distance between the plates
  - ☐ The capacitance of the sensor is typically around 50 to 100 pF, with the change being a few picofarads.
  - ☐ The diaphragm can be constructed from a variety of materials, such as plastic, glass, silicon or ceramic, to suit different applications.

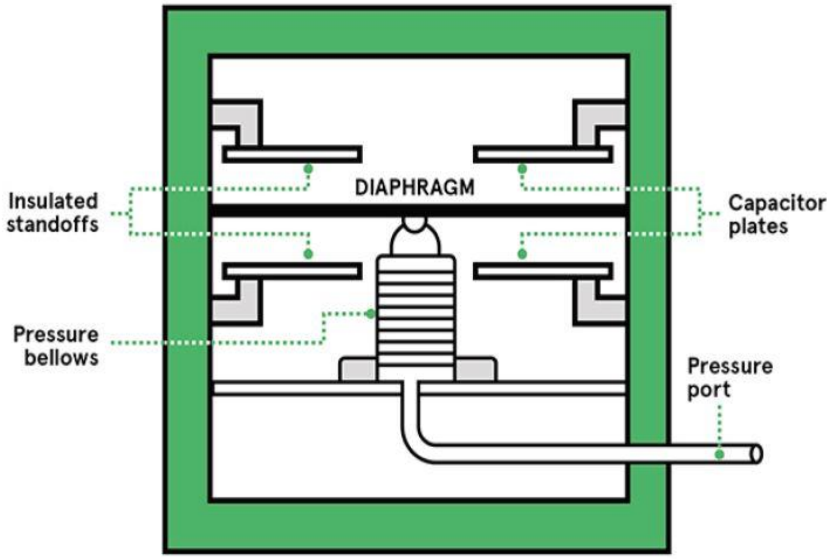


Fig-17: Diaphragm Pressure sensor system

The stiffness and strength of the material can be chosen to provide a range of sensitivities and operating pressures. To get a large signal, the sensor may need to be fairly large, which can limit the frequency range of operation. However, smaller diaphragms are more sensitive and have a faster response time.

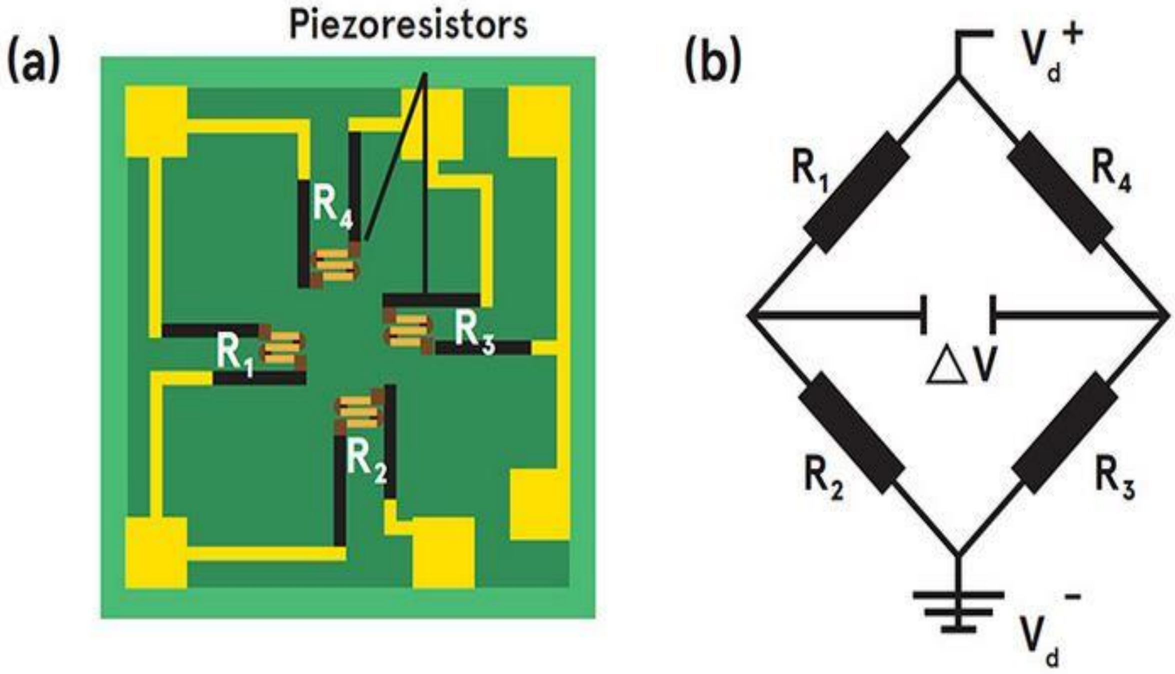


Fig-18: (a) Arrangement of Piezoresistors (b) Wheatstone bridge connection

THERMAL SENSORS AND ACTUATORS:

- One of the primary methods for electrical measurement of temperature involves changes in the electrical resistance of certain materials.
- In this, as well as other cases, the principal measurement technique is to place the temperature-sensing device in contact with the environment whose temperature is to be measured.
- The two basic devices used are the *resistance-temperature detector* (RTD), based on the variation of metal resistance with temperature, and the *thermistor*, based on the variation of semiconductor resistance with temperature

Metal Resistance versus Temperature Devices

- A metal is an assemblage of atoms in the solid state in which the individual atoms are in an equilibrium position with superimposed vibration induced by the thermal energy.
- As electrons move throughout the material, they collide with the stationary atoms or molecules of the material.
- When a thermal energy is present in the material and the atoms vibrate, the conduction electrons tend to collide even more with the vibrating atoms.
- This impedes (delays) the movement of electrons and absorbs some of their energy; that is, the material exhibits a *resistance* to electrical current flow.
- The graph in Figure 19 shows the effect of increasing resistance with temperature for several metals.
- To compare the different materials, the graph shows the relative resistance versus temperature.

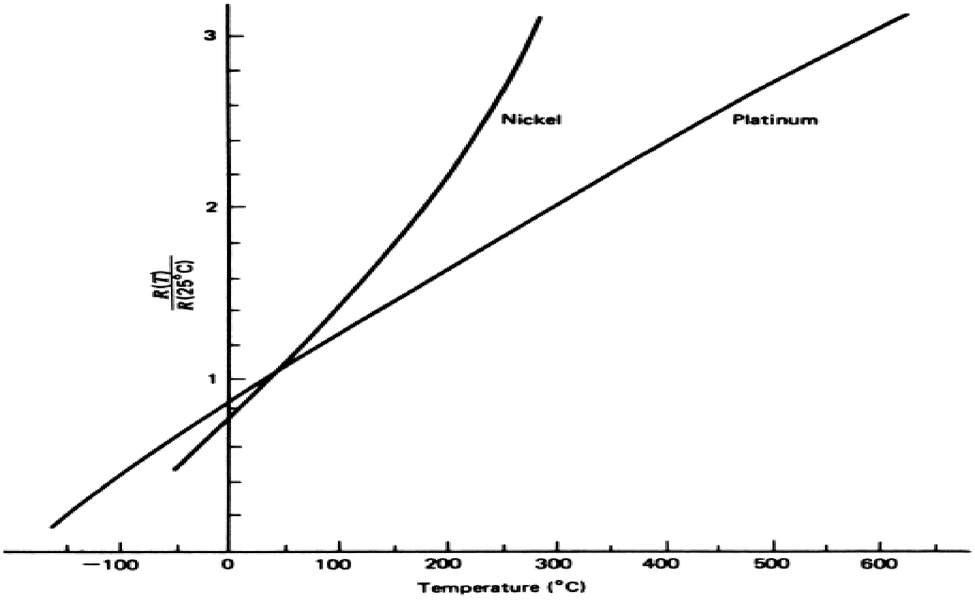


Fig-19: Temperature Vs resistance for different metals

The equation of this straight line is the linear approximation to the curve over the spanT_1 to T_2 . The equation for this line is typically written as

$$R(T) = R(T_0)[1 + \alpha_0 \Delta T] \qquad T_1 < T < T_2$$

where $R(T)$ = approximation of resistance at temperature T

$R(T_0)$ = resistance at temperature T_0

$\Delta T = T - T_0$

α_0 = fractional change in resistance per degree of temperature at T_0

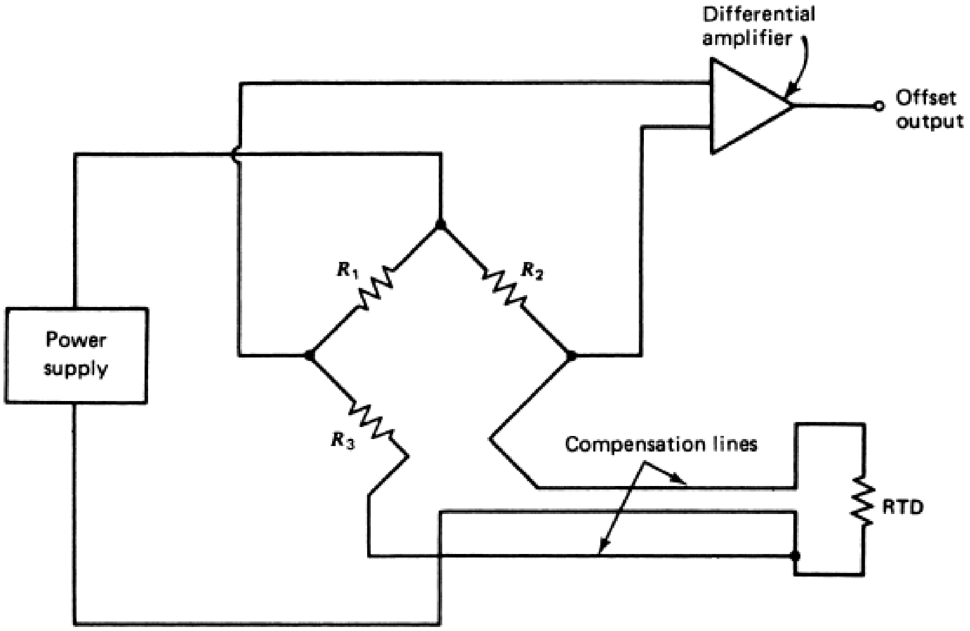


Fig-20: Typical RTD Circuit

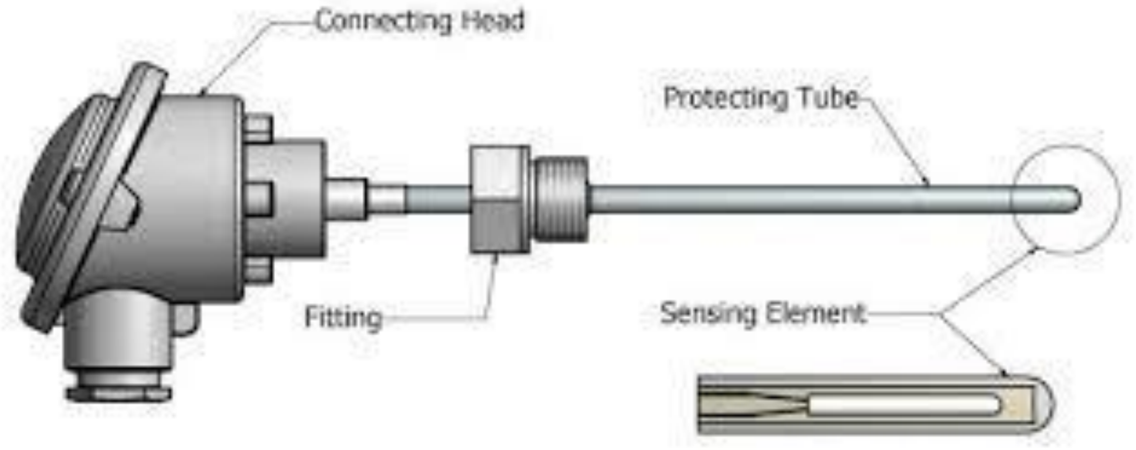


Fig-21: Picture of RTD

THERMISTORS:

The thermistor represents another class of temperature sensor that measures temperature through changes of material resistance. The characteristics of these devices are very different from those of RTDs and depend on the peculiar behavior of semiconductor resistance versus temperature.

Semiconductor Resistance versus Temperature

In contrast to metals, electrons in semiconductor materials are bound to each molecule with sufficient strength that no conduction electrons are contributed from the valence band to the conduction band.

- When the temperature of the material is increased, the molecules begin to vibrate. In the case of a semiconductor, such vibration provides additional energy to the valence electrons. When such energy equals or exceeds the gap energy.
- As the temperature is further increased, more and more electrons gain sufficient energy to enter the conduction band.
- It is then clear that the semiconductor becomes a better conductor of current as its temperature is increased—that is, as its resistance decreases.

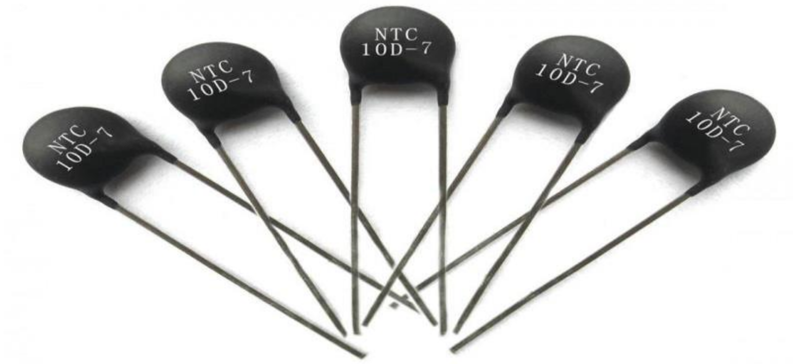


Fig-22: Thermistor Bead

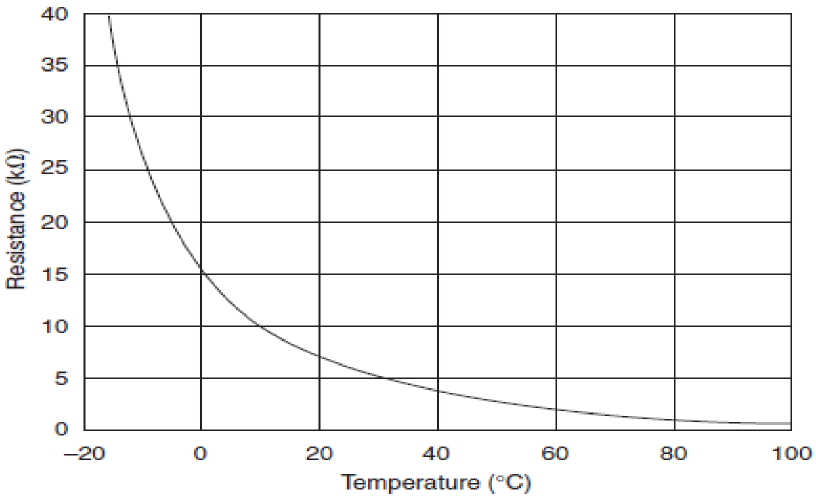


Fig-23: Temperature versus resistance response of Thermistor

THERMAL ACTUATORS:

- Actuation of microscale devices and structures can be achieved by injecting or removing heat.
- Temperature of microstructure raised by absorption of electromagnetic waves (including light), ohmic heating (joule heating), conduction and convection heating.
- Cooling achieved via conduction dissipation, convection dissipation, radiation dissipation, and active thermoelectric cooling.
- Many ink-jet printers eject ink droplets using thermal expansion of liquid links.

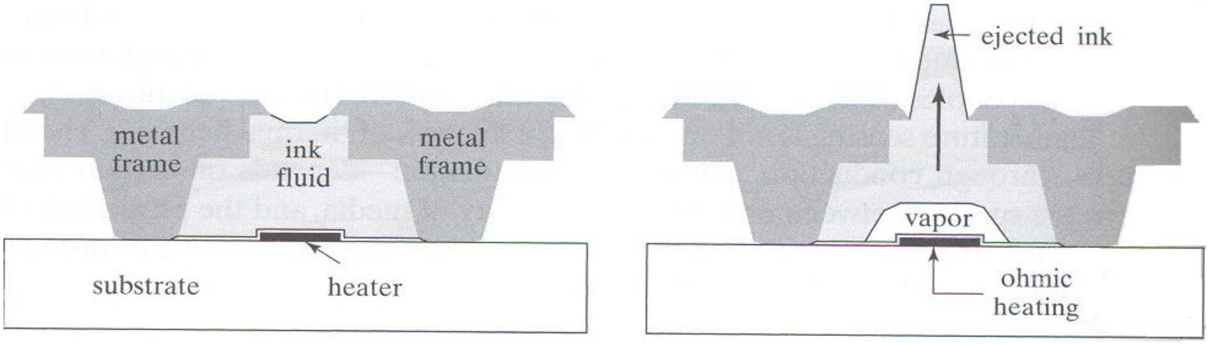


Fig-24: Example thermal actuator

Example: Thermal Inkjet Print Head

- Using resistive heating to produce tiny ink droplets. Also known as bubble jet. A typical MEMS inkjet print head has up to 600 nozzles (~10µm)

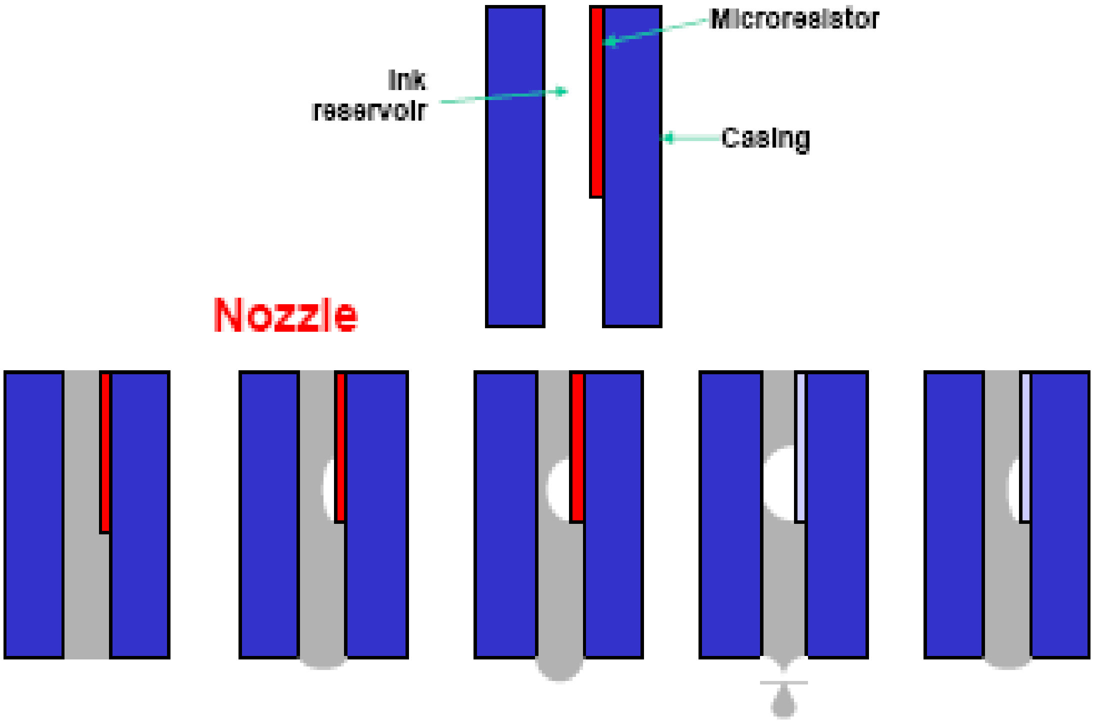


Fig-25: Inkjet Printer working phenomenon

The working procedure of the inkjet printer is as follows:

A micro-resistor creates heat → Heat vaporises ink to create a bubble → Bubble expands → A drop of ink is pushed out of a nozzle onto the paper → Heat turned off → Bubble collapses and vacuum is created → More ink into the print head from the cartridge.

Sensors and actuators based on thermal expansion:

Thermal expansion is the tendency of matter to change in volume in response to a change in temperature.

- The volumetric thermal expansion coefficient (TCE)

$$\alpha = \frac{\frac{\Delta V}{V}}{\Delta T}$$

- The linear expansion coefficient

$$\beta = \frac{\frac{\Delta l}{l}}{\Delta T}$$

- Relationship:

$$\alpha = 3\beta$$

- The thermal gases due to temperature change can be derived from the ideal gas law. For an ideal gas:

$$PV = nRT = NkT$$

- P is absolute pressure, V the volume, T the absolute temperature, n the number of moles, N the number of molecules, R universal gas constant (R= 8.3145 J/molK), k the boltzman constant (1.30866 x 10^{-23} J/K), N_A *is Avogadro no.*(N_A = 6.0221 x 10^{23})

$$k = R/N_A$$

Thermal bimorph principle:

This mechanism allows the temperature variation in microstructures to be shown as the transverse displacement of mechanical beams.

Consist of two materials joined along their longitudal axis acting as a single mechanical element.

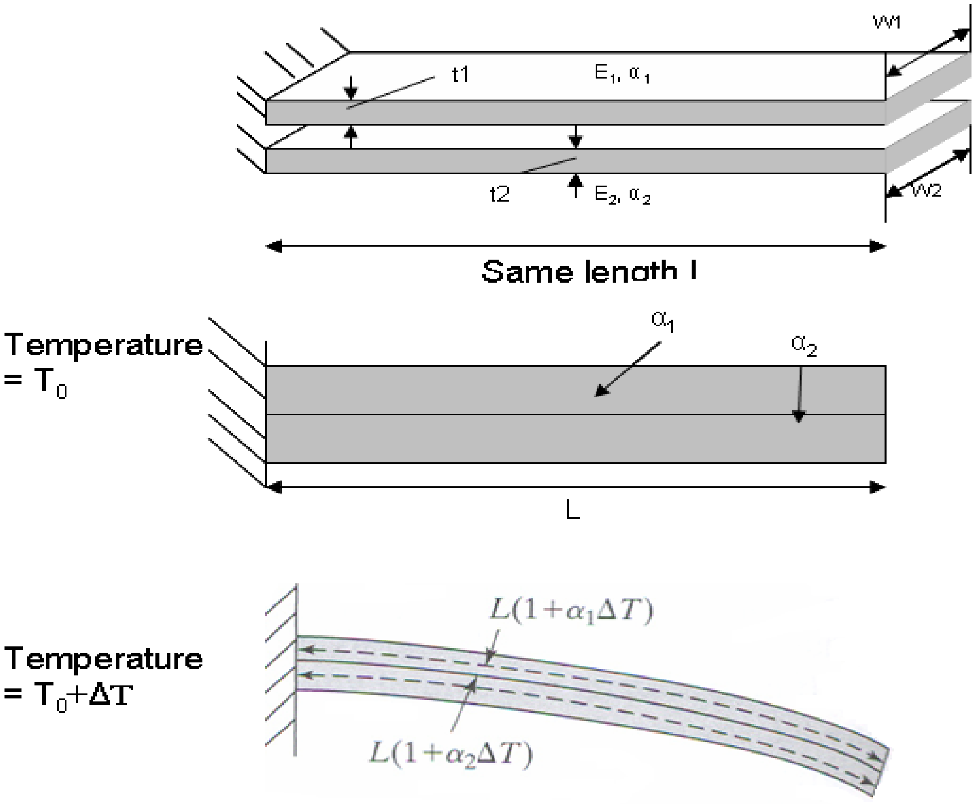


Fig-26: Thermal Bimorph principle.

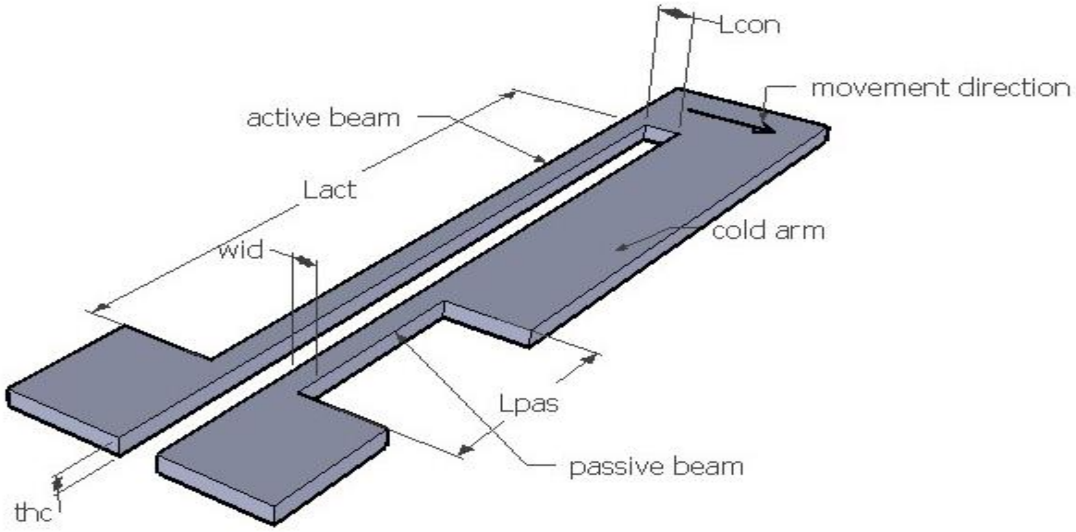


Fig-27: Full image of thermal bimorph transducer

A thermal bimorph actuator consists of a hot and cold region which are connected together. The bimorph actuator is made of one material. For a bimorph actuator only a portion of it is heated. If a current is passed through the entire system between the two fixed pads, the higher Joule heating in the thinner active beam would cause its expansion while the temperature of the cold arm will remain relatively unchanged.

The cold arm is connected to the fixed pad via a passive beam of the same cross-sectional area as the active beam. The passive beam allows flexibility of the cold arm and at the same time can be used to control the deflection based on its length.

The hot and cold arms are connected together by a connecting link which has an influence on the deflection. This design interface can be used to determine the deflection and actuation force for a thermal bimorph actuator as shown above. The deflection and force are estimated at the free tip of the actuator. The influence of the different geometric features of the actuator on its deflection can be examined.

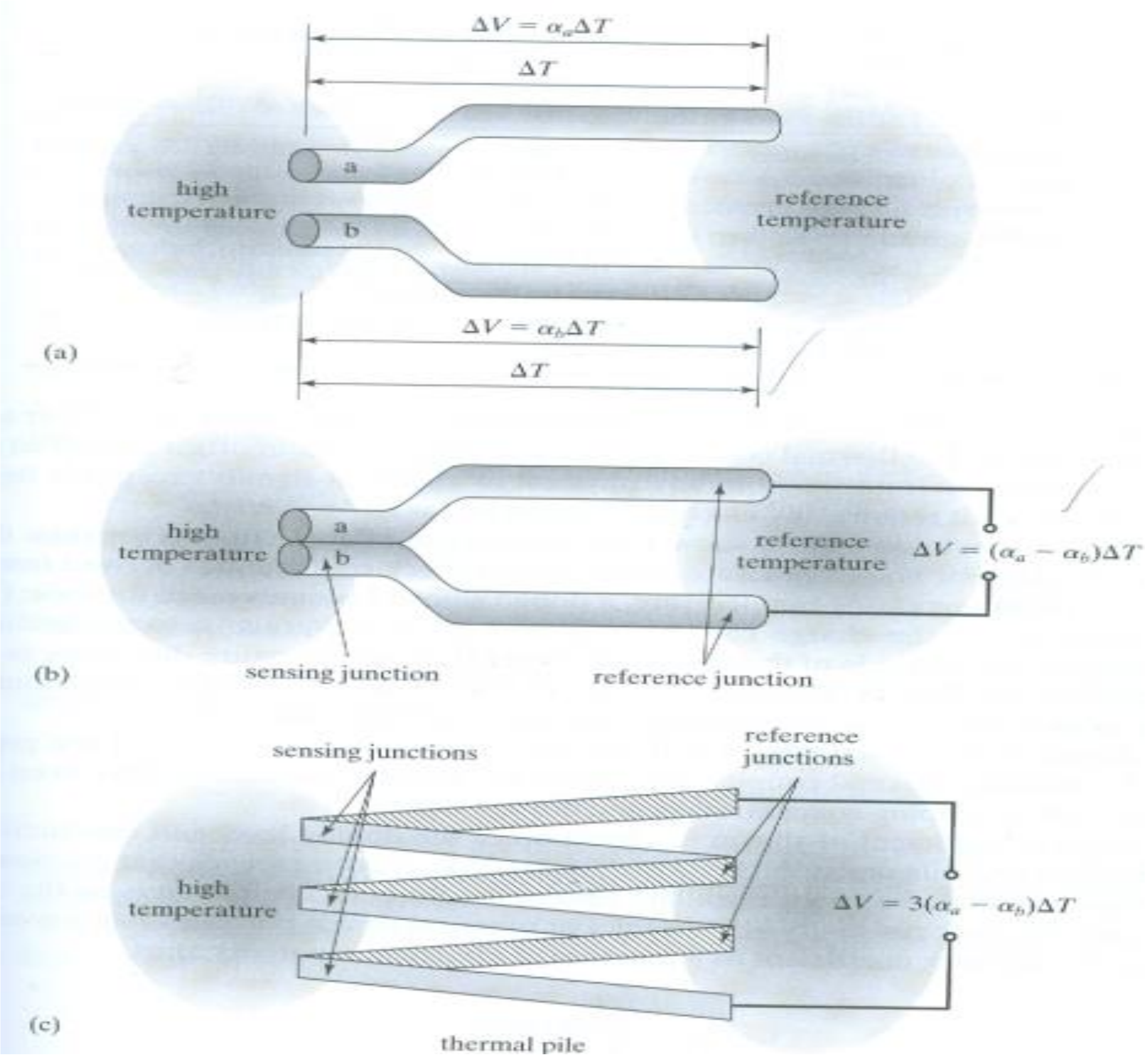


Fig-28: Thermocouple effect

Seebeck coefficient of thermal, $\alpha_{ab} = \alpha_a - \alpha_b$

Advantages of Thermal Couple:

1. Provides an output without offset and offset drift.
2. Not suffer from interference from any physical or chemical signals except for light.
3. Not require any electrical biasing and is self powered.

For non-degenerate silicon, Seebeck coefficient is derived from 3 main effects:

1. With increasing temperature, a doped silicon becomes more intrinsic
2. With increasing temperature, the charge carrier acquire a greater average velocity (buildup charge on the cold side of the semiconductor)

3. The temperature difference in a piece of silicon causes a net flow of phonons from hot to cold end.

Applications:

- Inertia Sensors
- Flow sensors
- Infrared sensors

THERMAL BIOSENSORS:

- THERMAL biosensors measure thermal energy released or absorbed in biochemical reactions.
- Thermal activities exist ubiquitously in Biological Processes, and hence widely applicable.
- Requiring no labeling of reactants, thermal bio sensing is a universally useful method, allowing direct interrogations of elementary processes in biochemistry without sophisticated cascades of reaction steps.

MEMS thermal sensors are often based on temperature detection.

I. Thermistors

- Rely on changes in their electric resistance with temperature.
- Allow measurement of absolute temperatures.
- Limited in sensitivity

II. Thermopile

- Set of Thermocouple Junctions connected in series.
- Allows measurement of differences in temperature between two Junctions.
- Offers excellent common-mode noise cancellation and zero offset, and therefore can be highly
- Sensitive.

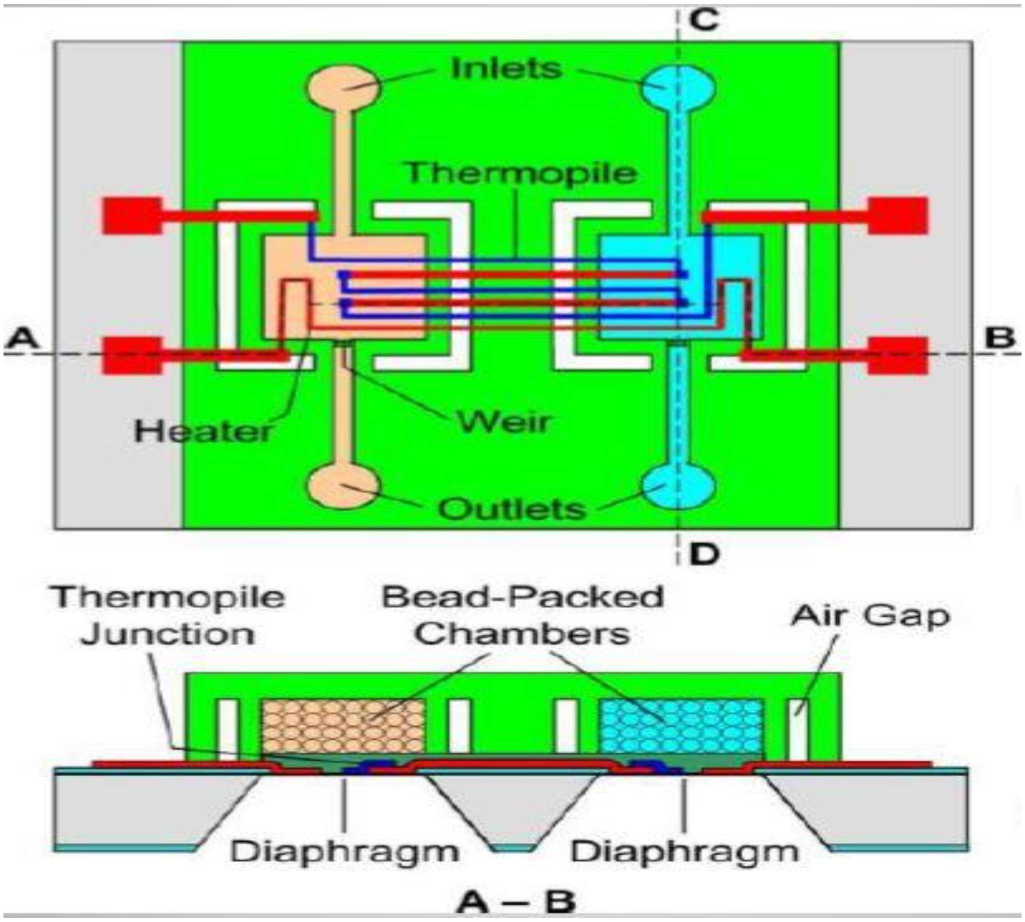
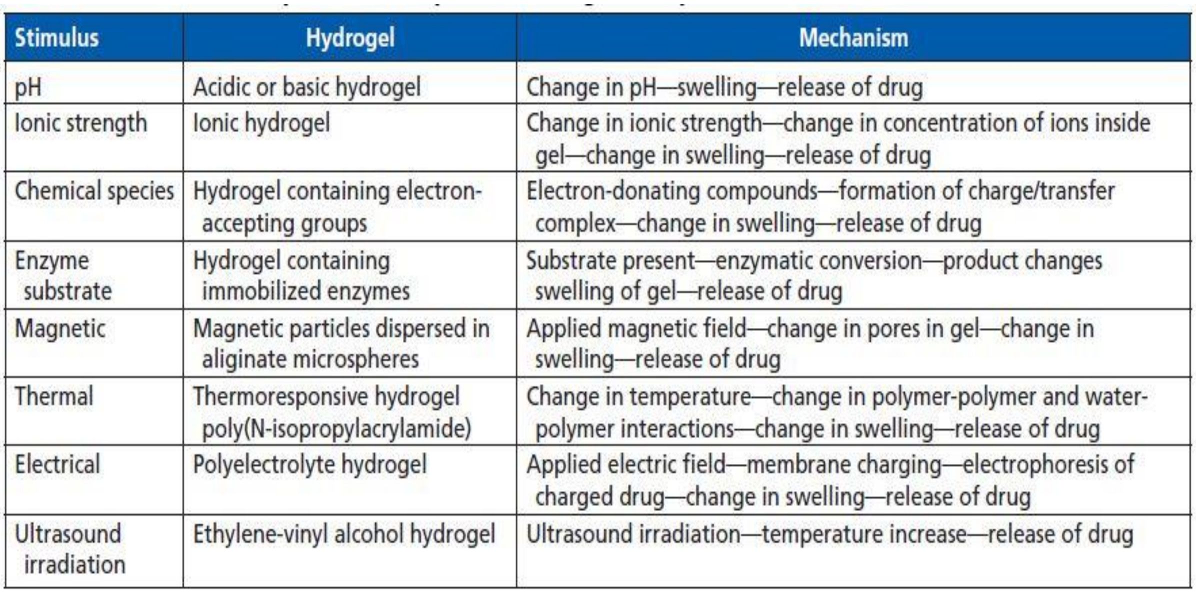


Fig-29: Thermal sensors in MEMS

- Device consists of a thermal sensor chip integrated with a microfluidic system featuring two identical chambers.
- An analyte sample solution and a reference buffer solution are respectively loaded into the chambers.
- The device can be used in Two modes: Flow-Injection mode and Flow-Through mode.
- An important feature of the microfluidic system is that the chambers are each based on a freestanding polymer diaphragm.
- The temperature difference induces a voltage in the thermopile, which is the device's direct output

INTELLIGENT MATERIALS AND STRUCTURES:

Table: 3 List of few intelligent materials and structures



Stimulus	Hydrogel	Mechanism
pH	Acidic or basic hydrogel	Change in pH—swelling—release of drug
Ionic strength	Ionic hydrogel	Change in ionic strength—change in concentration of ions inside gel—change in swelling—release of drug
Chemical species	Hydrogel containing electron-accepting groups	Electron-donating compounds—formation of charge/transfer complex—change in swelling—release of drug
Enzyme substrate	Hydrogel containing immobilized enzymes	Substrate present—enzymatic conversion—product changes swelling of gel—release of drug
Magnetic	Magnetic particles dispersed in aliginate microspheres	Applied magnetic field—change in pores in gel—change in swelling—release of drug
Thermal	Thermoresponsive hydrogel poly(N-isopropylacrylamide)	Change in temperature—change in polymer-polymer and water-polymer interactions—change in swelling—release of drug
Electrical	Polyelectrolyte hydrogel	Applied electric field—membrane charging—electrophoresis of charged drug—change in swelling—release of drug
Ultrasound irradiation	Ethylene-vinyl alcohol hydrogel	Ultrasound irradiation—temperature increase—release of drug

MAGNETIC SENSORS AND ACTUATORS:

- A magnetic sensor is a sensor that detects the magnitude of magnetism and geomagnetism generated by a magnet or current. There are many different types of magnetic sensors

Coiled:

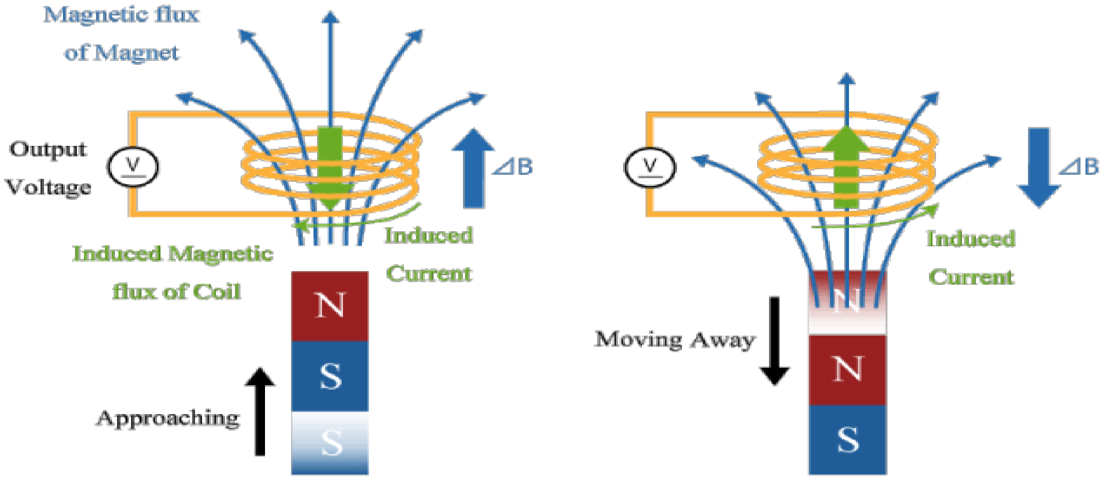


Fig-30: Principle of magnetic sensors

Coils are the simplest magnetic sensors that can detect changes of the magnetic flux density. As shown in Figure, when a magnet is brought close to the coil, the magnetic flux density in the coil increases by ΔB. Then, an induced electromotive force/induced current that generates a magnetic flux in a direction that hinders an increase in magnetic flux density is generated in the coil.

Conversely, moving the magnet away from the coil reduces the magnetic flux density in the coil, so induced electromotive force and induced current will be generated in the coil to increase the magnetic flux density.

Also, since there is no change in the magnetic flux density when the magnet is not moved, no induced electromotive force or induced current will be generated. By measuring the direction and magnitude of this induced electromotive force, it is possible to detect the change in magnetic flux density.

Because of its simple structure, a coil is not easily damaged. However, the output voltage depends on the rate of change of the magnetic flux. It may not be possible to use a coil to detect a fixed magnet or magnetic flux that changes very slowly.

REED SWITCH:

- A reed switch is a sensor in which metal pieces (reed) extending from both the left and right sides are enclosed in a glass tube with a gap at the overlapping position of the reeds. When a magnetic field is applied externally, these reeds are magnetized. When the reeds are magnetized, the overlapping parts attract each other and come into contact, then the switch turns on.

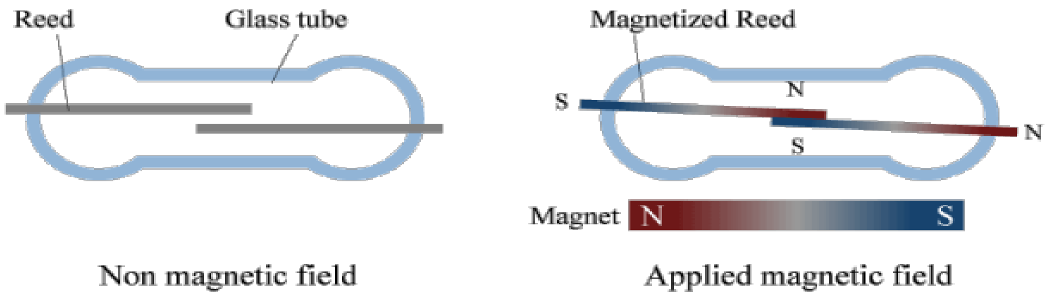


Fig-31: Reed Switch

HALL ELEMENTS:

It is based on the phenomenon that the electromotive force appears in the direction orthogonal to both the current and the magnetic field when applying a magnetic field perpendicular to the current to the object through which current is flowing.

When a current is applied to a thin film semiconductor, a voltage corresponding to the magnetic flux density and its direction is output by the Hall effect. The Hall effect is used to detect a magnetic field.

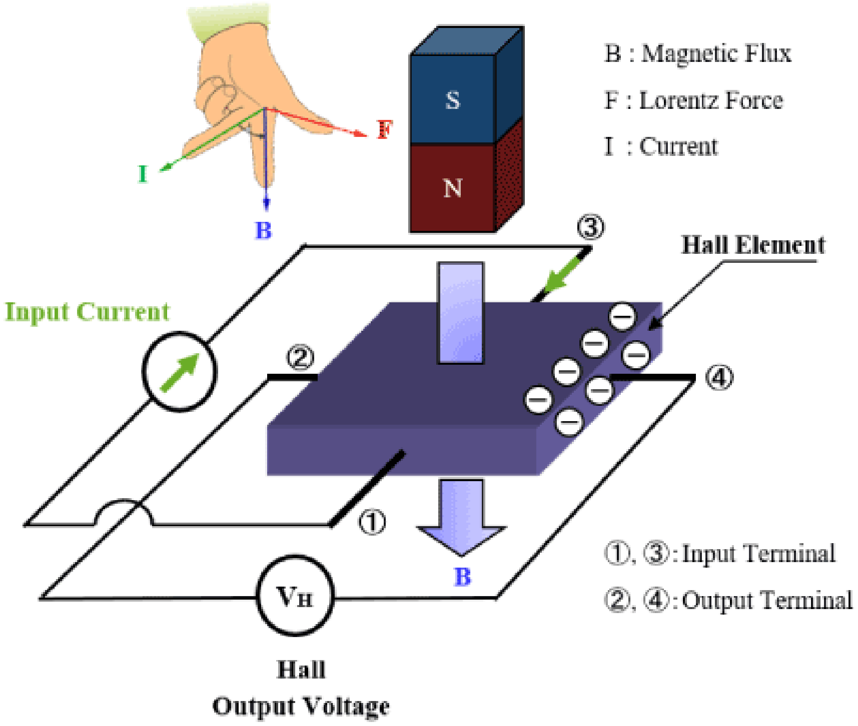


Fig-32: Hall Element principle

MAGNETORESISTIVE ELEMENT:

- An element that detects a magnetic field using a material, that resistance changes when magnetic force is applied, is called a magnetoresistive, (MR), element.

- Other than semiconductor magnetoresistive element, (SMR), there are three kinds of sensors as representative examples of the magnetoresistive element using a ferromagnetic thin film material such as anisotropic magnetoresistive element, (AMR), giant magnetoresistive element, (GMR), and tunnel magnetoresistive element, (TMR).

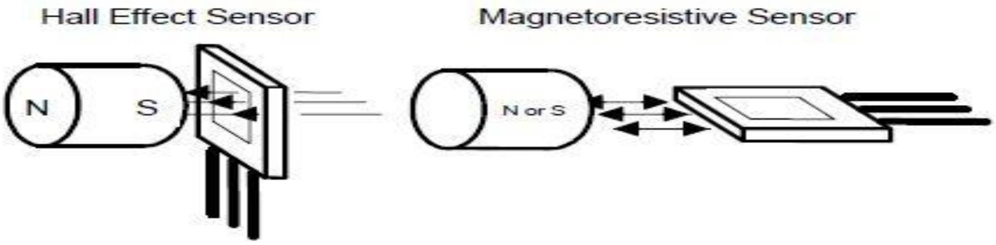


Fig-33: Magnetostrictive Element

SEMICONDUCTOR MAGNETORESISTIVE ELEMENT(SMR):

- Whereas the Hall element is a sensor that measures the Hall voltage generated by the Lorentz force, the magnetoresistive element is a sensor that utilizes the change in the resistance value caused by the Lorentz force.
- Figure shows how the resistance value of an N-type semiconductor magnetoresistive element (SMR: Semiconductor Magnetoresistive), changes. Metal electrodes are placed on a semiconductor thin film in the structure of SMR. When a clockwise current as shown in the figure flows through the semiconductor thin film, electrons which are carriers of N-type semiconductors flow counterclockwise, and the velocity of the vector is assumed as "v". When applying a magnetic field B oriented as shown in the figure, electrons undergo Lorentz force and the path becomes longer as being bent, so that the resistance value increases.

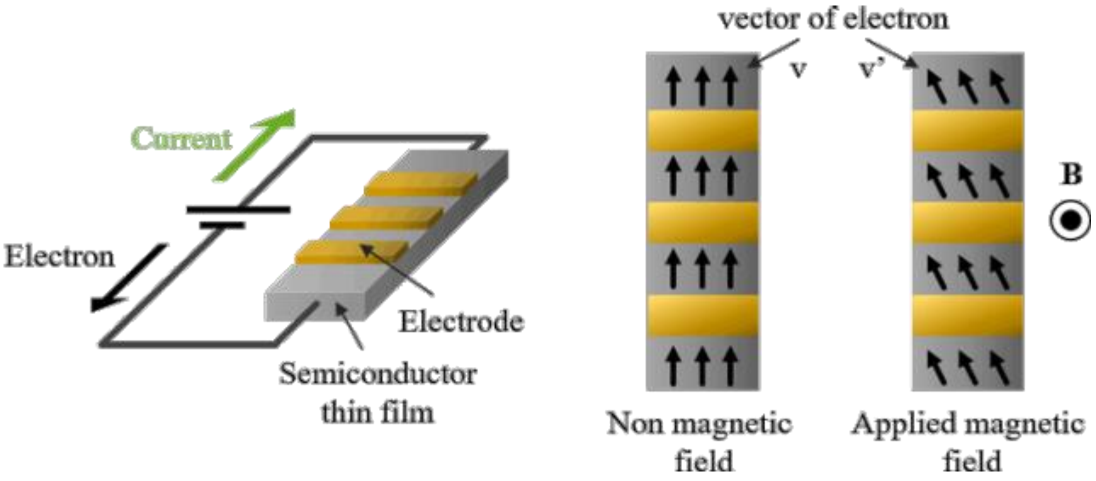


Fig-34: Magnetostrictive property using semiconductors

MAGNETIC ACTUATORS:

- Magnetic actuators and sensors use magnetic fields to produce and sense motion.
- Magnetic actuators allow an electrical signal to move small or large objects.
- To obtain an electrical signal that senses the motion, magnetic sensors are often used.
- Since computers have inputs and outputs that are electrical signals, magnetic actuators and sensors are ideal for computer control of motion.
- Hence magnetic actuators and sensors are increasing in popularity.

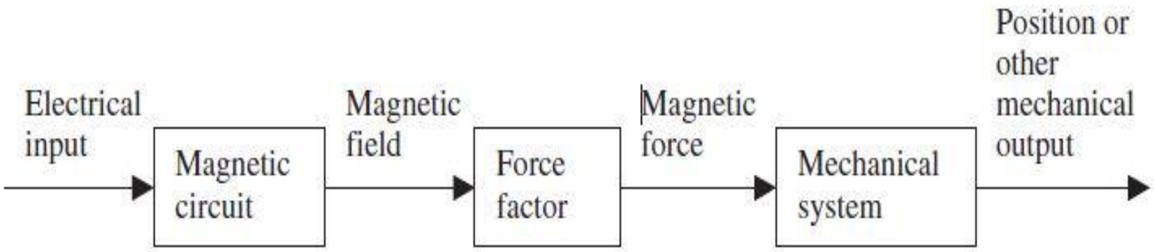


Fig-35: Block diagram of magnetic actuator

Input electrical energy in the form of voltage and current is converted to magnetic energy. The magnetic energy creates a magnetic force, which produces mechanical motion over a limited range. Thus magnetic actuators convert input electrical energy into output mechanical energy.

Typical magnetic actuators include

- Electrohydraulic valves in airplanes, tractors, robots, automobiles, and other mobile or stationary equipment
- Fuel injectors in engines of automobiles, trucks, and locomotives
- Biomedical prosthesis (artificial body) devices for artificial hearts, limbs, ears, and other organs
- Head positioners for computer disk drives
- Loudspeakers
- Contactors (electrically controlled switch), circuit breakers, and relays to control electric motors and other equipment
- Switchgear and relays for electric power transmission and distribution

ACTUATORS AND SENSORS IN MOTION CONTROL SYSTEMS:

Motion control systems can use nonmagnetic actuators and/or nonmagnetic sensors. The head assembly is a magnetic sensor that senses (“reads”) not only the computer data magnetically recorded on the hard disk but also the position (track) on the disk. To position the heads at various radii on the disk, a magnetic actuator called a voice coil actuator is used.

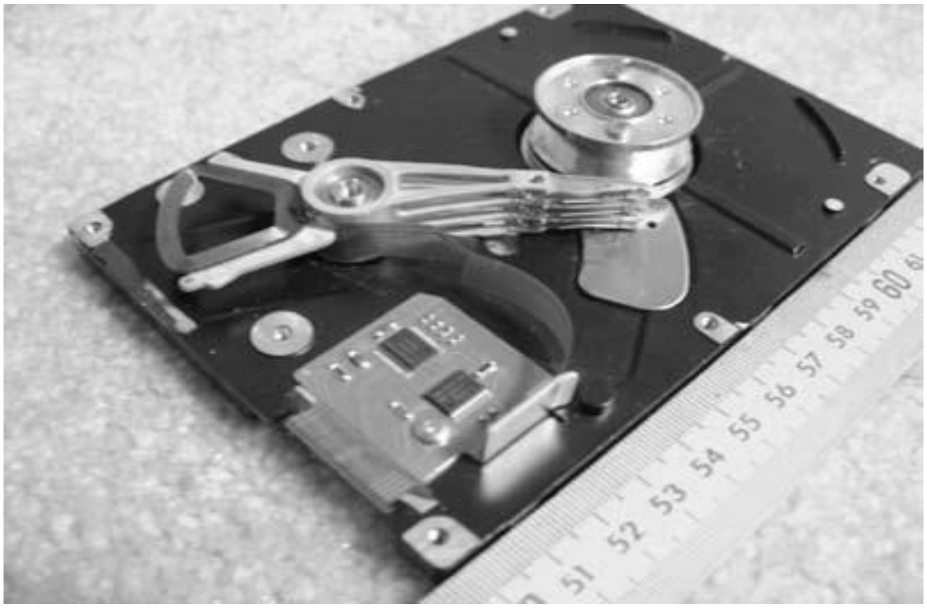


Fig-36: Typical Computer disk assembly

The actuator coil is the rounded triangle in the upper left. The four heads are all moved inward and outward toward the spindle hub by the force and torque on the actuator coil. Portions of the actuator and all magnetic disks are removed to allow the coil and heads to be seen.

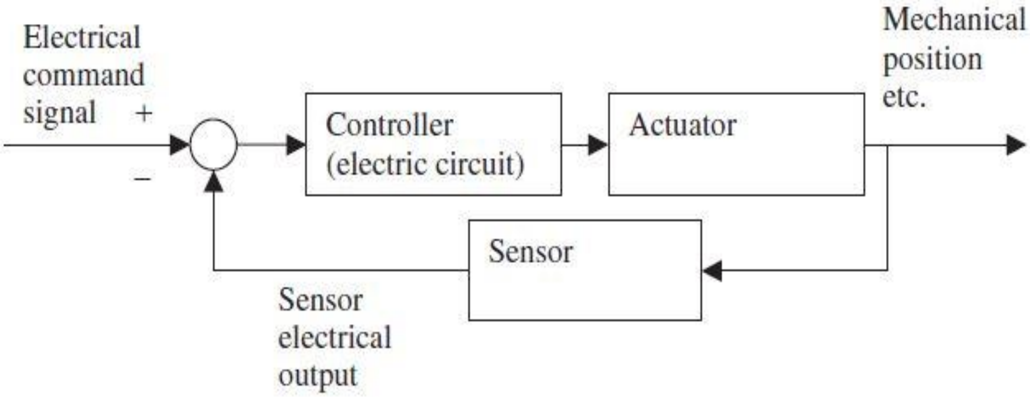


Fig-37: Basic feedback control system that may use both a magnetic actuator and a magnetic sensor.

An example of a motion control system that uses both a magnetic actuator and magnetic sensor is the computer disk drive head assembly shown in above figure.

- It contains both an actuator and a sensor. The sensor may be a magnetic sensor measuring position or velocity.
- The actuator may be a magnetic device producing a magnetic force.

- It is found that accurate control requires an accurate sensor.

Voice Coil Actuator:

- Instead of forces on steel, Lorentz force on current-carrying coils is used in many actuators. They are called “voice coil actuators” because of their common use in loudspeakers.
- From the Lorentz force equation, the force on an N-turn coil of average turn length l is

$F = NBIl.$

where B is the magnetic flux density perpendicular to the coil direction and F is perpendicular to both B and the coil direction. The directions follow the right-hand rule.

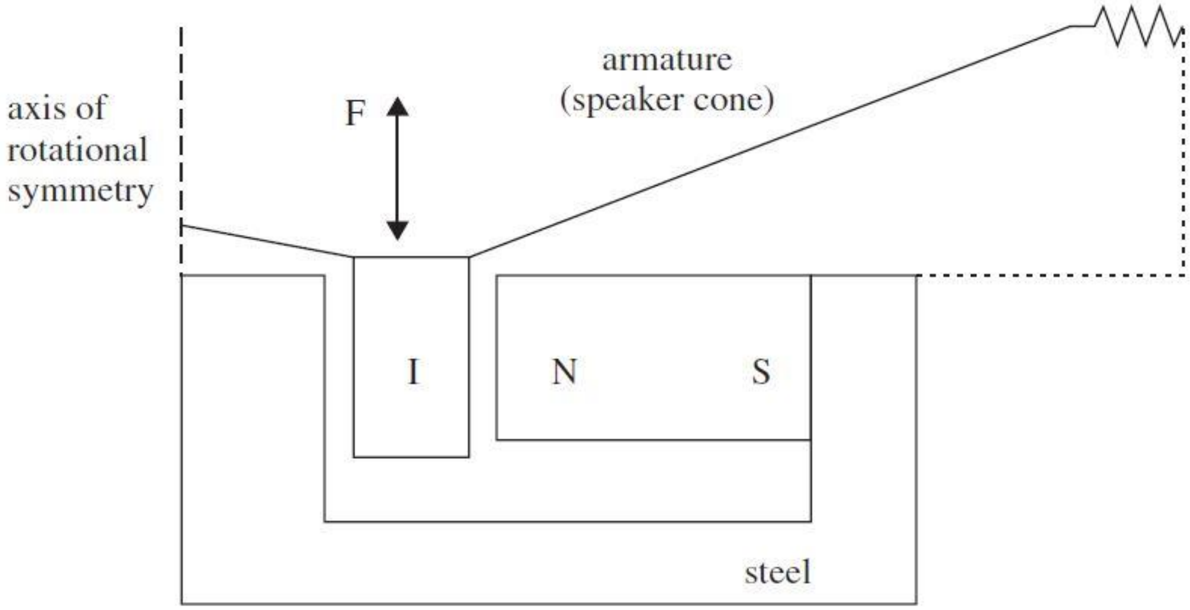


Fig-38: Typical voice coil actuator, shown driving a loudspeaker. The movable voice coil carries the current *I* and is subjected to the magnetic field from a permanent magnet with north (N) and south (S) poles.

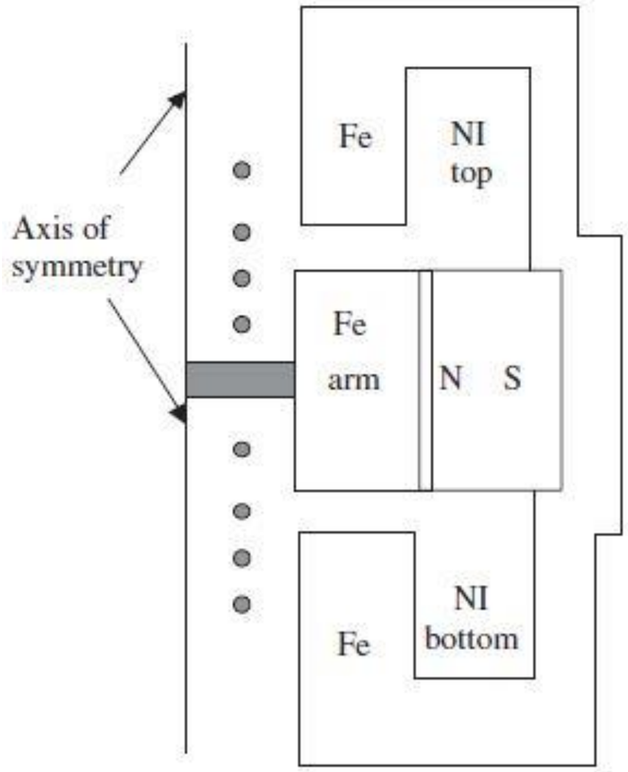


Fig-39: Actuator with both permanent magnet and coils in stator. The armature labeled “arm” moves either up or down.

- Other actuators are available that use both permanent magnets and coils. The advantage of using permanent magnets is that the **B** they produce does not require current or power loss as do coils.
- The **B** of the permanent magnets interacts with the **B** of coils to produce the force.
- It is a long-stroke actuator with one radially magnetized permanent magnet, a steel or iron armature, and two coils. The coils are wound and connected so that they both carry current in the same direction.
- For example, if they both carry current out of the page, then the lower pole of the moving iron armature has higher flux than the upper pole, and the armature experiences a downward force.
- Reversal of the current gives an upward force, and no current gives zero (balanced) force on the armature. Thus the armature experiences bidirectional force.
- The force varies with position because of the variation in both airgaps.

MAGNETIC MATERIALS USED FOR MEMS:

- Based on their B-H (Total magnetic flux density-Externally applied magnetic field) behavior, engineering materials are also typically classified into soft and hard magnetic materials.
- Soft magnetic materials are easy to magnetize and demagnetized, hence require relatively low magnetic field intensities.
- Soft magnetic materials are typically suitable for application where repeated cycles of magnetization and demagnetization are involved, as in electric motors, transformers, and inductors, where magnetic field varies cyclically
- Hard magnets, also referred to as permanent magnets, are magnetic materials that retain their magnetism after being magnetised.
- Permanent magnet (usually is hard magnetic material) is a passive device used for generating a magnetic field, and is useful in a variety of situations where it is difficult to provide electrical power or there are severe space restrictions where electromagnets are not allowed.
- The energy needed to maintain the magnetic field has been stored previously when the permanent magnet was magnetized and then left in a high state of remanent magnetization.
- The important properties of permanent magnetic materials are coercivity Hc and remanence Br. Samarium-cobalt is a permanent magnetic material used widely in 1960s

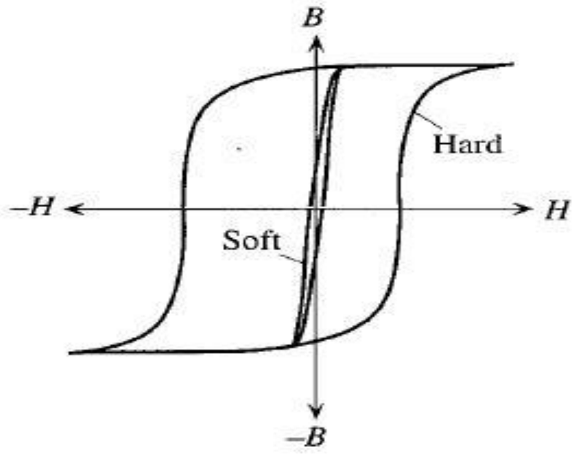


Fig-40: SOFT AND HARD MAGNETIC MATERIALS B-H Curve

- In the early 1980s, neodymium-iron-boron was developed as a low-cost high performance permanent magnet
- The presence of $Nd_2Fe_{14}B$(Neodymium Magnet), a very hard magnetic phase with greater coercivity and energy product (H*B), is what leads to the superior magnetic properties.
- Disadvantage of the above material is the need for powder sintering process which is complex.
- $Nd_2Fe_{14}B$ film has found wide application in compact recording devices, magnetic sensors and other integrated electromagnetic components

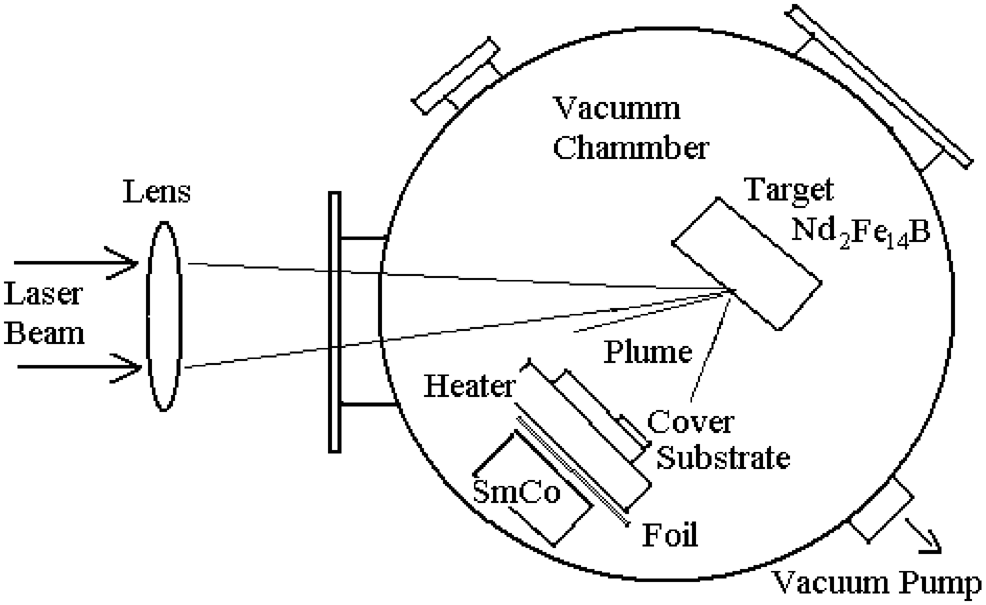


Fig-41: Illustration of the Experiment Setup

REFERENCES:

1. Tai Ram Hsu, Mems and Microsystems, Design and Manufacture, TMH, 2008.
2. Mohammedhad-el-hak, MEMS Introduction & Fundamentals, CRC Press, 2005.
3. Marc J. Madou, Fundamentals of Microfabrication and Nanotechnology, 3rd Edition, 2011, CRC Press. ISBN 9780849331800

4. Harsingh Nalwa, Encyclopedia of Nanoscience and Nanotechnology, American Scientific Publishers, 2007.

5. Neelina Malsch, Biomedical Nanotechnology. CRC, 2005

6. Richard Booker and Earl Boysen, Nanotechnology for Dummies, John Wiley & Sons, 2011

QUESTION BANK:

1) What are biomimetic substrates.? Explain in detail with neat example.

2) What are Microscaffolds.? Explain in detail how the process helps to attain biocellular coculture.?

3) With neat sketch explain the cellular co-cultures mechanism.

4) What are Microsensors.? Describe the working of one microsensor in detail.

5) Justify using Microactuators that it could be used in biomedical engineering

6) Elaborate the working of pressure sensors with neat sketch.

7) With few examples explain with neat sketch the working of thermal sensors and actuators.?

SATHYABAMA
INSTITUTE OF SCIENCE AND TECHNOLOGY
(DEEMED TO BE UNIVERSITY)
Accredited "A" Grade by NAAC | 12B Status by UGC | Approved by AICTE
www.sathyabama.ac.in

SCHOOL OF BIO & CHEMICAL ENGINEERING

DEPARTMENT OF BIOMEDICAL ENGINEERING

UNIT – III - MEMS in Healthcare – SBMA7007

PRINCIPLE OF MOEMS:

- MOEMS is a miniaturized system combining optics, micromechanics and microelectronics.
- MOEMS technology requires a different set of rules for operation when compared with the normal MEMS devices.
- Mostly, MOEMS have emerged to provide unparalleled functionality in telecommunication applications.
- Although the ultimate speed of these devices is unlikely to compete with solid-state electro-optic devices, the precision that can be achieved with MOEMS contributes to good performance and negligible signal degradation in the channels, thereby enabling a flexible all-optical system.
- System bandwidth and power consumption are the key issues. Using fiber links and optical methods, MOEMS technology demands precision interfaces and integrated components in order to achieve reliable and available quality of service (QoS).

The advantages of MOEMS are as follows:

- The speed of operation is high
- High bandwidth: Can handle many signals simultaneously
- Insensitivity to electromagnetic interference
- Can be used in harsh environments
- Secured and reliability
- MOEMS have emerged to provide unparalleled functionality in telecommunication applications.

Manufacturers of these devices are forecasting new opportunities in information technology, health care, military, industrial, and test and measurement sectors. Some of the important applications of MOEMS are listed as follows.

- Free-space optical switches, routers and beam splitters
- Focusing components
- Tunable filters
- Display and projection systems
- Guided optic devices and tuners

One very important combined process that is being used in micromanufacturing the MOEMS devices is the LIGA process. LIGA is a German acronym for lithography, electroplating, and molding. The process states that each layer of the different material is deposited lithographically and these layers are different thicknesses and can overlap one another depending upon what the MOEMS device is being designed for. One layer is usually used as a sacrificial layer to fill in and support a void area.

The subsequent layer can be used to make a mold for the next layer. The succeeding layer will overlap the first and be molded into shape by the second. Then the first two layers can be removed. This in turn leaves a freestanding structure.

The research subjects of interest of MOEMS are:

- Properties of light and their exploitation with respect to MOEMS
- Optical switching principle, concept, design, and applications
- Beam splitting and microlens fabrication
- Principle of Spatial Light Modulation
- Light detector or wavelength separator using micro-optic waveguide (MOW)
- Mechanical and optical MEMS (MOEMS) products have made the transition out of the laboratory and into the marketplace with a plethora of new products, including a strong entry into the consumer electronics field (mobile phones, cameras, laptop computers, games, etc.)
- Mechanical and MOEMS devices have been around since the 1980s, and it appears that this market finally has achieved mass-market acceptance in IT peripherals. A primary reason is the demand for read-write heads, ink-jet heads, and microdisplays.

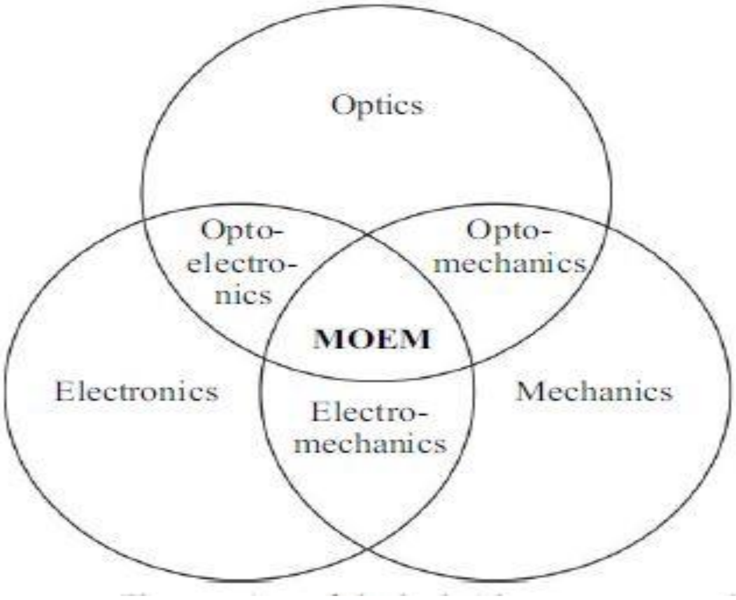
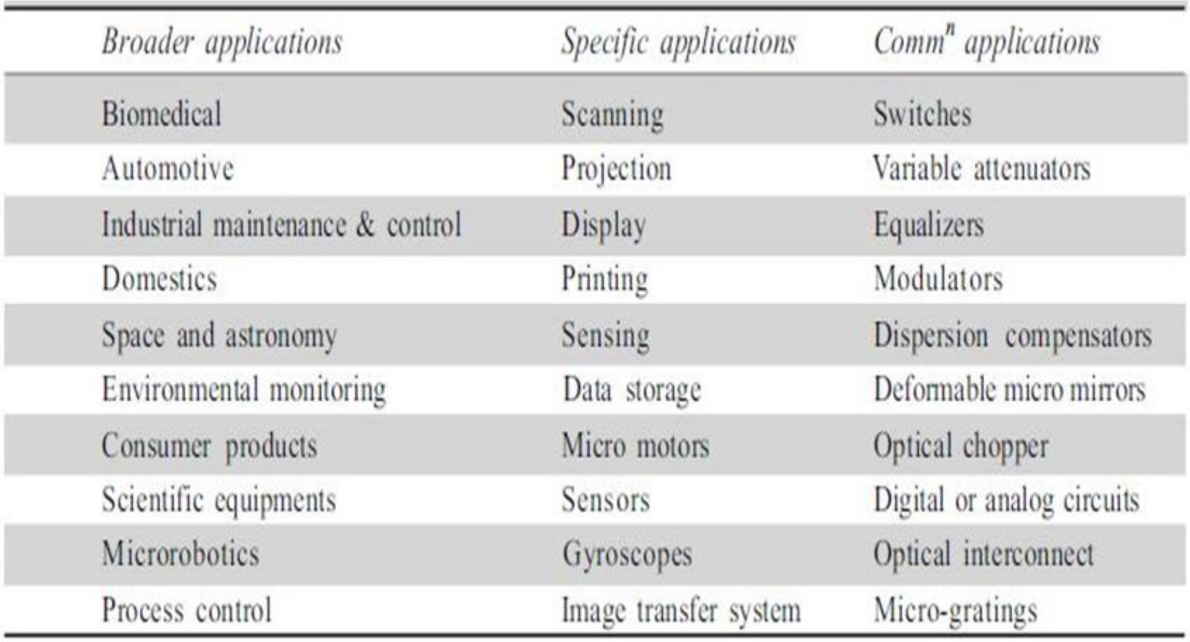


Fig-1: In illustration of the hybrid systems—MOEMS

Table-1: Application of MOEMS:



Broader applications	*Specific applications*	*Comm^n applications*
Biomedical	Scanning	Switches
Automotive	Projection	Variable attenuators
Industrial maintenance & control	Display	Equalizers
Domestics	Printing	Modulators
Space and astronomy	Sensing	Dispersion compensators
Environmental monitoring	Data storage	Deformable micro mirrors
Consumer products	Micro motors	Optical chopper
Scientific equipments	Sensors	Digital or analog circuits
Microrobotics	Gyroscopes	Optical interconnect
Process control	Image transfer system	Micro-gratings

LIGHT MODULATOR:

- Modulation means “to change”. Light modulator modulates or changes some of the parameters of the light.
- The important parameters are wavelength and direction. Modulators are often called manipulator.
- The modulators can also fragment, combine and polarize the incident light as and when required.
- All these manipulations work on various principles. Accordingly, there are various types of modulators.
- Two very important different technologies have been developed and studied extensively.
- The first one is based on micromechanics that involves movement of physical parts and utilizes reflection and diffraction.
- The second type of technology involves liquid crystals and uses the advantage of polarization
- Modulation of light is essential in high-end display applications.
- The TV image and computer screen displays are called high-end display devices.
- The modulators used for these high-end applications are primarily of two types, such as square-structured micromirror 2D array type and ribbon-structured micromirror type.

- The square-structured MOEM modulators uses the binary (ON/OFF) switching method and the modulators are called Digital Micromirror Device (DMDO) which uses the reflection principle, and this technology has been defined what is known as Digital Light Processing (DLPO) technology.
- The ribbon-structured modulators are called Silicon Light Machines (SLM), which use diffraction principle, and this technology has been defined what is known as Grating Light Valve (GLV)

BEAM SPLITTER:

A beam splitter (BS) is a class of optical device that divides a light beam into two separate beams, hence the name beam splitter. Beam splitter can be a diffractive optic device. It is believed that the Beam splitter is an optical version of a copying machine. The splitted output beams can be sent in any direction of interest.

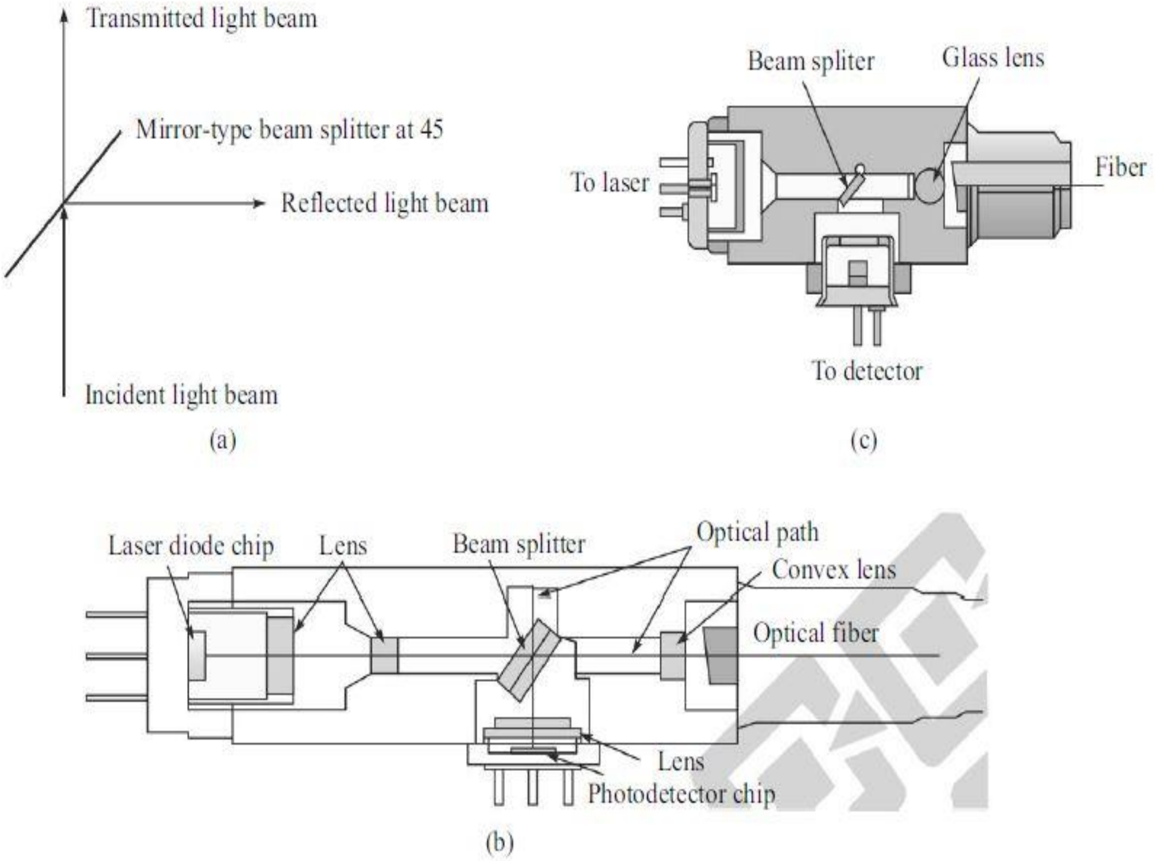


Fig-2: (a) Principle of beam Splitter, (b) Beam Splitter in operation, (c) Beam Splitter in a package

Full divergence angles as large as 60^o are possible for splitting light signals that have a wide range of wavelengths. In most cases, however, the splitter is usually placed at 45^o with reference to the source and target platform. If the beam splitter is placed in between an optical path at an angle 45^o, a portion of the incident beam energy gets through the splitter and the remaining portion is reflected in a direction 90^o from the input beam.

Some small portion of the beam, which is passed through the splitter, is absorbed within the beam splitter itself. Because of this feature the beam splitter is considered as an optical window. It has a metallic or dielectric coating on one side with definitive reflecting and transmitting characteristics. The splitters are known as mirror-type beam splitter since some portion of the energy is in fact reflected from the splitter.

The typical reflection ratio varies from application to application. Reflection percentages can range from 30% to 80%. A time invariant constant reflection-to-transmission ratio over a large spectral range is desirable. Beam splitters are very sensitive to polarized light due to the reason that the polarization of light is changed when it is incident on a beam splitter oriented at 45^o.

In a typical mirror-type beam splitter, the S-polarization state is reflected more than the average amount of reflection and the P-polarization state is reflected less than the average when a randomly polarized input light is incidented.

DIGITAL MICROMIRROR DEVICE:

The digital micromirror device, or DMD, is the micro opto electro mechanical system (MOEMS) that is the core of the trademarked Digital light processing (DLP) projection technology from Texas Instruments.

Size of the micromirror is :

- Matrix of micromirrors

  1024 x 768 mirrors for example
- Size of the mirrors: 16 x 16 µm
- Each micromirror consist of CMOS memory cell

Fig-3: Typical Digital Micromirror Device (DMD) from Texas Instruments

From operational point of view DMD is a precision lightswitching device, capable of modulating the light digitally by the use of huge numbers of microscopic mirrors, which are arranged in a definitive manner, usually in the form of rectangular array. The separation between the micromirrors in the array is in the order of micrometer.

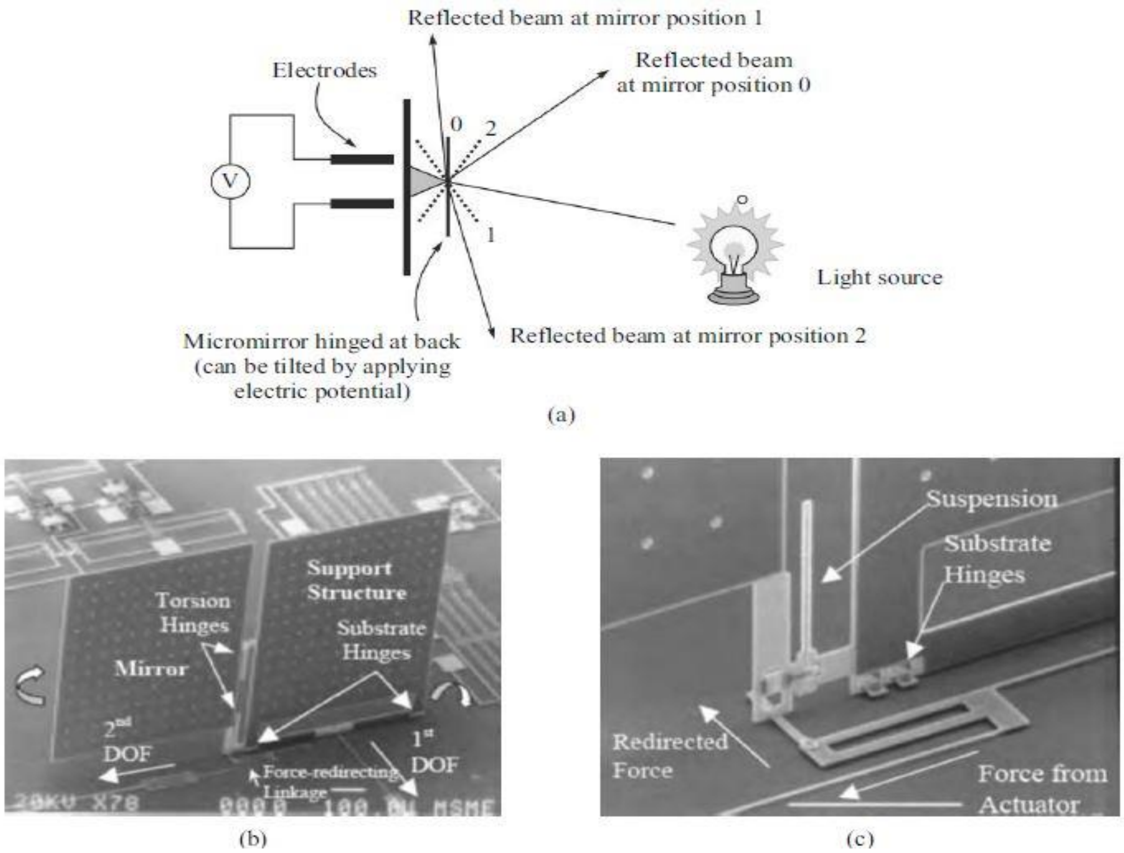
The device is in fact a Spatial Light Modulator (SLM), primarily used for imaging applications. The micromirrors in the device are reflective elements and their shapes are flat, rectangular and polished. Approximately more than one quarter of a million numbers of mirrors (typically 640*480 pixels) is fabricated into a single device.

The device is a unique combination of optical, mechanical and electrical systems and is much more than a typical IC (Integrated Circuit) chip.

The functions of the micro-mirrors are to:

1) Direct the light signals toward a dedicated pixel space

2) Switch the light signal in the order of thousand times per second



(a)

(b) (c)

Fig-4: (a) Principle of operation of a typical micromirror, (b) SEM (Scanning Electron microscope) image of the micromirror (c) Close up view of hinges

Principle of operation:

By utilizing electrostatic actuation method the micromirror is rotated or tilted to a pre-defined state to achieve controlled optical signal transmission (Fig-4). The angle of rotation could vary from 1^o to 45^o depending upon the application requirement. In position control system the reflected light is observed and calibrated in terms of displacement or angle, which could be proportional to the input physical parameter, for instance, vibration magnitude of a rotary shaft.

Optical switching through micromirror is achieved by integrated actuation mechanism. Micromirror is usually hinged in the base and can be tilted by applying electrostatic force. Any amount of tilting is achieved through the application of equivalent electric potential (Fig-4). Figure (b) shows a SEM (Scanning Electron microscope) of 2 degree-of-freedom (2-DOF) micromirror.

The mirror is called torsional micromirror. Figure 4(c) is the close-up of torsion hinge suspension and force redirecting linkage. This linkage provides roughly 5 times the range of motion of the unmodified thermal actuators. The mirror consists of two large plates approximately 500µmx500µmx4.25µm.

The right-hand panel is a support structure, which rotates on substrate hinges on an axis in the plane of the substrate. The left-hand panel is the actual mirror, and is suspended from the support structure by two U-shaped torsion springs. The mirror is constructed by sandwiching a 0.75 mm oxide layer between the 2 mm thick poly-1 layer and the 1.5 mm thick poly-2 layer

PRINCIPLE OF OPERATION OF DMD:

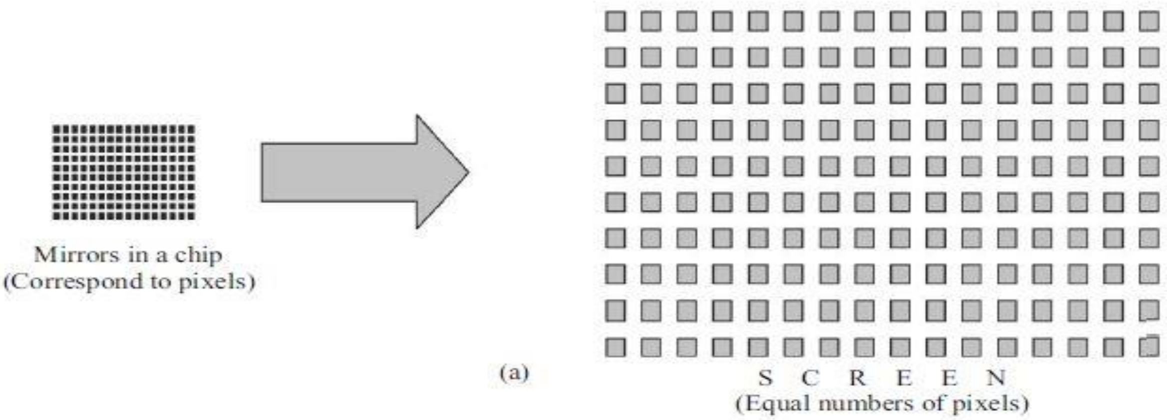


Fig-5: (a) : Mapping between the pixel space on the screen and the DMD mirrors

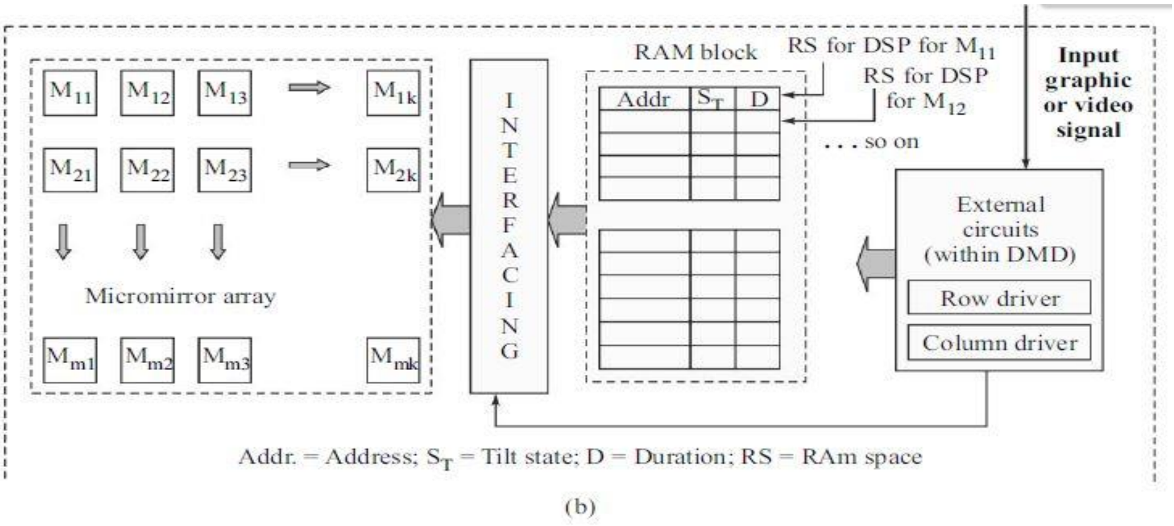


Fig-5: (b) : Schematic diagram of an array of micromirrors for display applications

The light source (lamp) is modulated in the DMD chip. Note that the lamplight is a constant light source. Its intensity has to be modulated in response to incoming video signal. After being modulated the light falls on the dedicated pixel space. Each mirror corresponds to a single pixel in the projected or displayed image (Fig. 5 a). The 3D construction is such that the mirrors are capable of switching into ON and OFF state. When screen is ON, the mirror reflects light incoming from the lamp source. External circuit controls the mirrors. Each mirror is hinged and interfaced with a CMOS RAM memory block, accountable to store/provide display-specific information.

The size of RAM depends on the number of mirrors present in the DMD. The entire block of RAM is divided and allocated to each mirror in order to store three most important display-specific parameters (DSP) such as address of the mirror, the tilting direction (ON or OFF) and the timing of tilting. The interfacing circuits, RAM block and mirror arrays are extremely complex. For the purpose of understanding Fig 5 (b) illustrates a schematic view of such a device, although a DMD chip is entirely different from this representation. There are row drivers, column drivers and timing circuitry built into the device.

Applying the electrostatic force through microelectrodes constructed into the mirror can tilt an addressable mirror(For reference see Fig.5 (a)). A particular mirror is made either ON or OFF by addressing it through RAM memory in terms of applying electrostatic voltage to the microelectrodes.

The video signal to be displayed is available as equivalent electrical signal. The incoming video signal has to be decoded in such a way that the electrodes, which control each micromirror, must be activated at the appropriate time with accurate duration of tilt. The incident light from the lamp is reflected from each micromirror and then amplified by the projection lens and directed to the pixel space (screen). Tilting direction and the duration of tilt assures modulation of incident lamplight.

Basic units of DMD (Texas Instruments):

The display system consists of the following nine units.

- Projector lamp
- Memory

- Condensing lens
- Color filter (wheel)
- Shaping lens
- Processor
- DMD
- Projection lens
- Screen

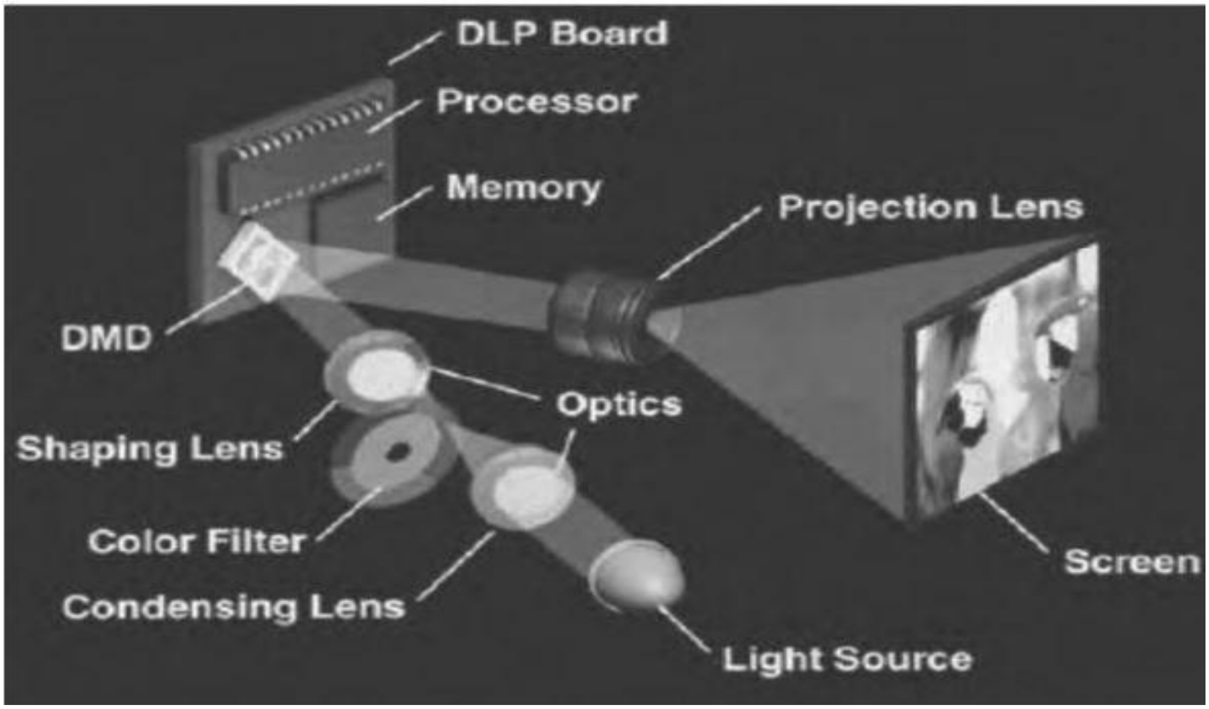


Fig-6: Basic Units of Digital Micromirror Device (DMD)

The projector lamp is a source of light that is focused onto the DMD. The light from the lamp (source) is passed through the condensing lens. The condensing lens focuses the light toward the DMD. The color filter is a transparent wheel consisting of three basic colors. The white light from the lamp is modulated into colored light by this filter and made to fall on the micromirrors of the DMD device through the shaping lens. The wheel spins illuminating the DMD sequentially with red, green, and blue light. The video signal to be displayed is fed to the DMD. The mirrors are turned ON depending on how much of each color is needed for displaying.

DLP board consists of three units, namely the processor, memory and the arrays of micromirrors. The electrical video signal is decoded and fed to the corresponding electrode pairs that control the micromirror for tilting. Further, the duration of the ON-OFF timing of each micromirror determines the level of intensity (called grayscale) of the pixel. The level of intensity in the pixel is in turn related to the color of the video signal.

Grayscale output is achieved by pulse width modulation (PWM). Brighter pixels correspond to longer pulses, darker pixels to shorter pulses. The reflected light from each micromirror is then amplified by the projection lens and splashed onto the front or back of the screen. The display of image on the back of the screen corresponds to rear-projection set.

A ‘1’ or ‘0’ in the RAM cell tilts the mirror ±10 degree. That is a ‘1’ in the memory causes the mirror to rotate +10 degrees, while a ‘0’ in the memory causes the mirror to rotate –10 degrees. A mirror rotated to +10 degrees reflects the lamp light into the projection lens and the pixel appears bright at the screen, where as the mirror rotated to –10 degrees misses the projection lens and the pixel appears dark.

Rapid switching of the mirrors is a desirable feature. The settling time is very fast (approximately 16 micro second) and far more than the normal human eye. The input video data rates and data bus widths are designed and specified in such as way that the memory-mirror array must be refreshed 48–60 times during a single video frame so as to enable to provide a display with 16 million possible colors. One can note that the system can produce more than 16 million colors.

The switching speed is very much related to the number of colors it can display. The size of DMD chip is approximately 0.625 inch. The size and fill factor of a single mirror is about 16 mm^2 and 90%, respectively. Fill factor is the ratio of reflective area to the actual area of the micrometer. The three-chip based projection systems are called high-definition system. This system consists of three high-resolution DMDs. Each DMD is for the one primary color of red, green or blue (RGB).

OPTICAL SWITCH:

An optical switch is a device that selectively switches optical signals from one channel to another. The switching can be temporal or spatial. The switch is designed for regulating light beams. By using the switch, light can be directed in the same direction or in another according to the requirement. There are mainly two types of switches based on the way the mirrors are activated. They are interception type and rotation type. The former type (interception) uses multiple mirrors requiring large linear actuation and the design is very complex. The latter type of switch is called tortional micromirror type and uses single mirror requiring large angular actuation.

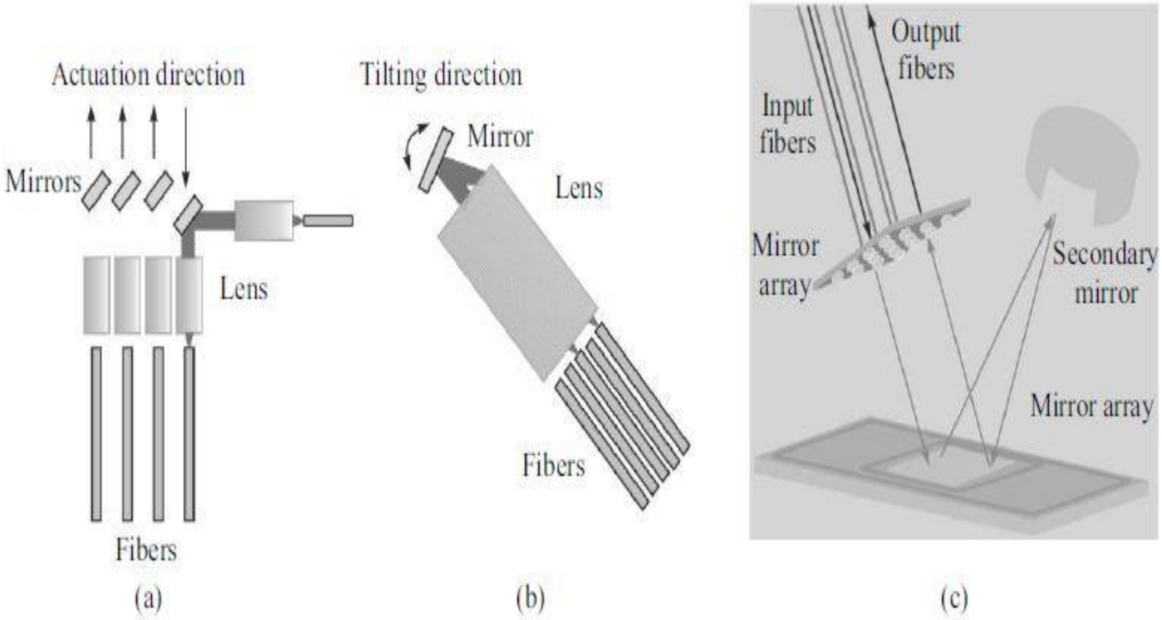


Fig-7: Optical switch; (a) Beam interception type; (b) Beam rotation type; (c) Light can be directed in an direction

- Regardless of their types the switches are activated using the principle of electrostatic actuation.

Accordingly, there are four types of switches, namely,

- Single input single output
- Multiple input single output
- Single input multiple output
- Multiple input multiple output

Some optical switches are based on a tiny pivoting bar with a gold-plated micromirror at one end that fits in a tiny space between two optical fibers lined up end to end. In the Off state the micromirror rests below the cores (through which the light signal travels) of the two fibers, allowing light signals to travel across the gap from one core to the other.

When a voltage applied to the far end of the bar helps to lift the mirror between the fibers, where it reflects incoming light rather than permits its passage. Figure below shows a simple 2D single input multiple output optical switches. It has one input port and four output ports.

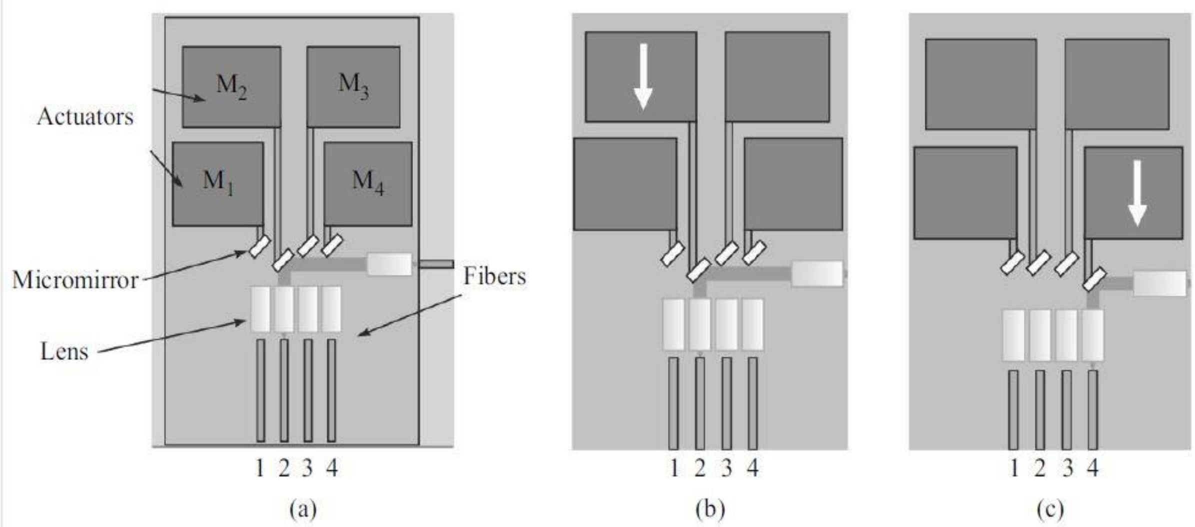


Fig-8: (a) 2D single input multiple output beam interception type optical switches (b) M2 is activated by the electrostatic actuation (c) M4 is activated by the electrostatic actuation

The incoming light signal can be directed to any of the output port that is connected to the optical fiber through the microlens arrangement. If the light signal is required to be directed to the optical fiber number 2 then the corresponding motor M_2 must be activated by the electrostatic actuation (Fig.(b)). Similarly, if the light signal is required to be directed to the optical fiber number 4 then the corresponding motor M_4 must be activated (Fig. (c)).

- The tortional type switch consists of tortional micromirror and corresponding electrode.
- The micromirrors and electrodes are fabricated on separate substrates as shown in Figure below:

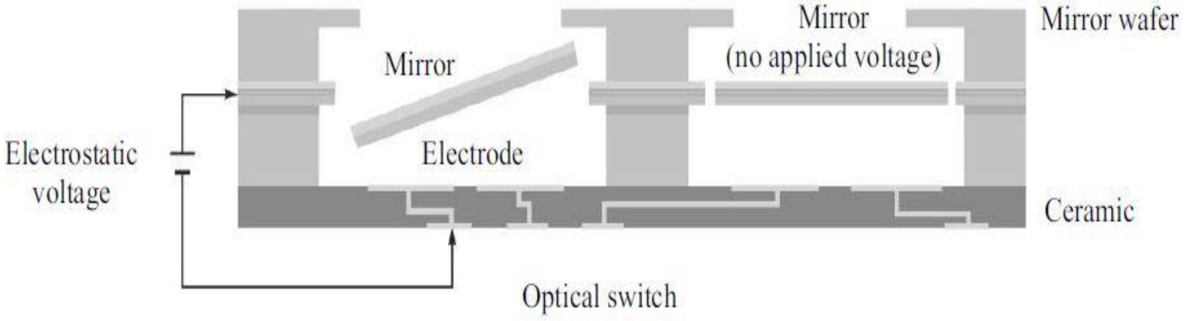


Fig-9: Schematic diagram of a micro optical switch with two tortional mirrors

The electrodes are situated on the ceramic layers. Special self-alignment mechanism are designed for assembling the mirrors and electrodes. If a bias voltage is applied to the electrode, the mirror is attracted by the electrode and tilted. The incident light thus can be reflected and redirected. The mirror is designed to tilt around x and y-axes.

LIGHT DETECTORS:

Light detectors or Light sensors are photoelectric devices that convert light energy (photons) whether visible or infra-red light into an electrical (electrons) signal. A Light Sensor generates an output signal indicating the intensity of light by measuring the radiant energy that exists in a very narrow range of frequencies basically called "light", and which ranges in frequency from "Infra-red" to "Visible" up to "Ultraviolet" light spectrum.

Photoelectric devices can be grouped into two main categories, those which generate electricity when illuminated, such as *Photo-voltaics* or *Photo-emissives* etc, and those which change their electrical properties in some way such as *Photo-resistors* or *Photo-conductors*. This leads to the following classification of devices.

Photo-emissive Cells – These are photodevices which release free electrons from a light sensitive material such as caesium when struck by a photon of sufficient energy. The amount of energy the photons have depends on the frequency of the light and the higher the frequency, the more energy the photons have converting light energy into electrical energy.

Photo-conductive Cells –

- These photodevices vary their electrical resistance when subjected to light.

- Photoconductivity results from light hitting a semiconductor material which controls the current flow through it.
- Thus, more light increase the current for a given applied voltage.
- The most common photoconductive material is Cadmium Sulphide used in LDR photocells.

Photo-voltaic Cells –

- These photodevices generate an emf in proportion to the radiant light energy received and is similar in effect to photoconductivity.
- Light energy falls on to two semiconductor materials sandwiched together creating a voltage of approximately 0.5V.
- The most common photovoltaic material is Selenium used in solar cells.

- **Photo-junction Devices –** These photodevices are mainly true semiconductor devices such as the photodiode or phototransistor which use light to control the flow of electrons and holes across their PN-junction.
- Photojunction devices are specifically designed for detector application and light penetration with their spectral response tuned to the wavelength of incident light.

The photoconductive cell/Light dependent resistor (LDR):

Most common type of photoconductive device is the Photoresistor which changes its electrical resistance in response to changes in the light intensity. The commonly used Photoconductive Cell is called the Light Dependent Resistor or LDR. Made from semiconductor material such as cadmium sulphide that changes its electrical resistance from several thousand Ohms in the dark to only a few hundred Ohms when light falls upon it by creating hole-electron pairs in the material.

Materials used as the semiconductor substrate include, lead sulphide (PbS), lead selenide (PbSe), indium antimonide (InSb) which detect light in the infra-red range with the most commonly used of all photoresistive light sensors being Cadmium Sulphide (Cds).

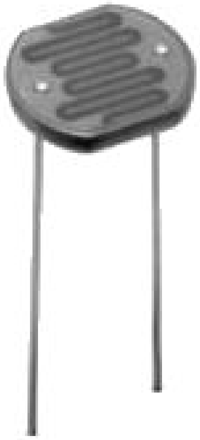


Fig-10: LDR Structure

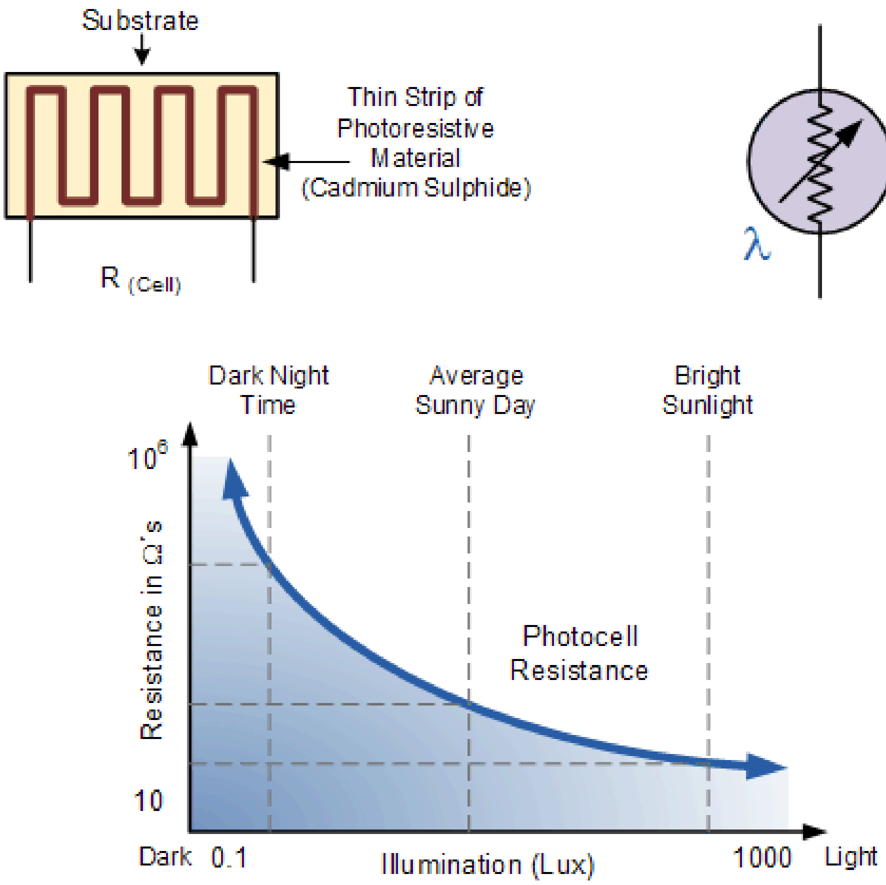


Fig-11: Symbol, Characteristics of LDR

The Photodiode:

The construction of the Photodiode light sensor is similar to that of a conventional PN-junction diode except that the diodes outer casing is either transparent or has a clear lens to focus the light onto the PN junction for increased sensitivity.

Fig-12: Structure of a photodiode

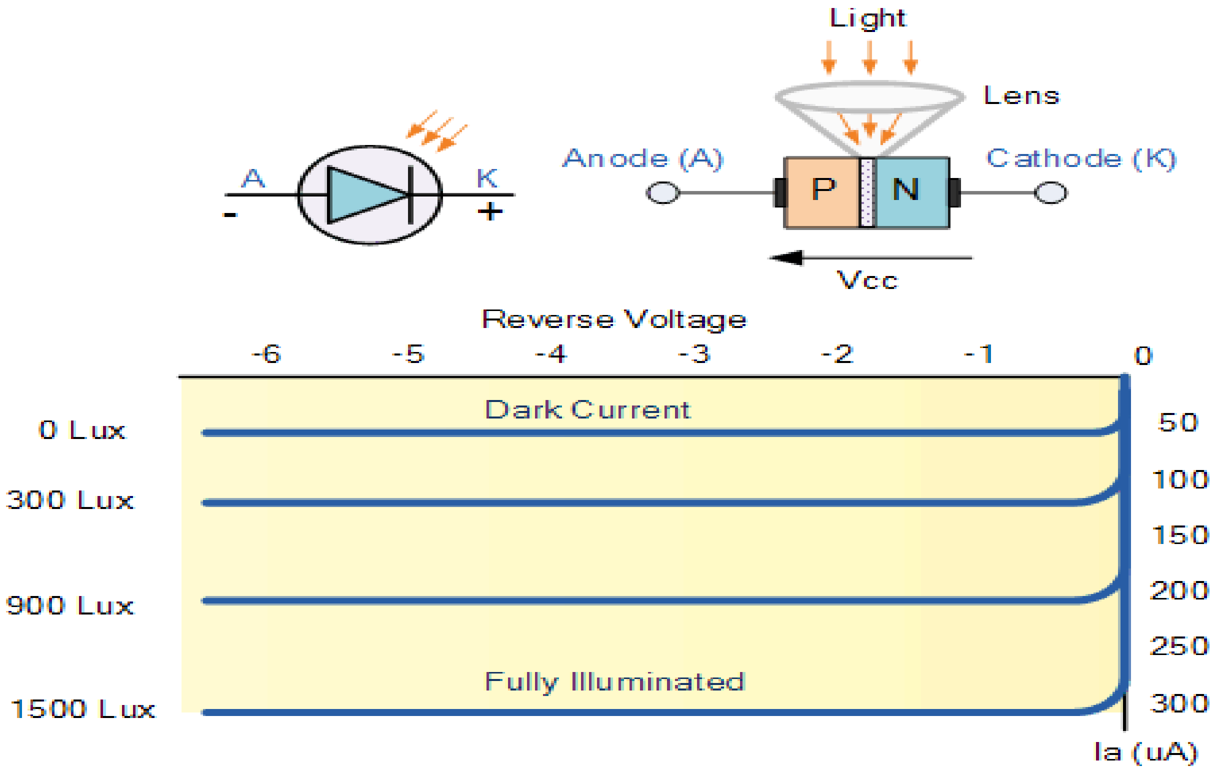


Fig-13: Symbol & Characteristics of Photodiode.

MICROFLUIDIC SYSTEMS:

The study of transportation of fluids and their mixtures at a microscale level is known as microfluidics.

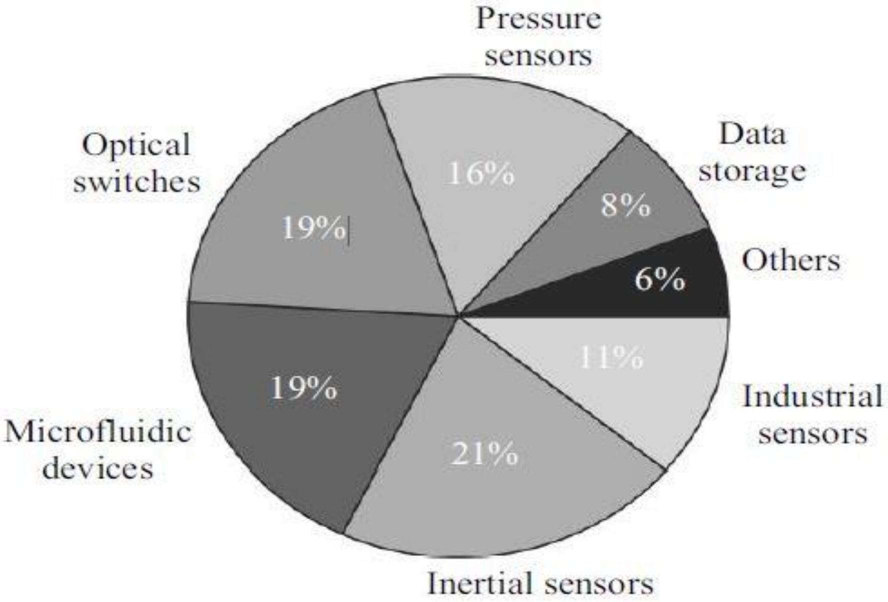


Fig-14: An approximate illustration of MEMS products in various sectors

Microdevices, which are used to transport and store fluid are called microfluidic systems (MFS). Typically the MFS handle fluid volumes in the order of nanoliter.

Some of the important building blocks of microfluidic systems are:

1)Microchannel

2) Microvalves

3) Micronozzles

4) Microreservoirs

5) Micropumps

Some important applications of microfluidics are

- Ejection of inkjet droplets in printers

- Microfluidic oscillator and micro heat exchangers
- Tuning of optical-fiber properties
- Micropumping of gases and liquids
- Drug screening and delivery
- In-vitro diagnostics
- Biological and genetic analysis (e.g. DNA detection)
- Chemical analysis and synthesis
- Environmental pollutant detection and analysis.

Advantages of MEMS microfluidics compared to conventional fluidic systems are:

- The miniaturized system requires less reagent (species or samples) resulting in faster, accurate and reliable measurements
- The capillary action changes significantly when the fluids pass through microscale diameter channels.
- As the scale becomes smaller, the dimensions of a device reach a certain size and the fluid particles or the solvent become comparable in size with the channel or the device itself.

LAB ON CHIP (LoC):

The chemical, clinical and bio-clinical laboratories the instrumentation and analytical equipment and devices are becoming smaller, simpler, and smarter suggesting miniaturization Microfluidics prefers to the design & development of tools, devices related to microscale levels for medical, chemical and biotechnological research. These devices are rather called tools, which have been emerged as biochip or lab-on-a-chip (macroscale test-tube based instrumentation and analytical equipment within the laboratory)

The advantages of LoC (Lab on Chip) are,

- Smaller liquid consumption

- Good response time
- Faster analysis and diagnosis
- Better statistical results and certainty
- Improved possibilities for automation
- Decrease in health and environmental risks
- Reduced costs

IMPORTANT CONSIDERATIONS ON MICROSCALE FLUID:

The behavior of fluid is significantly changed as geometric scale decreases. In this respect following considerations are to be noted. The physical, technological, and biological significance in flows of gases and liquids at the microscale level necessitate the study of properties of fluids. The dominant physical quantities change in the micro-world. Because of scaling effect the large surface forces, high shear and extensional rates, high heat and mass transfer rates make microfluidics a challenging technology.

The control of fluid flow in miniaturized devices and porous media is critical. The physical phenomenon such as intermolecular forces, slip, diffusion and bubbles are the main active agents at the microscale level. In the microworld the surface forces and surface tension start to dominate. When the channel of the order of one micrometer the surface tension is extremely large.

The design of MFS(microfluidic systems) concerns selection of appropriate method for inletting or pumping the liquids into microchannels against two major forces such as surface tension and the externally applied pressure. The diffusion-based characteristics of the laminar flow are sometimes exploited for sample preparation and analysis. The laminar flow behavior of fluids is also considered in the design and development process of microfluidic devices.

The Newtonian fluid mechanics and flow in confined geometries are significant. The flow of thin films spreading under gravity or surface tension gradients is considered important. The handling of fluids with liquid-gas interface in micro channels, valves, pumps, mixers, separators and reactors, excels engineering and scientific challenges. Fluid transportation in a typical microchannel is accomplished based on many phenomenological methods. The control of fluid transportation apparently depends upon the wall surface physicochemistry due to the fact that the fluids exert hydrophobic or hydrophilic force from the channels. The flow behavior of fluids is influenced by the presence of ions, polymers, biomolecules, etc.

FLUID ACTUATION METHODS:

The microfluidic systems are of two types based on the way the microvolume fluid is transported (or its position is manipulated). Accordingly, the systems are called

1) Continuous flow systems

2) Liquid droplet-based system

The position manipulation of microvolume liquid is sometimes called fluid actuation. Conventional pumps, valves, and channels actuate the fluids in continuous-flow systems. In a droplet-based system, however, they are actuated by exploiting the surface tension. In essence, the systems use surface tension gradient to move, combine, and mix liquid droplets. The droplet based system is also called digital fluidic microsystem.

Fig-15: Figure illustrating the surface tension.

When we sandwich 2 electrodes with water and potential is applied, it results in the change of hydrophilic or hydrophopic character of the region. This causes the transportation of the liquid along the region, where it can then be separated into a smaller segment. Henceforth application of potential causes liquid to segment out further. This procedure results in a digitized fluidic circuit.

This procedure has attracted much attention because it eliminates the need for traditional pumps and valves. It also involves less volume of water involved. All these mechanism can control the surface tension.

Some of the important mechanisms are:

1) Dielectrophoresis

2) Thermocapillary

3) Electrowetting

4) Electro-osmosis

5) Electrothermal

6) Light-actuated microfluidic device called optoelectrowetting

DIELECTROPHORESIS (DEP):

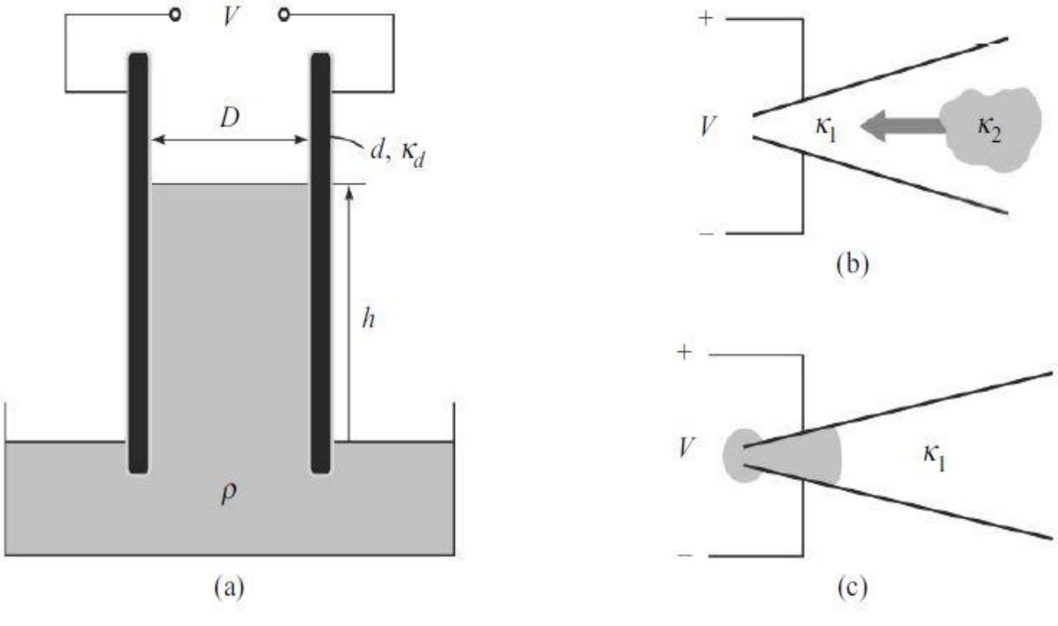


Fig-16: (a) Pellat's dielectrophoretic force experiment; (b) The dielectric liquid is attracted to regions with stronger electric field; (c) The liquid surface follows the electric field lines

Experiment was conducted by Pellat He did this by utilizing two planar, parallel and opposed electrodes, placed vertically with one end submerged into an insulating, dielectric liquid as shown in Fig (a). From the experiment it was found that if a potential difference between the two electrodes is applied, a force is exerted on the liquid, trying to impel it upward.

Because of applied potential difference, the hydrophobic and hydrophilic character of the region changes. This causes the development of a force.The magnitude of this force, and therefore the height of rise of the liquid, is proportional to the magnitude of the applied voltage.

The mathematical equation that governs the DEP phenomenon can be written as,

$$h \approx \frac{k_d \varepsilon_0 V^2}{4 g \rho d D}$$

where

V is the applied potential difference,

r is the density,

k_d is the dielectric constant of the liquid, h is height of rise of liquid,

d is the thickness of the dielectric coating, D is the distance between the planar-parallel electrode,

$\varepsilon_o = 8.854 \mathrm{x} 10^{-12}$ Farad/meter is the permittivity of the free space,

$g = 9.81\ m/s^2$ is the gravitational force.

The effect will be similar if the electrodes are not placed parallel as shown in Fig. (b). The force that starts to act on the liquid is called dielectrophoretic force. The dielectrophoretic force appears when a medium (liquid) is exposed to a non-uniform electric field. The liquids are pulled toward the regions of stronger electric field (Fig. (c)). In essence, the dielectrophoretic phenomenon can be utilized in microfluidics to transport and manipulate microvolume of liquid on a surface (channel).

Typical microfluidic Channel:

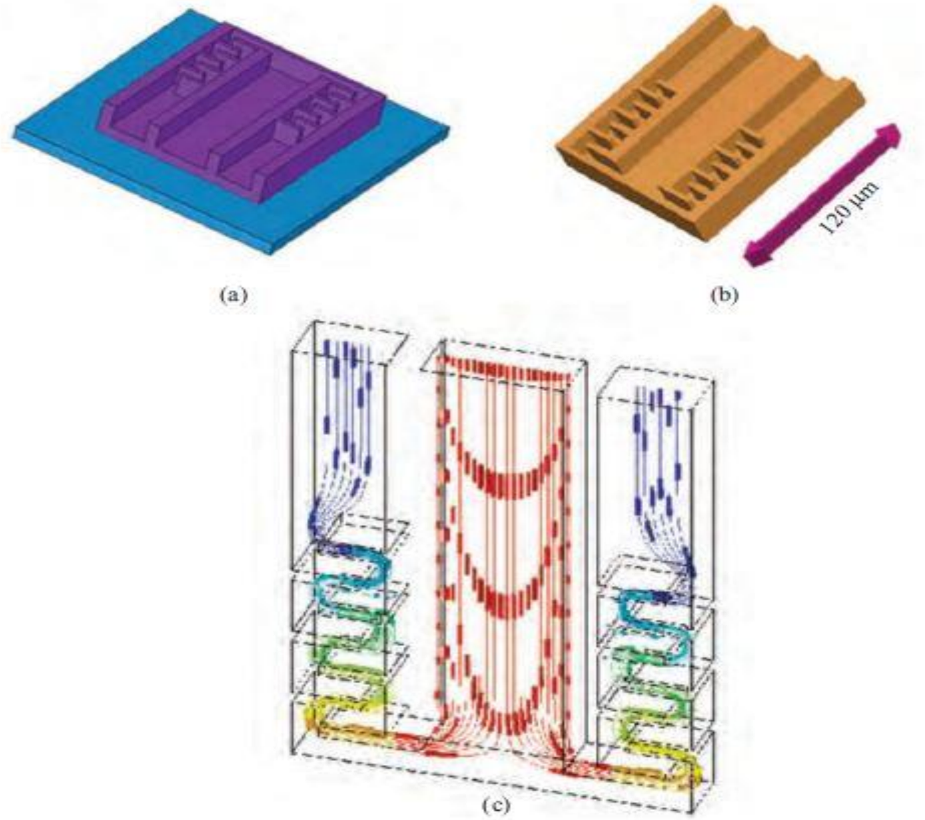


Fig-17: a)Two dimensional view of typical microfluidic channel, b) segmental view, c) Flow profile of the microfluidic channel

Above figure illustrates a typical microfluidic channel, which consists of a surface micro-machined labyrinth, having one central inlet and two outlets. This device imported from Ansys CAD software, is a model, which is approximately 100x120 mm dimension, with a channel depth of 10 mm. The top of this device is not shown because of clarity, but is made by sealing another layer onto the top surface. Fusion bonding technique can be employed to join the channel and the top layer.

The labyrinth can function as a pressure drop or pulse attenuator for blood flow and can be used in clinical diagnosis. Blood can flow into the central inlet and out through the two flanking outlets at a reduced pressure. Figure (c) shows the streamline coded in pressure (Central input channel = high pressure; Two output channel = low pressure), plus particles that follow the streamlines. In essence, the device can be utilized for the purpose of liquid analysis such as:

- Determination of pressure drop across the device
- Determination of velocity profile
- Computation of pressure applied to walls
- Transfer of heat from fluid to structure and vice-versa.
- Obviously, the above liquid (blood) parameters within the channel can be analysed.

MICROFLUID DISPENSER:

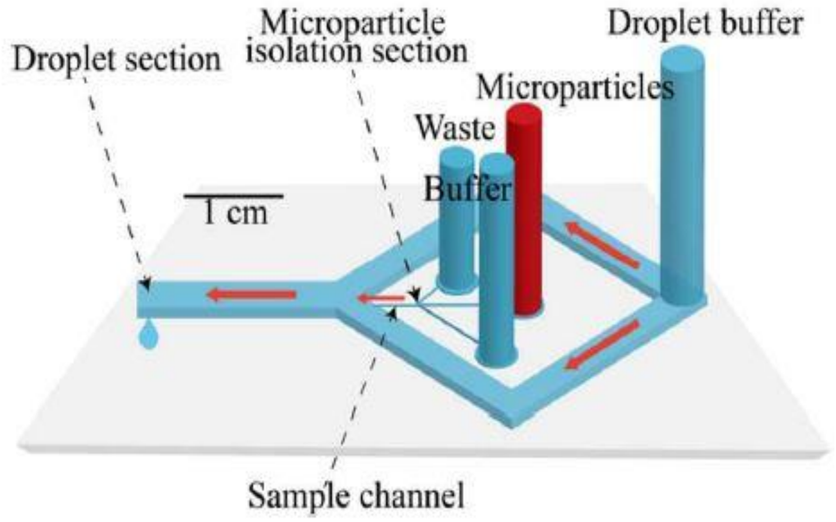


Fig-18: Typical microfluidic dispenser structure

Above figure shows the schematic of the microfluidic chip identifying individual reservoirs and flow directions. Reservoir in red supplies microparticles that flow into the waste reservoir until the optical trap isolates them into the sample channel leading to the droplet delivery section. Channels in the isolation section are 10 µm tall, the droplet buffer channels are 160 µm high and 3 mm wide, while channel lengths are according to scale. (Red arrows indicate flow direction).

The microfluidic device incorporates a separate isolation region to deliver single cells to the droplet generation section for distribution as droplets, an approach that shields the particle isolation section from the mN range surface tension forces In this, an on-chip droplet buffer reservoir generates μl s^{-1} flow rates in wide channels that bifurcate at the droplet buffer inlet and wrap around the isolation section.

Cells flowing into the intersection of these bulk channels via the sample channel at the end of the isolation section are carried by these relatively large flows along the 20 mm length of this channel to the microfluidic device exit, rapidly amplifying the μm translation achieved by the optical trap to mm range. This process moves particles away from the crowded isolation section to the exit where a hydrophobic orifice aids freefalling droplet generation making them easily accessible.

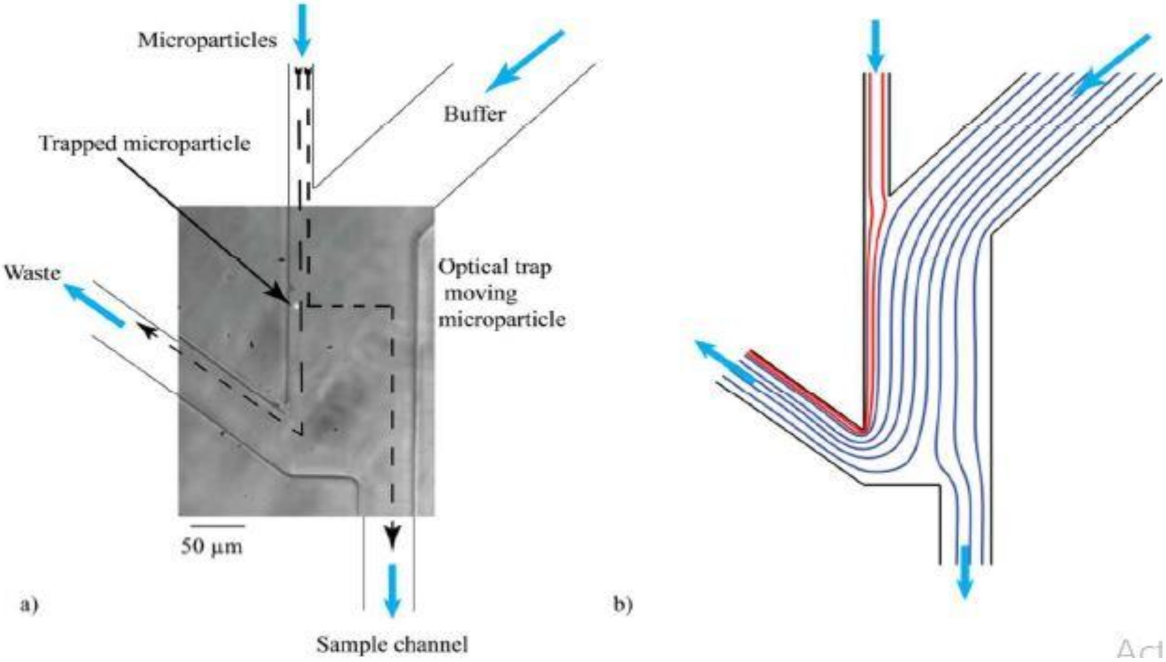


Fig-19: (a) Schematic of the microparticle isolation section, (b) Flow profile.

MICRONEEDLE:

Microfluidic systems promise to revolutionize health care by providing equipments for precise delivery and control of biological fluids. To achieve this in many situations, microneedles are used. Microneedles are attractive from a design perspective as they are also compatible with MEMS fabrication process.

Because of their small size they can be fabricated to provide a range of geometries and flow characteristics.

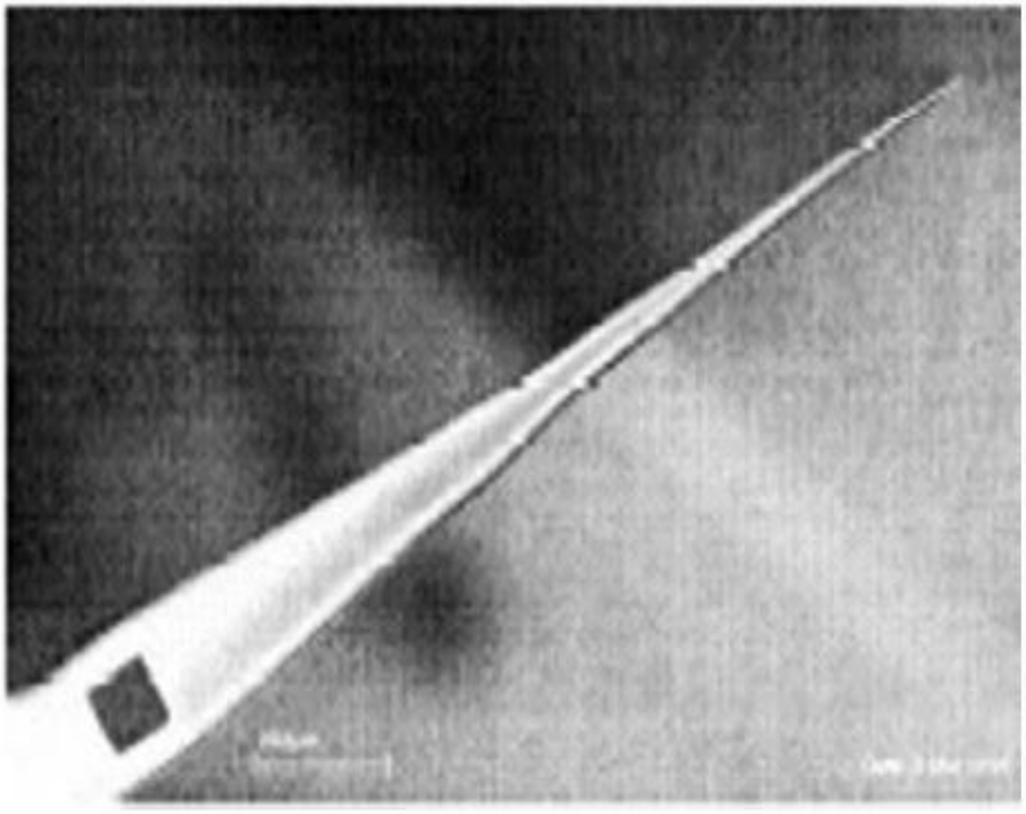


Fig-20: Microsensor of Berkeley Sensor and Actuator Center at University of California

Microneedle are considered as an important BioMEMS devices and especially very useful for the following applications. Collection of samples for biological analysis Delivery of cell or cellular extract based vaccines Providing interconnection between the microscopic and macroscopic devices Extra and Intracellular neuronal recording.

- For a laminar flow, the average flow rate Q can be expressed as,

$$Q = \frac{4ba^3}{3\mu}\left(-\frac{dP}{dx}\right)\left[1 - \frac{192a}{\pi^5 b}\sum_{i=1,3,5\ldots}^{\infty}\frac{\tan h(i\pi b/2a}{i^5}\right]$$

which is obtained by integrating x-directed velocity profile of a rectangular duct with y and z as cross section. Here 2a is the length of the walls, 2b the length of other wall, dP/dx is the pressure gradient which can be estimated to be,

$$\frac{dP}{dx} = -\frac{4\tau_s}{D}, \text{ where } \tau_s = \frac{0.332\mu U}{x}\sqrt{\Re_x}$$

τ_s is shear stress of the plate, x is the distance along the plate, $\Re_x$ is the Reynolds number based on the distance x. The above expression is based on the assumption that the rectangular fluid duct behaves as a collection of four places. The average velocity can be expressed as

$$U = \frac{Q}{4\,ab}$$

MICROPUMPS:

It's a continuous flow system. A mechanical machine that moves fluid or gas continuously by suction pressure is known as a pump. Micropumps are MEMS devices, which are primarily used for microfluidic applications. The cost-effective transport of small quantities of biochemical fluidic samples, in the range of microliters per minute, has been an important challenge for micropumps

These devices operate with flow rates in the range of nanoliter to microliter per minute. Diaphragm based micropumps shown in fig. below are common

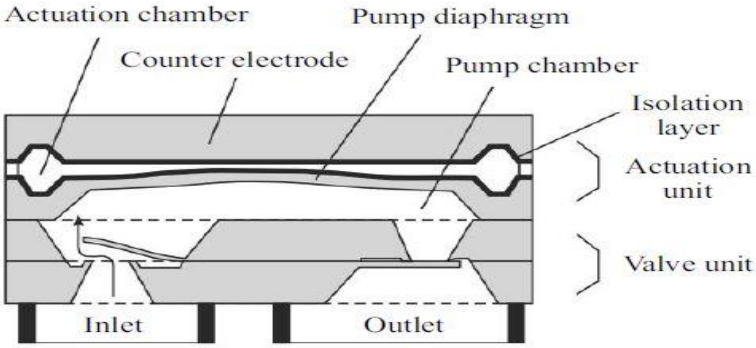


Fig-21: Cross-sectional view of a diaphragm-based micropump assembly

The important part of the micropumps is the diaphragm. The back and forth operation of the diaphragm is achieved by applying AC signal. The material should have high electromechanical properties such as high electrostrictive strain, high energy density, and (iii) high displacement voltage ratio. Polymer is chosen as the suitable material. Mostly, vinylidene fluoride-trifluoroethylene polymers are used, as they possess these properties.

These are called high-energy electron irradiated poly. Besides diaphragm, the other parts and sections of the micropumps are listed below.

- Counter electrode
- Isolation layer
- Actuation chamber
- Pump chamber
- Inlet valve
- Outlet valve
- Inlet microtube
- Outlet microtube

As mentioned, the pump is electrically driven. The AC supply with appropriate frequency is applied across the two electrodes. The diaphragm itself constitutes one electrode.

The other terminal of the AC supply is applied to the counter electrode. Isolation layer is a design criterion and it has high impedance. The operation of the micropump is shown in Fig. 21. The figure shows cross-sectional view of a pump assembly. By applying AC voltage the diaphragm can be deflected up and down (back-andforth). During positive cycle of the applied signal, the diaphragm makes upward movement. Because of this a suction pressure is developed within the pump chamber. The pressure makes it possible to open the cap of the inlet valve and to allow fluids to enter into the pump chamber. During this half-cycle the cap of the outlet valve is closed, as the cap exists at the other end of the orifice.

During negative excursion of the applied AC signal the diaphragm makes downward movement causing the cap of the outlet valve to open. The downward movement makes it possible to allow the fluid to pump away from the chamber.

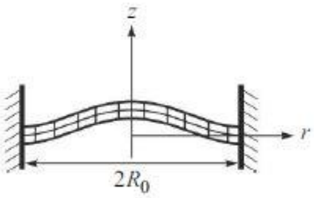
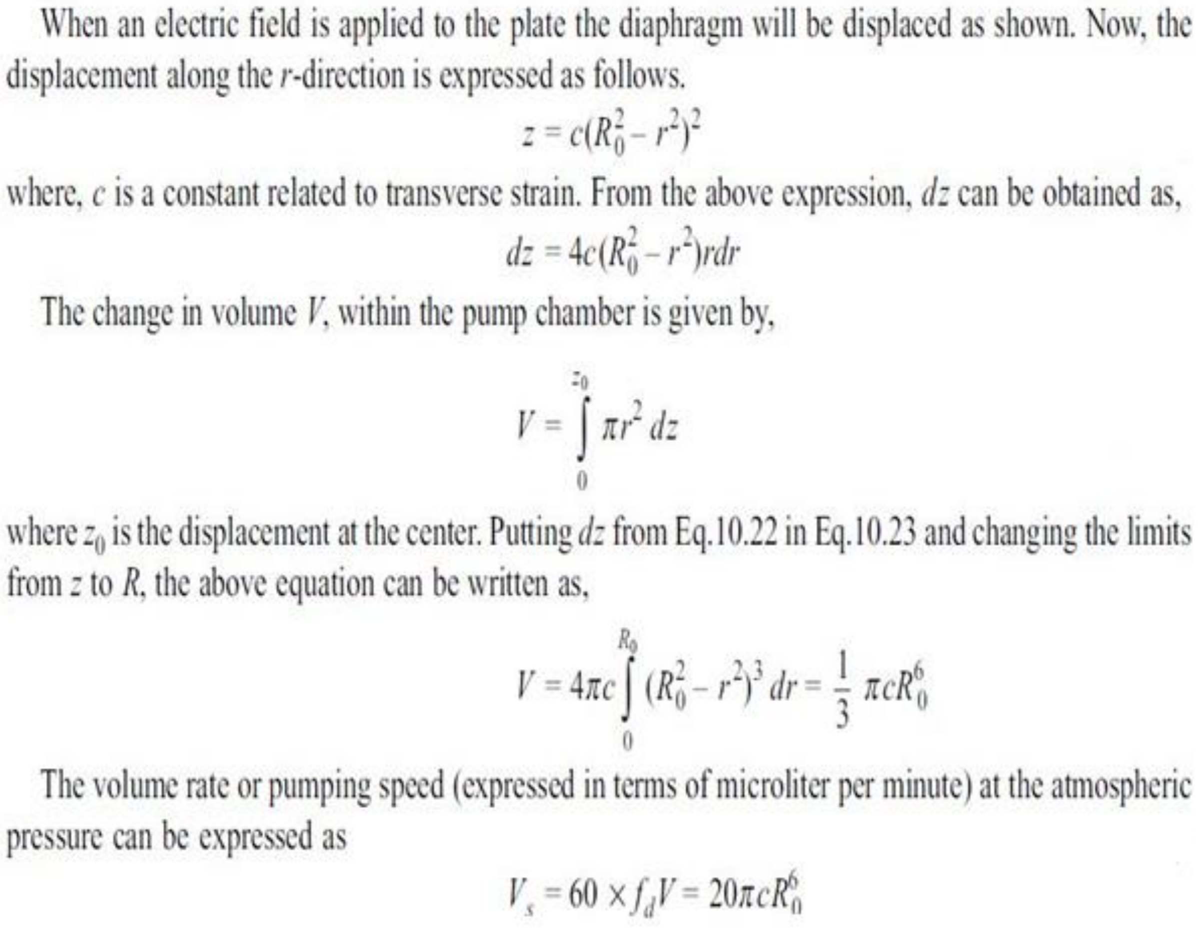


Fig-22: Deflection of diaphragm under an electric field

The pump can be modeled by considering the diaphragm as a circular plate. It is assumed that the circular plate with clamped edges is subjected to uniform mechanical pressure in the lateral direction. Let the radius of the plate be R_0 and the horizontal and vertical axes are denoted as r and z, respectively as shown in Fig.22.



When an electric field is applied to the plate the diaphragm will be displaced as shown. Now, the displacement along the *r*-direction is expressed as follows.

$$z = c(R_0^2 - r^2)^2$$

where, *c* is a constant related to transverse strain. From the above expression, *dz* can be obtained as,

$$dz = 4c(R_0^2 - r^2)rdr$$

The change in volume *V*, within the pump chamber is given by,

$$V = \int_0^{z_0} \pi r^2\, dz$$

where z_0 is the displacement at the center. Putting *dz* from Eq.10.22 in Eq.10.23 and changing the limits from *z* to *R*, the above equation can be written as,

$$V = 4\pi c \int_0^{R_0} (R_0^2 - r^2)^3\, dr = \frac{1}{3}\pi c R_0^6$$

The volume rate or pumping speed (expressed in terms of microliter per minute) at the atmospheric pressure can be expressed as

$$V_s = 60 \times f_d V = 20\pi c R_0^6$$

where f_d is the frequency of diaphragm. Typical values of pumping rate are 50–70 microliter per minute at the applied voltage of 2–3 Vpp. The pump pressure can be about 600 Pa at this voltage. The operational frequency ranges from 10–30 Hz. The overall dimensions of MEMS micropump can be approximately 5000x5000x1000 µm with respect to the length, width and height, respectively. Other driving methods such as electromagnetic, electrothermal etc. can be employed to vibrate the diaphragm.

APPLICATIONS OF BIOMEMS-HEALTHCARE:

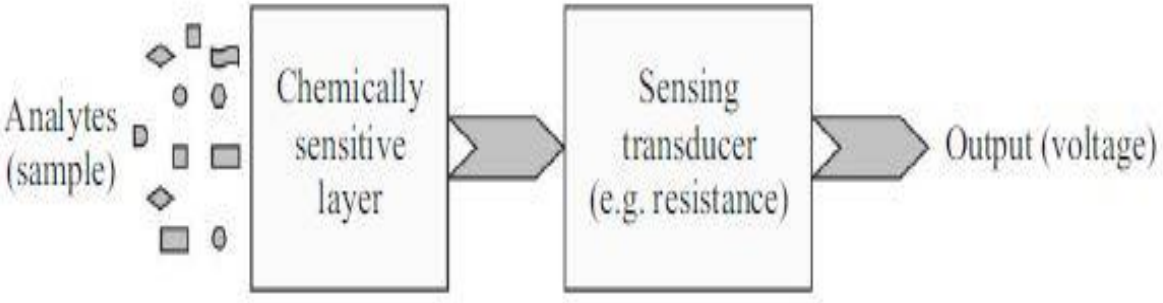
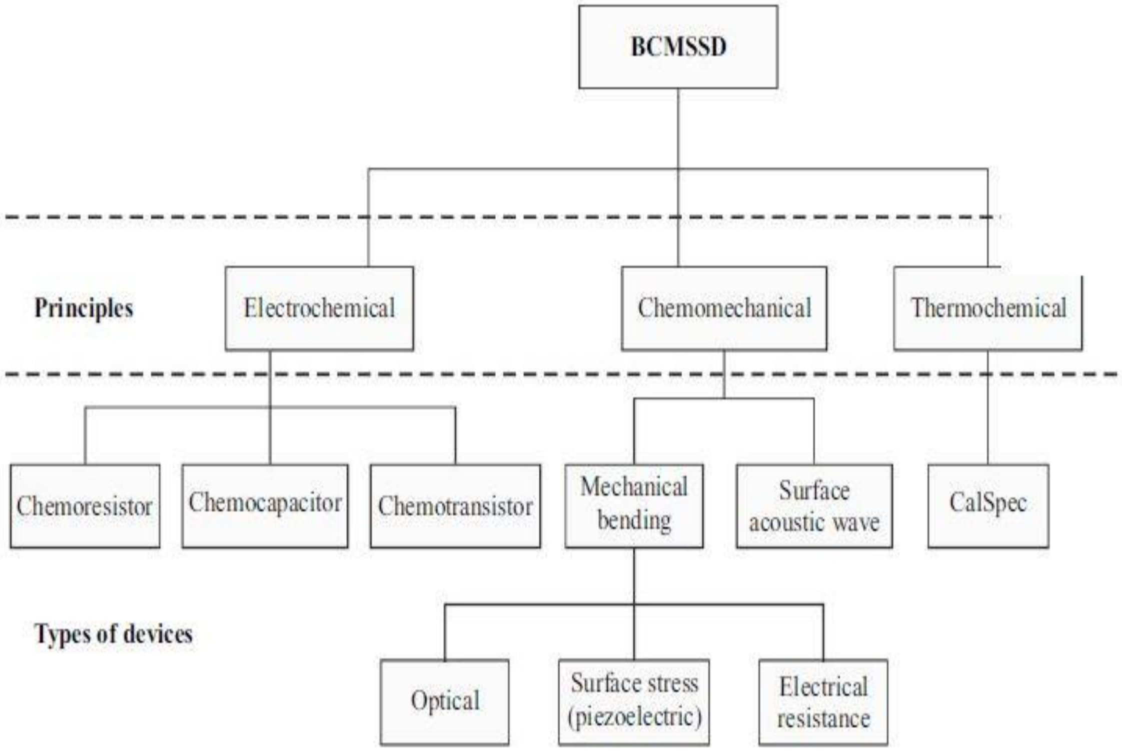


Fig-23: Principle of operation of Bio-MEMS sensors

BCMSSD - Biochemical microsystems sensory devices



Biochip slide for testing protein arrays:

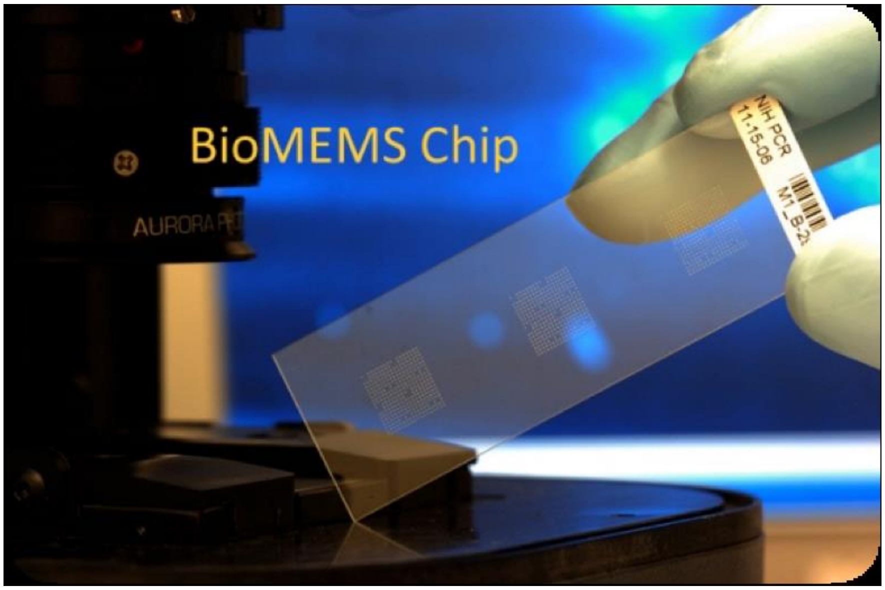


Fig-24: BioMEMS Chip from Argonne National Laboratories

Drug delivery:

Fig-25: MicroCHIPS Subcutaneous Active Drug Delivery System

Biomems sensor placement:

BioMEMS sensor placement depends on the device and its application. A sensor can be

- Topical (applied to skin or placed in the mouth)
- Externally connected (*in vitro* or external with *in vivo* or internal device)
- Implanted devices (totally *in vivo*)

Fig-26: Infrared ear thermometer (from NASA Jet Propulsion Laboratory]

Externally connected Sensors:

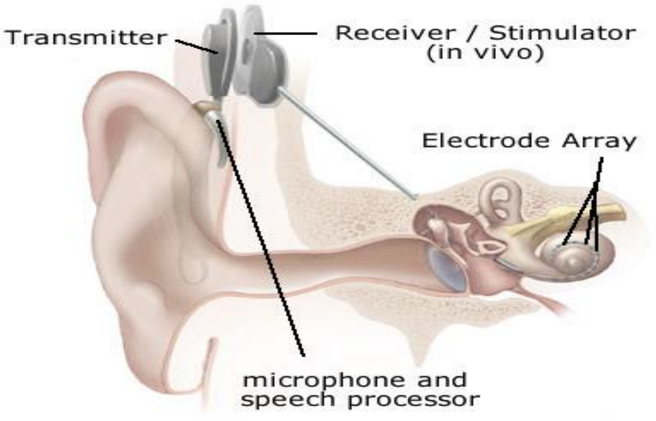


Fig-27: Externally connected sensors at the ear

Externally connected sensors are devices that can contain both an *in vivo* part and an external part. An example of such a device is the cochlear implant shown in this figure. These devices contain a microphone, a speech processor, a transmitter and receiver/stimulator, and an electrode array. The microphone picks up sounds and selects and arranges the sounds for the transmitter.

Once received from the transmitter, the receiver/stimulator converts these signals to electric impulses which are used to stimulate the array. The array then stimulates different regions of the auditory nerve.

Implanted devices:

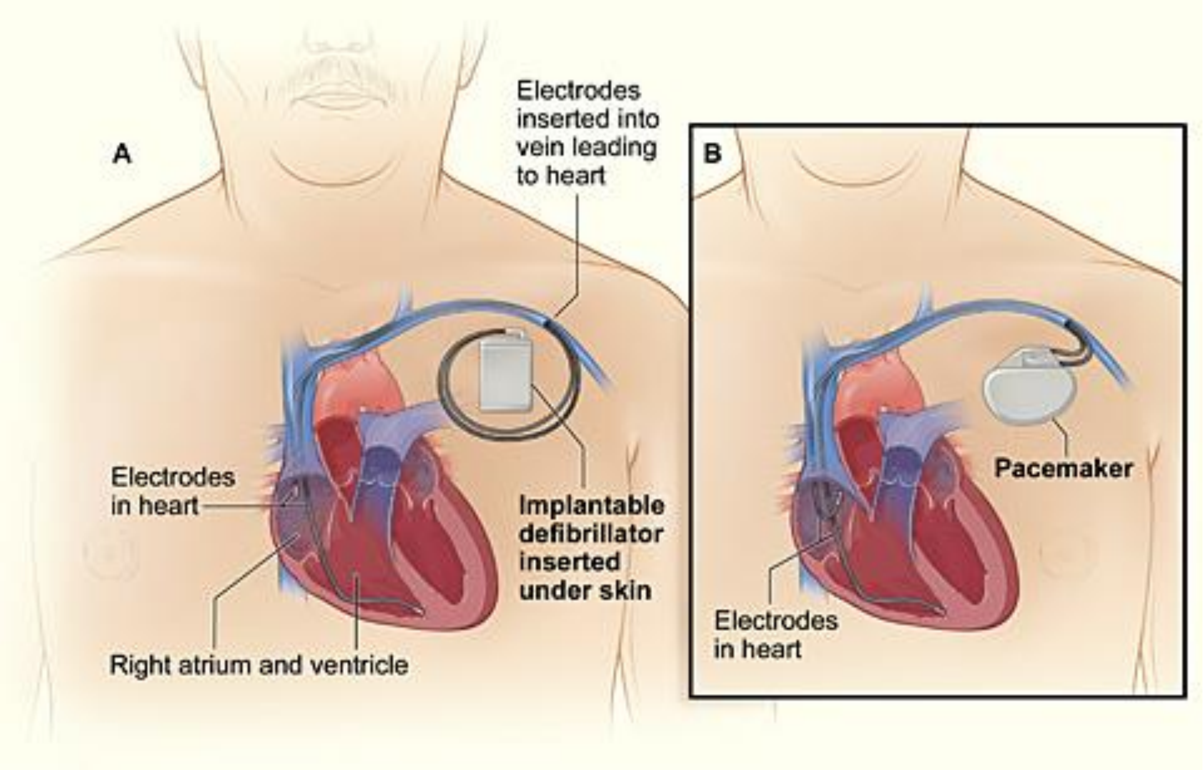


Fig-28: Implanted devices in the heart- pacemaker & defibrillator

Biological Molecule Sensors:

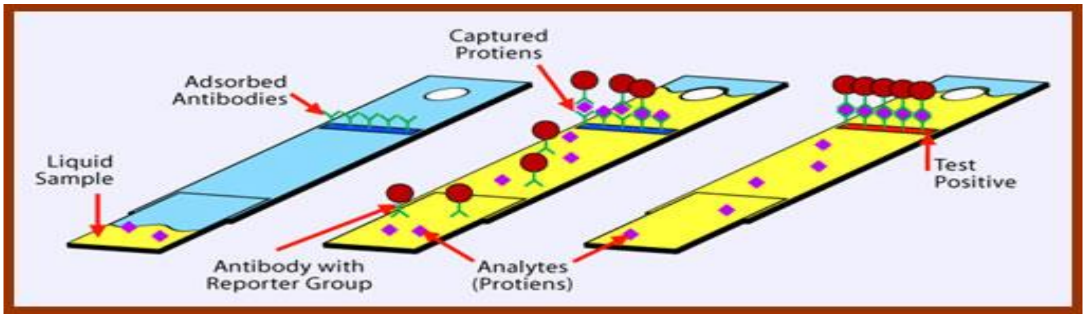


Fig-29: Example of biological molecule sensors-the pregnancy test kit

Glucometers:

This is an external glucometer that requires the patient to place a droplet of blood on the MEMS sensor. To get the blood sample, the patient must prick a finger. The glucose in the blood reacts with the enzymes on the coating of the biosensor. Gluconolactone is produced releasing an electron.

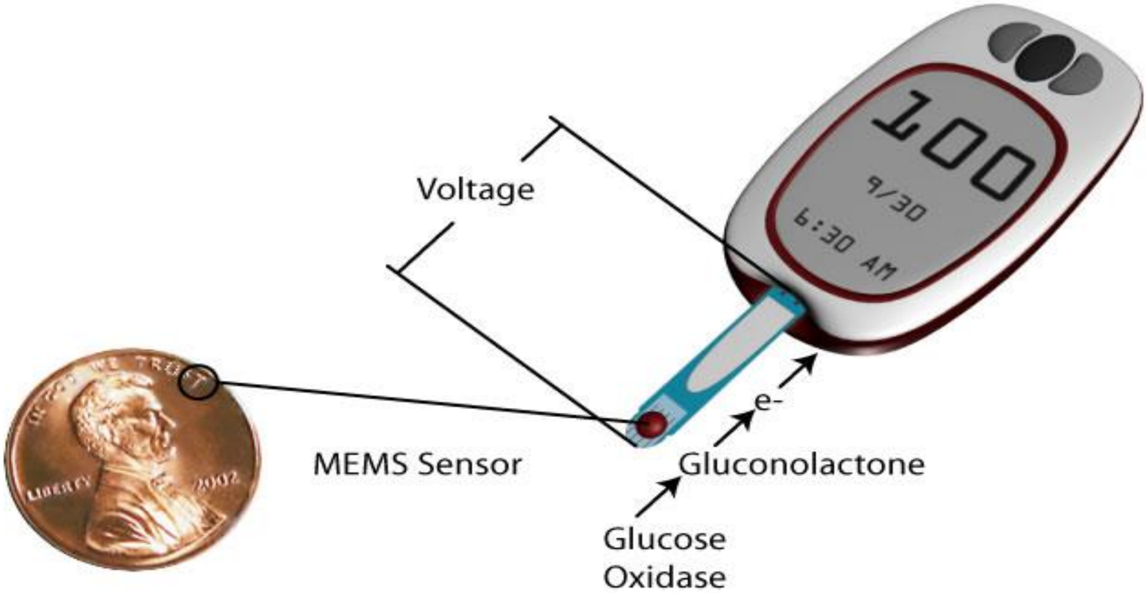


Fig-30: Glucometer

MICRO TOTAL ANALYSIS SYSTEM:

With the help of microfluidics, the different steps involved in applying arrays to screenings or diagnostics can be integrated into small devices resembling miniaturized, automated laboratories.

This approach has been termed the micro total analysis system (μTAS). Such systems should contain elements for the pretreatment, separation, post-treatment, and detection of samples.

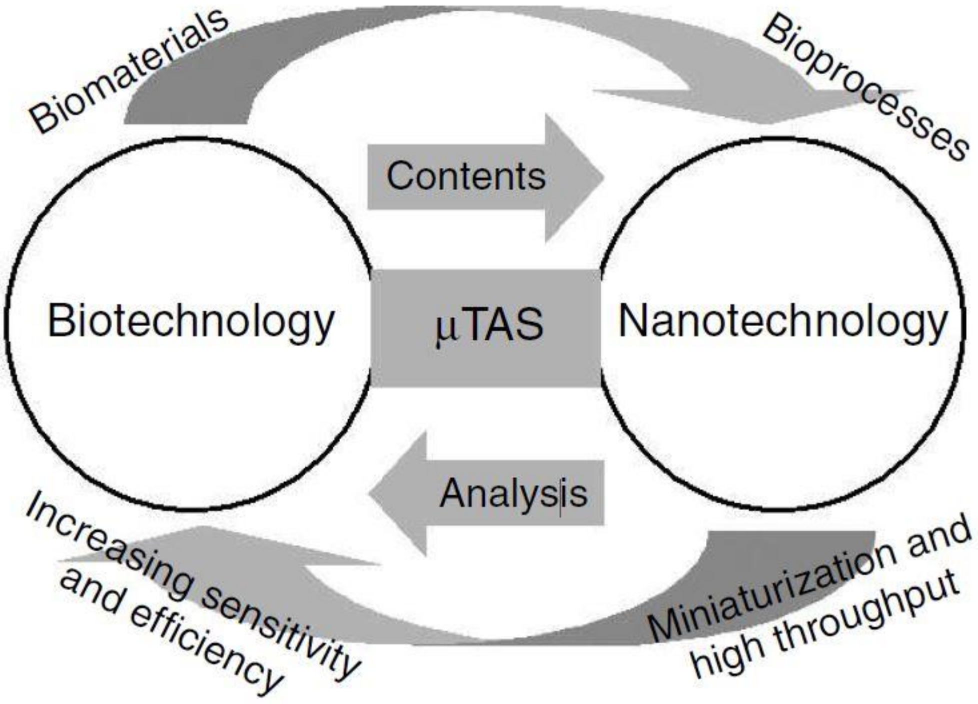


Fig-31: Micro Total Analysis System

REFERENCES:

1. Tai Ram Hsu, Mems and Microsystems, Design and Manufacture, TMH, 2008.
2. Mohammedhad-el-hak, MEMS Introduction & Fundamentals, CRC Press, 2005.
3. Marc J. Madou, Fundamentals of Microfabrication and Nanotechnology, 3rd Edition, 2011, CRC Press. ISBN
9780849331800

4. Harsingh Nalwa, Encyclopedia of Nanoscience and Nanotechnology, American Scientific Publishers, 2007.

5. Neelina Malsch, Biomedical Nanotechnology. CRC, 2005

6. Richard Booker and Earl Boysen, Nanotechnology for Dummies, John Wiley & Sons, 2011

QUESTION BANK:

1) Discuss the principle of MOEMS.?
2) What are light modulators.? Explain its operation with neat sketch.
3) Define beam splitter.?
4) What are digital micro mirror devices.? Explain the working of it with a simple example.?,
5) What are light detectors.? Explain with few examples.
6) Illustrate the two different types of optical switches with neat sketch.
7) What are Microfluidic systems? Explain the operation of a simple fluid actuation system.?,
8) What is dielectrophoresis. Explain in detail with neat sketch
9) Discuss the operation of a microfluid dispenser.?
10) What is a microneedle.? Explain the operation with neat sketch
11) Explain the micro pumps and illustrate with suitable example the working of it.
12) List out the applications of BioMEMS in healthcare and drug delivery.?
13) What are micrototal analysis systems.?

SCHOOL OF BIO & CHEMICAL ENGINEERING

DEPARTMENT OF BIOMEDICAL ENGINEERING

UNIT – IV - MEMS in Healthcare – SBMA7007

What is nanotechnology?

Nanotechnology literally means any technology on a nanoscale that has applications in the real world. Nanotechnology encompasses the production and application of physical, chemical, and biological systems at scales ranging from individual atoms or submicron dimensions, as well as the integration of the resulting nanostructures into larger systems.

The definition of a nanoparticle is an aggregate of atoms bonded together with a radius between 1 and 100 nm. It typically consists of 10 – 10^5atoms. Continued improvements in lithography for use in the production of nano components have resulted in line widths as small as 10 nm in experimental prototypes.

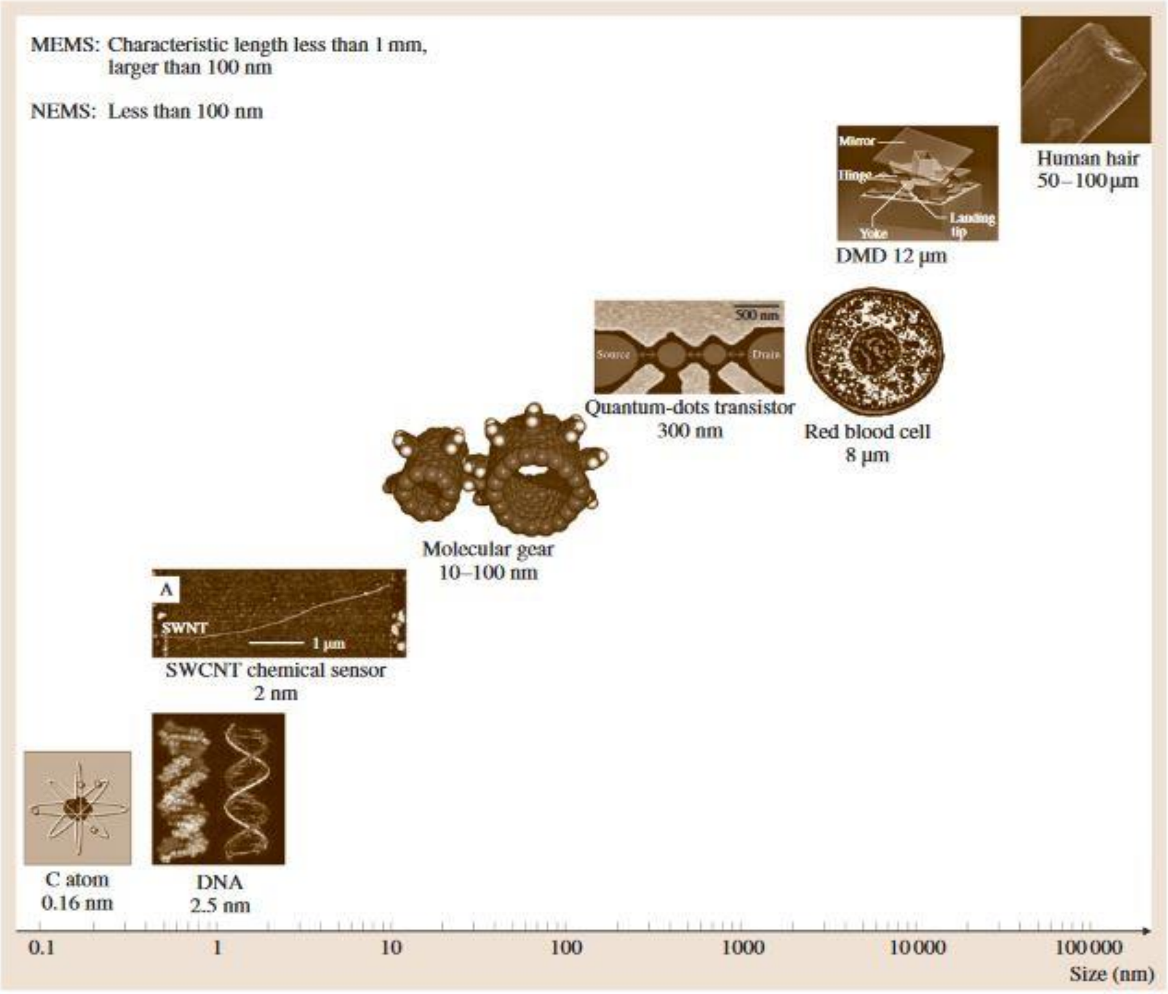
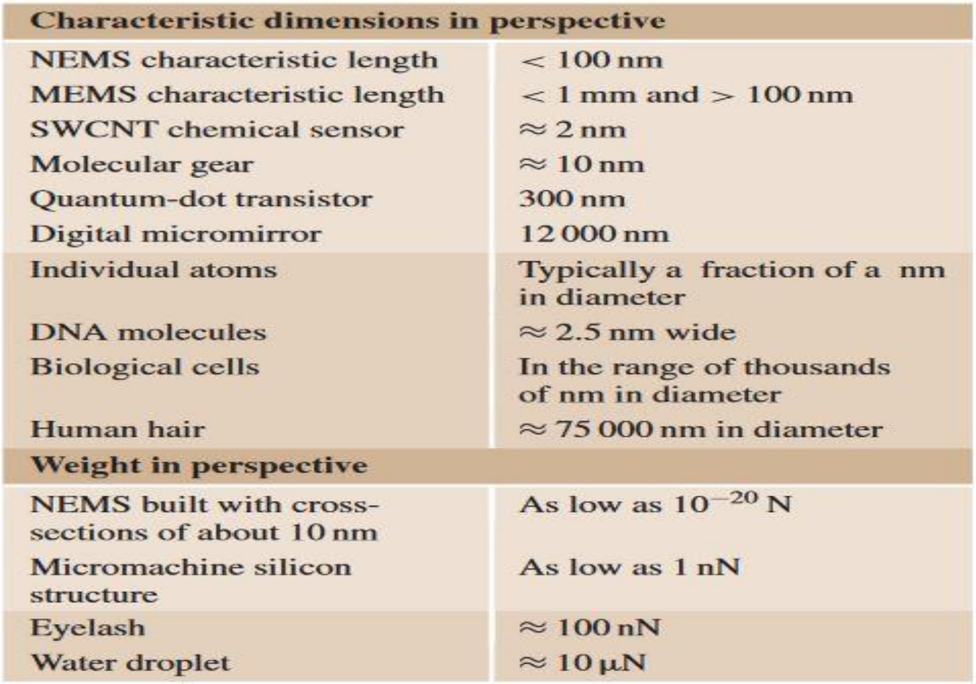


Fig-1: Different sizes of matter

Table-1: Dimensions of various components



Characteristic dimensions in perspective	
NEMS characteristic length	< 100 nm
MEMS characteristic length	< 1 mm and > 100 nm
SWCNT chemical sensor	≈ 2 nm
Molecular gear	≈ 10 nm
Quantum-dot transistor	300 nm
Digital micromirror	12 000 nm
Individual atoms	Typically a fraction of a nm in diameter
DNA molecules	≈ 2.5 nm wide
Biological cells	In the range of thousands of nm in diameter
Human hair	$\approx 75\,000$ nm in diameter
Weight in perspective	
NEMS built with cross-sections of about 10 nm	As low as 10^{-20} N
Micromachine silicon structure	As low as 1 nN
Eyelash	≈ 100 nN
Water droplet	≈ 10 μN

APPLICATIONS OF NANOTECHNOLOGY IN DIFFERENT FIELDS:

- Possible for a variety of industrial, defense, consumer, and biomedical applications.
- Accelerometers
- Silicon-based piezoresistive pressure sensors-absolute pressure sensing for engines & for disposable blood pressure sensors
- Capacitive pressure sensors for tire pressure measurements
- Thermal inkjet printheads
- Micromirror arrays for digital projection displays
- Optical cross-connections in telecommunications.
- Chemical/biosensors and gas sensors, microresonators, infrared detectors and focal-plane arrays for Earth observation, space science, and missile defense applications, picosatellites for space applications,

- Fuel cells, and many hydraulic, pneumatic, and other consumer products.
- Magnetic storage systems.
- Microcantilevers with integrated sharp nanotips for scanning tunneling microscopy (STM) and atomic force microscopy (AFM)
- Quantum corrals
- Nanowires, carbon nanotubes, quantum wires (QWRs), quantum boxes (QBs),
- Quantum-dot transistors, nanotube-based sensors, biological (DNA) motors,
- Nanoelectronics can be used to build computer memory using individual molecules or nanotubes to store bits of information, molecular switches, molecular or nanotube transistors, nanotube flat-panel displays,
- Nanotube integrated circuits, fast logic gates, switches, nanoscopic lasers, and nanotubes as electrodes in fuel cells.
- BioMEMS/BioNEMS are increasingly used in commercial & defense applications.
- They are used for chemical and biochemical analyses (biosensors) in medical diagnostics (e.g., DNA, RNA, proteins, cells, blood pressure and assays, and toxin identification)
- Tissue engineering
- Implantable pharmaceutical drug delivery
- A large variety of biosensors are based on micro/nanofluidics
- Micro/nanofluidic devices offer the ability to work with smaller reagent volumes and shorter reaction times, and perform analyses multiple times at once.
- The second type of biosensors includes micro/ nanoarrays which perform one type of analysis thousands of times.
- Micro/nanoarrays are a tool used in biotechnology research to analyze DNA or proteins to diagnose diseases or discover new drugs.

- Microarray of silicon nanowires, roughly a few nm in size, to selectively bind and detect even a single biological molecule, such as DNA or protein, by using nanoelectronics to detect the slight electrical charge caused by such binding, or a microarray of carbon nanotubes to electrically detect glucose.
- Sensors for detection of biological germs, chemical or nerve agents, and mustard agents, and chemical precursors to protect subways, airports, water supplies, and the population at large
- BioMEMS/BioNEMS are also being developed for minimal invasive surgery, including endoscopic surgery, laser angioplasty, and microscopic surgery.
- Other applications include implantable drug-delivery devices (micro/nanoparticles with drug molecules encapsulated in functionalized shells for site-specific targeting applications)
- A silicon capsule with a nanoporous membrane filled with drugs for long-term delivery.

NANO-FYING ELECTRONICS:

Nanofying electronics can be illustrated using following examples:

- Generating light with nanotechnology
- Sensing things with nanotubes
- Building MEMS — those teeny-tiny electromechanical machines
- Making computer brains one molecule at a time
- Connecting devices with nanotubes and nanowires

(1) Lighting up tomorrow:

Using of Quantum dots:

Quantum dots are nano-size crystals that emit light. The wavelength they emit depends on the size of the crystal. Quantum dots are composed of various materials, such as lead sulfide, zinc sulfide, cadmium selenide, and indium phosphide. Quantum dots are useful because, depending on their size and composition, they emit a particular wavelength, or color, of light after an outside source, such as an ultraviolet light, excites the electrons in them.

Getting quantum dots energized:

Quantum dots are useful because when you add energy to their electrons, the electrons act like they're in one big atom — and when we add energy to the electrons in any atom, what you get is light. This occurs when an electron moves to a higher energy level and then falls back again to its normal energy level. A small quantum dot emits higher-energy photons — with a shorter wavelength — than a large Q-dot can. A quantum dot of a particular size — a relatively large size, to be exact — emits red light, which is the longest wavelength of visible light; smaller quantum dots produce different colors.

If we keep going down smaller and smaller, we shall eventually get to a tiny quantum dot that emits blue light — the shortest wavelength of visible light. If we come up with really large quantum dots you might get them to emit infrared light. Few other quantum dots might emit ultraviolet light, outside the visible spectrum. It turns out that the smaller the quantum dot, the larger the gap between energy levels

Where to get quantum dots?:

Quantum dots can be fabricated using the following techniques

- Chemical reaction (precipitation)
- Chemical vapor deposition (CVDs)

Putting quantum dots to do work:

The first application of quantum dots will be for biological labels used in medical imaging. Researchers tag proteins and nucleic acids with quantum dots; when they shine ultraviolet light on a sample, the quantum dots glow at a specific wavelength and indicate the locations of attached proteins. Quantum dots have advantages over materials currently used for this application — for example, they glow longer. Researchers are also hoping that quantum dots could eventually provide energy-efficient lighting for general use — in your home, office, or neighborhood street lamp.

In these applications, a light-emitting diode (LED) or other source of UV light would shine on quantum dots, which would then light up. By mixing different sizes (and the associated colors) of quantum dots together, we could generate white light. Generating light from quantum dots would work like generating fluorescent light — but without that bulky fluorescent tube.

This method would also avoid the wasted heat that you get with our typical incandescent light bulb. Passing an electrical current through an LED also generates light. A company called QD Vision is attempting to use techniques developed at MIT to design a quantum-dot LED: a layer of quantum dots sandwiched between conductive organic layers. Passing a current through the dots generates light (next page figure). Flat-panel TV displays using quantum-dot LEDs may provide more vibrant colors than current flat-panel displays based on Liquid Crystal Display (LCD) technology.

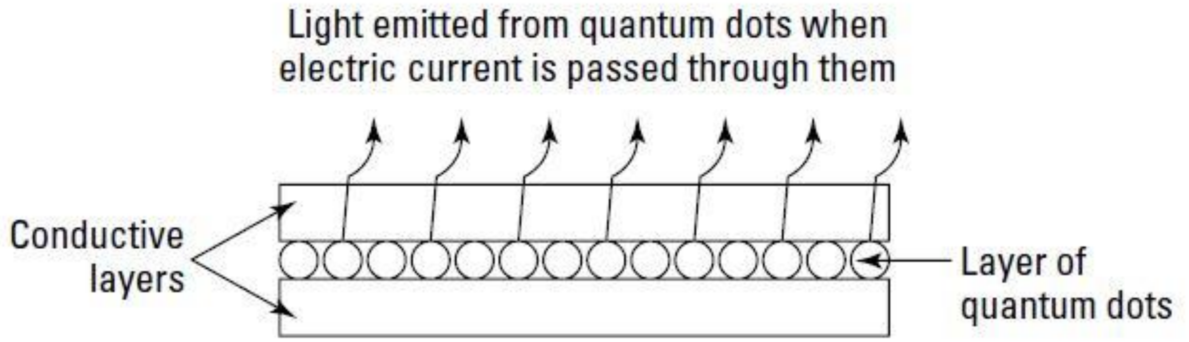


Fig-2: Structure of a quantum dot LED.

(2) Getting light from nanotubes:

A nanotube is a nanometer-scale hollow tube-like structure. Researchers at IBM have found that when you flow electrons through semiconducting carbon nanotubes, the nanotubes emit light at specific wavelengths — a nano-scale version of electroluminescence (converting electrical energy into light).

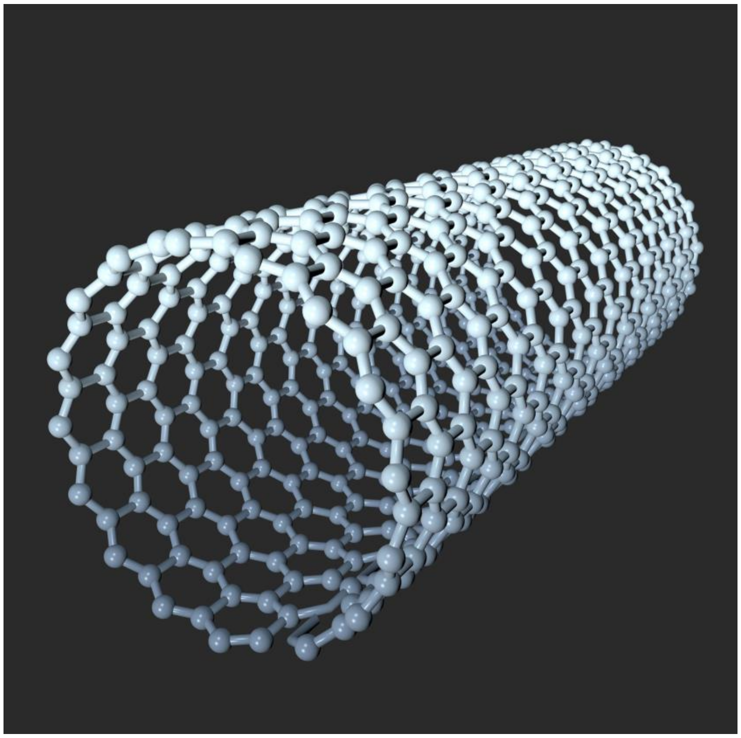


Fig-3: Structure of a nanotube

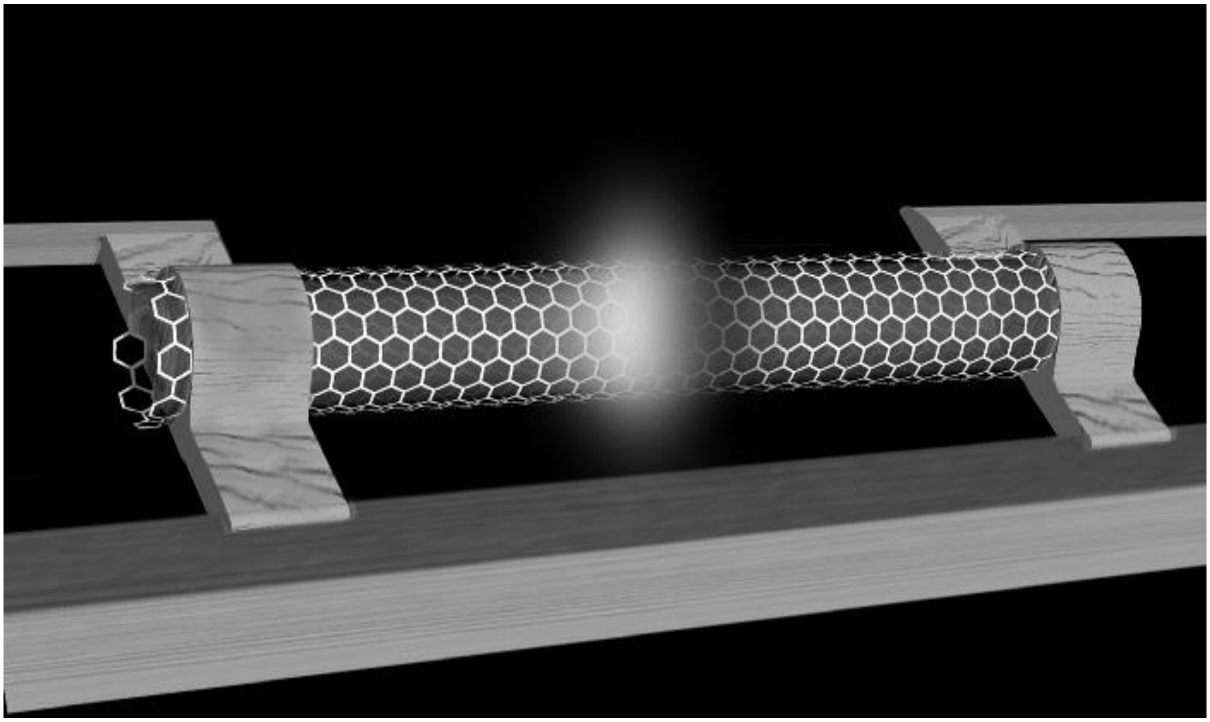


Fig-4: A nanotube used as a channel for electrons in an FET. (IBM)

If a nanotube generates light at a specific wavelength, it's similar to the light generated at the same wavelength when electrons move between these two states (each with its own energy level) in an atom or molecule:

Conductance: An electron in a conductance state is free to move around from atom to atom in the nanotube. Electrons in a conductance state have a higher energy level than those in a valence state.

Valence: An electron in a valence state occupies an orbital in the outer shell of an atom in a nanotube, at a lower energy level than those in a conductance state.

- The energy level of an electron in a carbon nanotube is determined by the diameter of the nanotube; as with quantum dots, a smaller diameter means a higher energy level.

Therefore, the wavelength of the light generated also depends upon the diameter of the nanotube.

Sensing the environment:

❖ Detecting Chemicals:

Nanosensors are available that use carbon nanotubes as sensor elements to detect chemical vapors — even if said vapors are scarcely present, with concentrations measured in parts-per-billion (ppb), within mere seconds.

Chemical vapors can also change the conductance of a carbon nanotube when a molecule bonds to the surface. This bonding can either increase or decrease the amount of electrons available for conductance in the nanotube. They detect the change in conductance when a semiconducting carbon nanotube comes into contact with certain chemicals.

For example, nitrogen dioxide (NO_2) reduces the number of electrons available in a carbon nanotube. When NO_2 bonds to the surface of a carbon nanotube, it filches an electron for its own use — which decreases the conductance of the nanotube. On the other hand, ammonia (NH_3) combines with water vapor in the air to form a molecule that can contribute an electron to the carbon nanotube, increasing its conductance.

Chemical vapors that have been shown to change the conductance of a nanotube include nitrogen dioxide, ammonium, carbon monoxide, carbon dioxide, methane, hydrogen, and oxygen. Molecules that include these groups have also been shown to be detectable by nanotubes.

For example, nitrotoluene — a chemical used in many explosives and containing nitrogen dioxide — has an effect on a carbon nanotube similar to that of nitrogen dioxide — so it may be detectable by the same means. One interesting application of these nanosensors is the detection of trace levels of vapors from explosives.

Because most explosives are made of molecules containing nitrogen dioxide (NO_2), nanosensors may be able to detect trace amounts of those vapours. This potentially greater sensitivity might eventually help airport security personnel detect (for example) bombs in luggage. One pothole is that all chemical vapours are having some influence upon the electrical characteristics of CNT (carbon nanotube) including explosives and other useful vapours.

To solve this problem researchers suggest to coat the CNTs. For example, coating the nanotubes with a polymer called polyethyleneimine allows the sensor to detect NO_2 but minimizes its sensitivity to NH_3. Coating nanotubes with a different polymer called nafion stops NO_2 from getting through — but allows the sensor to detect NH_3.

Example: A Chemiresistor device:

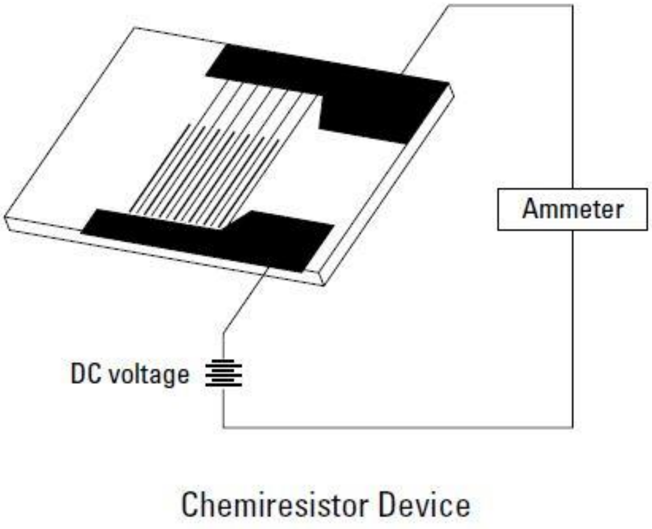


Fig-5: Structure of a Chemiresistor device joined with ammeter

In a chemiresistor, carbon nanotubes are laid between metal electrodes; you apply a constant voltage between those two electrodes. If the conductance of the carbon nanotubes remains constant, the resulting electrical current also remains constant. If the conductance of the carbon nanotube — and therefore the current — changes, then a chemical is present that caused the change. A sensor of this type can detect NO_2 levels of less than 50 parts per billion.

The surface area — and presumably the sensitivity — of this type of detector is increased by constructing each electrode in the shape of multiple "fingers." We then interleave the fingers from the two electrodes and lay carbon nanotubes between the interleaved fingers.

BUILDING COMPUTER BRAINS FROM MOLECULES:

- Computer chips have been miraculously shrinking over the years to become more powerful.
- But as the components of chips — stuff like transistors, diodes, and memory cells — continue to shrink, there's less distance between those components; the increased density in the chip creates problems.
- Nanotechnology may take us the rest of the way to creating computer chips based on molecular-scale devices (or even smaller nano-devices) that can solve many of these problems.

Few problems associated:

(1) Noise: Leakage of electrons from one device — a transistor, for example — to another or from one part of a device to another. As the thickness of the insulating layers is reduced, their effectiveness is also reduced. This shrinkage increases leakage of electrons and produces electrical "noise" in the circuit.

(2) Heat: Generation of heat from having so many transistors and other devices in one small space.

(3) Cost: As the feature size of components shrinks, the cost of manufacturing equipment used to create the components increases.

How nano can help?

Building transistors and other devices used in computer chips either from organic molecules or from nanowires, nanotubes, and nanoparticles the size of a molecule may be a way to minimize these problems. This technique is called molecular electronics.

Projected benefits:

a) Quieter.

b) Cooler.

c) Cheaper.

Example for molecular electronics:

The conventional electronics have Gate, Source and Drain in a MOSFET embedded along the substrate of the semiconductor (Silicon or Germanium). Usually the Gate is provide to ensure that it allows current flow between drain and source. When voltage between source to drain is high (Vds) current will not flow between them because of zero gate source voltage (Vgs). When the gate source voltage (Vgs) is slightly increased beyond the threshold voltage, current flows between source and drain thereby making the field effect transistor conduct.

For Molecular electronics we have Gold plated electrodes in the place of anode and cathode. In between them we have molecules of carbon, oxygen, nitrogen, sulphur, hydrogen atoms. When we need conduction, the gold electrodes are energised and it makes the molecules to combine together and make conduction to take place.

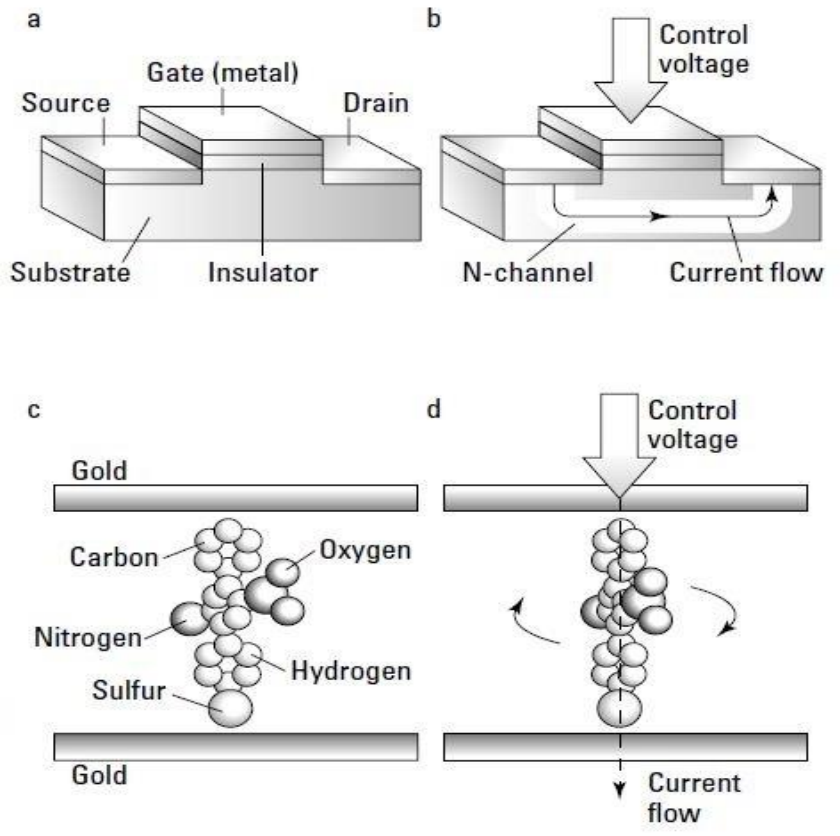


Fig-6: Example application of molecular electronics

Properties of Nanomaterials:

❖ **Definition of nanoparticles or nanomaterials**

- Nanomaterials or the Nanoparticles are the set of particles or the substances where atleast one dimension is less than approximately 100nm. or it can be also classically illustrated as the follows:
- Nanomaterial is an object that has atleast one dimension in the nanometer scale approximately 1-100nm.

Classification of Nanomaterials:

- Classification of the nanostructured materials and systems essentially depends on the number of dimensions which lie within the nanometer range.

a)Zero dimension structures

- Examples:Nanoparticles;Nanograins;Nanoshells;Nanocapsules;Nanorings;Fullerenes;colloidal particles; activated carbon; nanoporous silicon; quasi crystals.

b) One dimension structures:

- Examples: Nanorods; Nanofilaments; Nanotubes; quantum wires; nano wires.

c) Two dimension structures:

- Examples: discs; platelets; ultrathin films; super lattices; quantum wells.

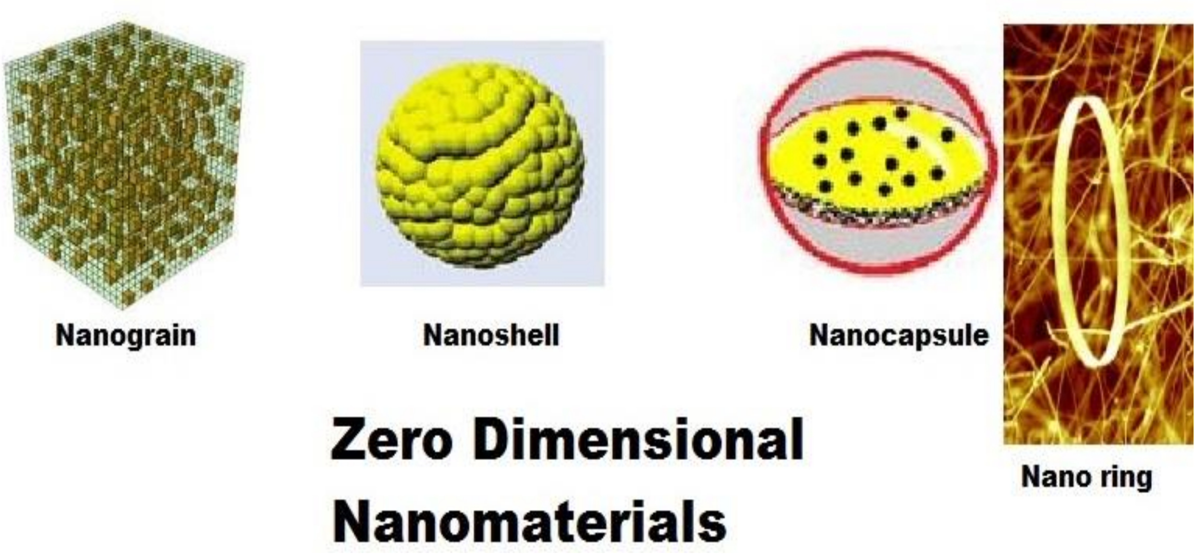


Fig-7: Example structures of zero dimensional nanomaterials

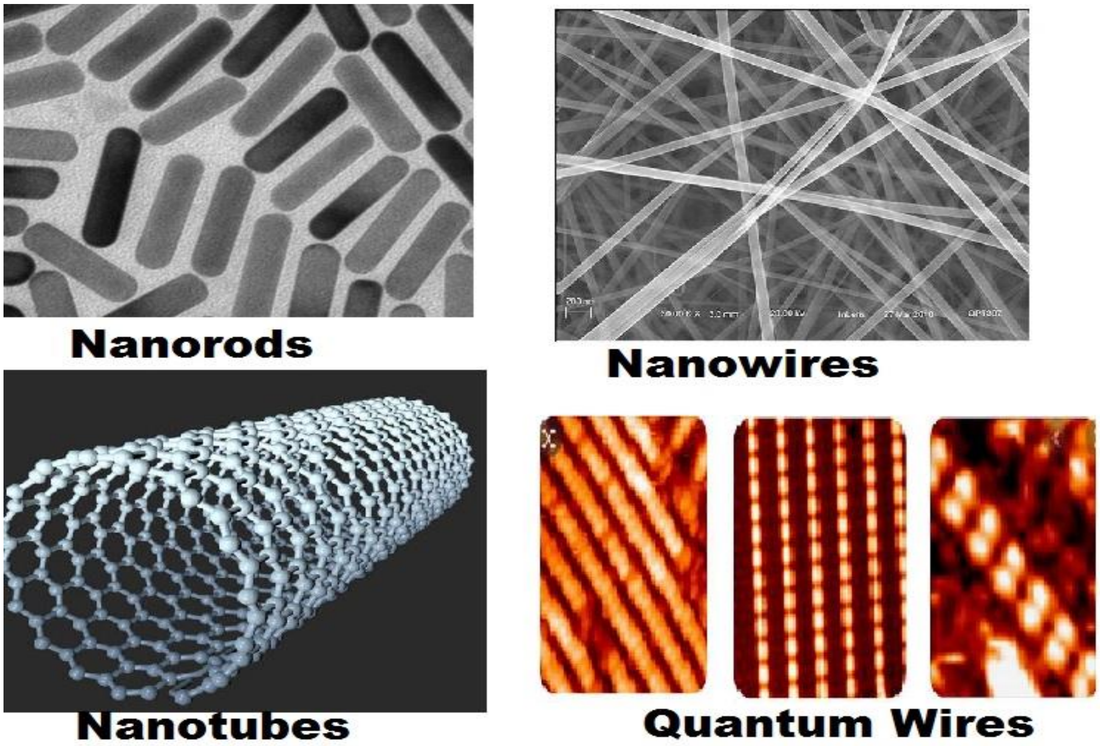


Fig-8: Example structures of one dimensional nanomaterials

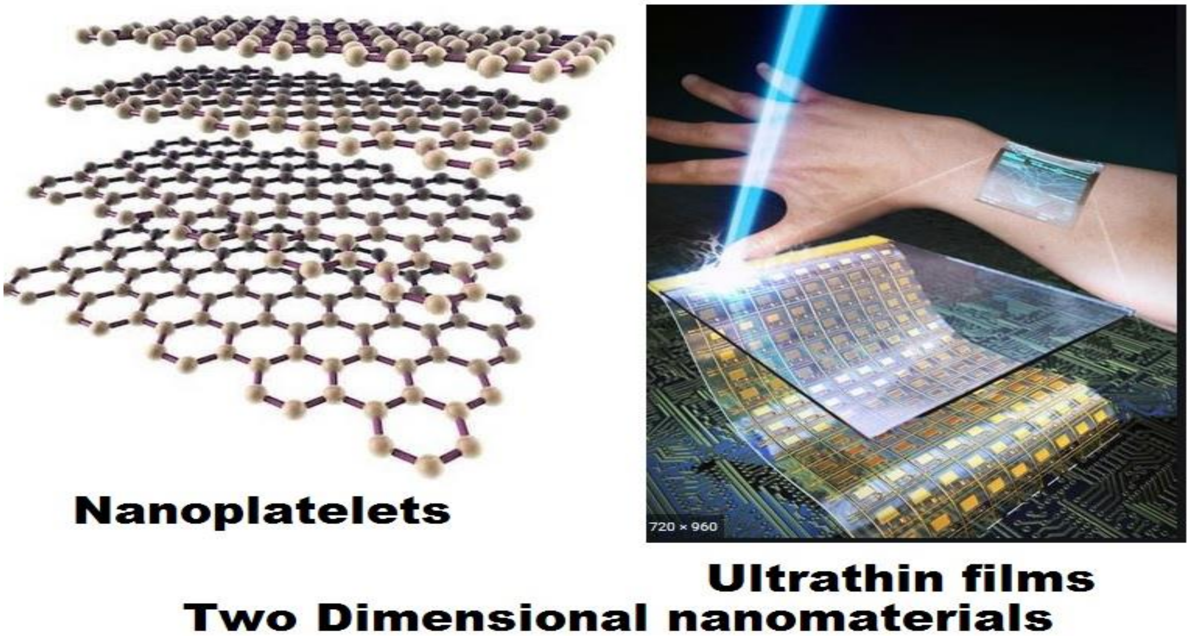


Fig-9: Example structures of two dimensional nanostructures

- Some known physical properties of nanomaterials are related to different origins:
- for example, (i) large fraction of surface atoms, (ii) large surface energy, (iii) spatial confinement, and (iv) reduced imperfections.
- The following are just a few examples:

(1) Nanomaterials may have a significantly lower melting point or phase transition temperature and appreciably reduced lattice constants, due to a huge fraction of surface atoms in the total amount of atoms.

(2) Mechanical properties of nanomaterials may reach the theoretical strength, which are one or two orders of magnitude higher than that of single crystals in the bulk form. The enhancement in mechanical strength is simply due to the reduced probability of defects.

(3) Optical properties of nanomaterials can be significantly different from bulk crystals. For example, the optical absorption peak of a semiconductor nanoparticle shifts to a short wavelength, due to an increased band gap. The color of metallic nanoparticles may change with their sizes due to surface plasmon resonance.

Physical Properties:

Some known physical properties of nanomaterials are related to different origins:

(i) large fraction of surface atoms,

(ii) large surface energy,

(iii) spatial confinement, &

(iv) reduced imperfections

<u>Other few physical properties:</u>

1) Significantly lower melting point or phase transition temperature & reduced lattice constants

2) Mechanical strength is one or two orders of magnitude higher than that of single crystals in the bulk form. The enhancement in mechanical strength is simply due to the reduced probability of defects.

3) The color of metallic nanoparticles may change with their sizes due to surface plasmon resonance when subjected to light.

4) Electrical conductivity decreases with a reduced dimension due to increased surface scattering except in polymeric fibrils where there is ordering of the microstructure.

5) Ferromagnetism of bulk materials disappears and transfers to superparamagnetism in the nanometer scale due to the huge surface energy.

6) Any heat treatment increases the diffusion of impurities, intrinsic structural defects and dislocations, and one can easily push them to the nearby surface

MECHANICAL PROPERTIES:

- Stress: $\sigma = F/S$
- Strain: $\varepsilon = \Delta l / l_0$

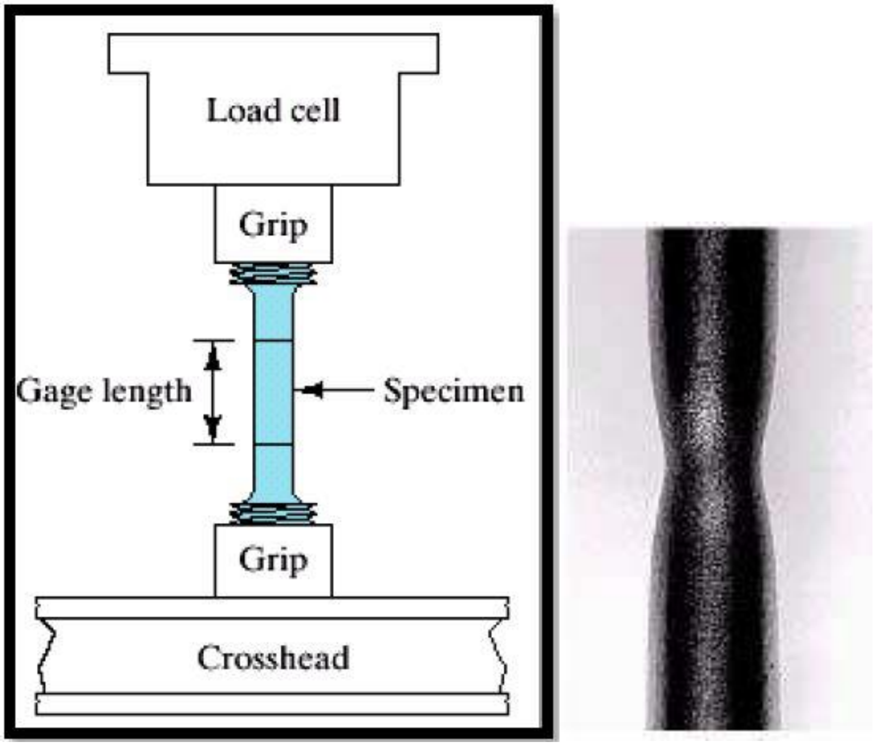


Fig-10: A nanomaterial subjected to stress between crossheads

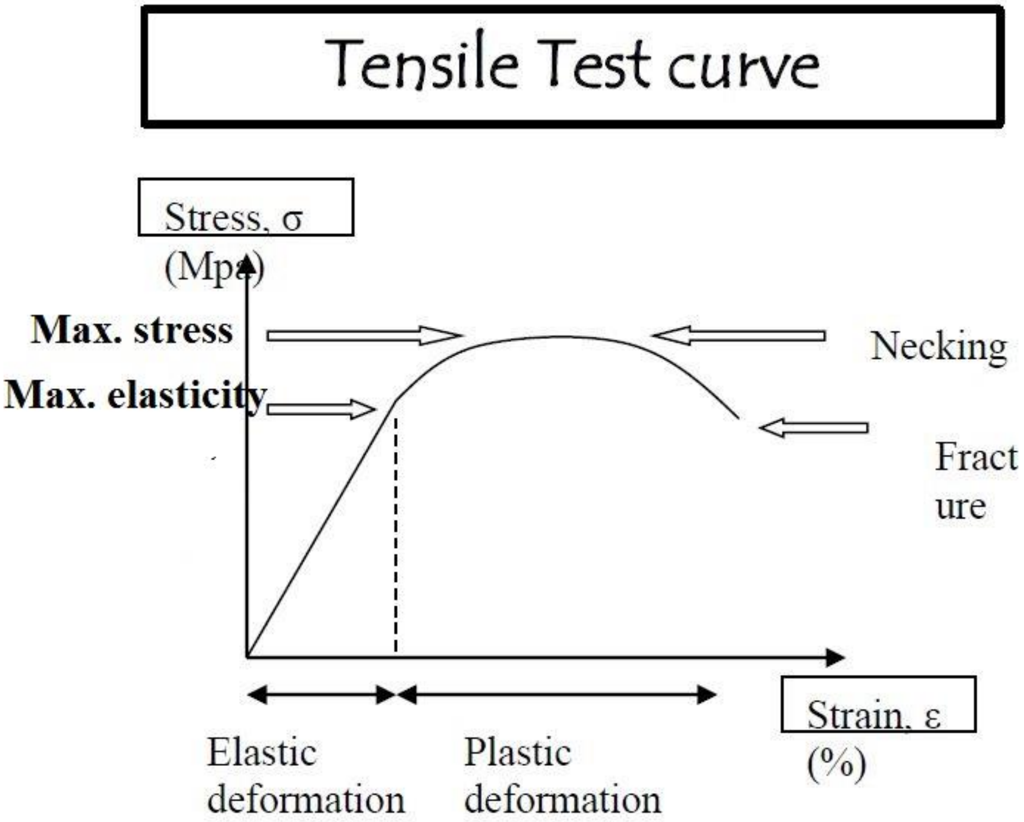


Fig-11: Tensile stress curve relationship for a nanomaterial

Some of the mechanical parameters of the nanomaterials are:

- **Yield strength:** maximum stress before permanent strain
- **Tensile strength:** maximum stress
- **Ductility:** measure of deformation (Lf – Lo)/ Lo
- **Toughness:** ability to absorb energy: area under curve

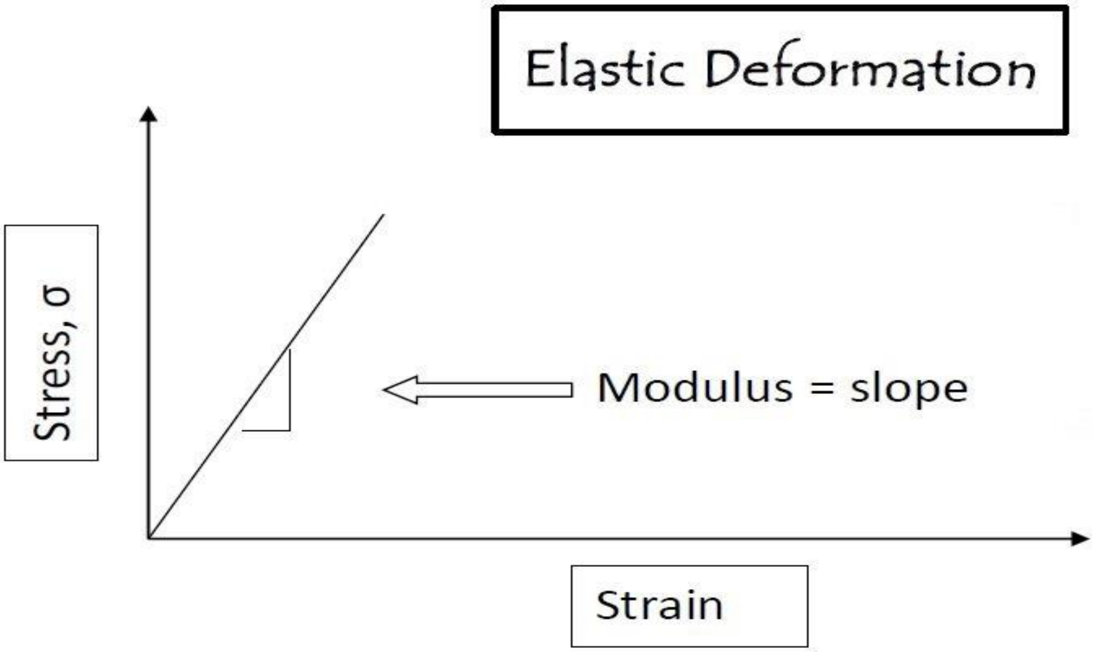


Fig-12: Stress versus strain relationship in a nanomaterial

Hardness:

It refers to the resistance to plastic deformation and also it's a measure of depth or size of indentation.

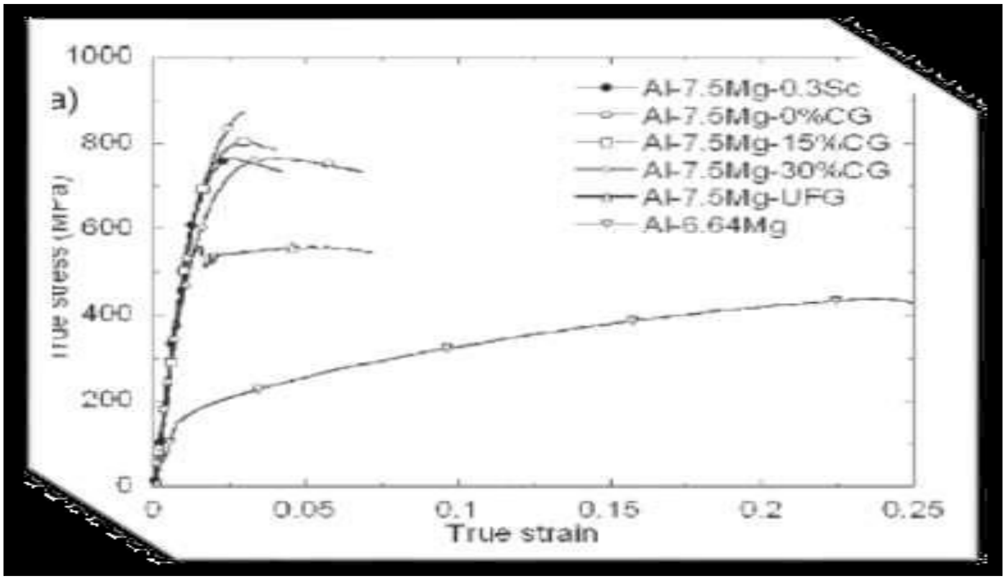


Fig-13: Graph of True stress versus true strain for selected nanomaterials

Mechanical properties of nanomaterials compared to coarse grain materials:

- Higher Young modulus and tensile strength (to 4 times higher)
- Lower plastic deformation
- More brittle

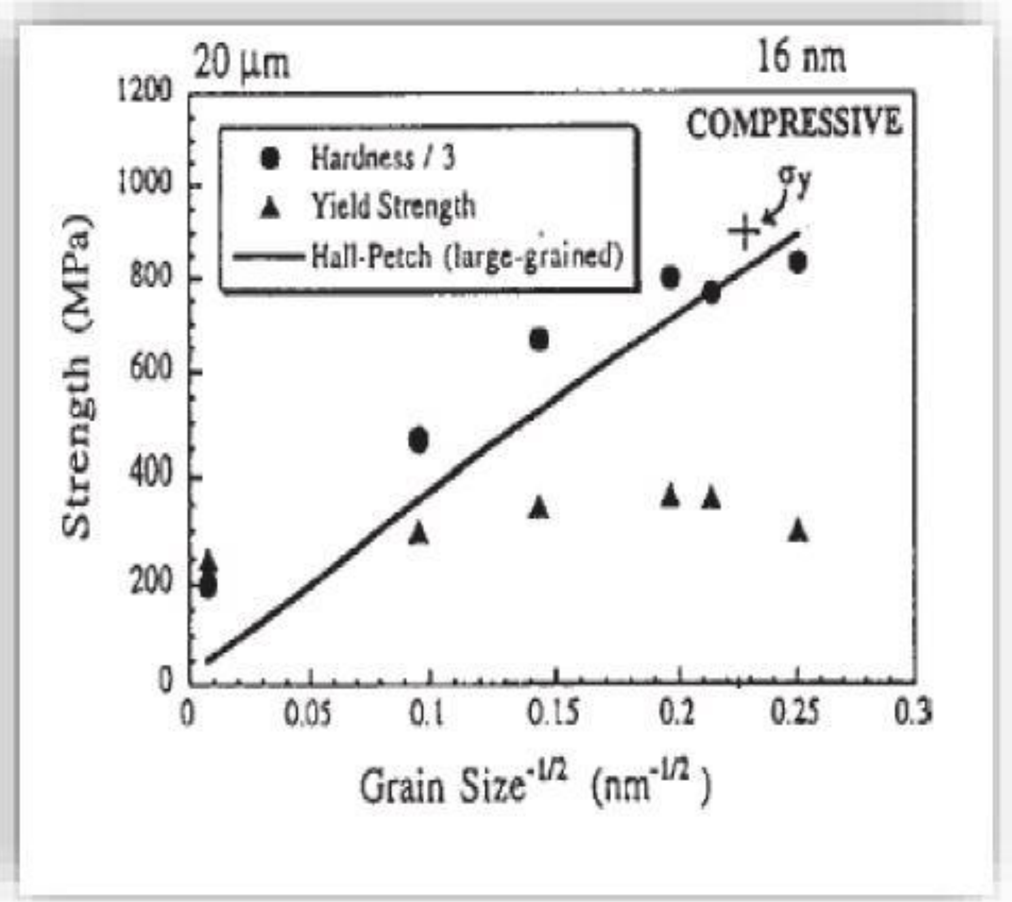


Fig-14: Response of strength versus nanomaterial grain size.

MAGNETIC PROPERTIES:

In a normally ferromagnetic material, nano scale reduces the moment, but it can be restored by applying a magnetic field

Superparamagnetic nanoparticles:

a) By surface coating using appropriate polymeric stabilizers/surfactants (carboxylates, phospates, cathecols)

b) By deposition of a layer of inorganic metals (e.g., gold), nonmetals (e.g., graphite), or oxides (e.g. SiO_2)

c) By generating polymeric shells that avoid cluster growth after nucleation (composite particles, nanocapsule).

d) By the formation of lipid-like coatings (e.g., liposomes/ lipid NPs) around the magnetic core.

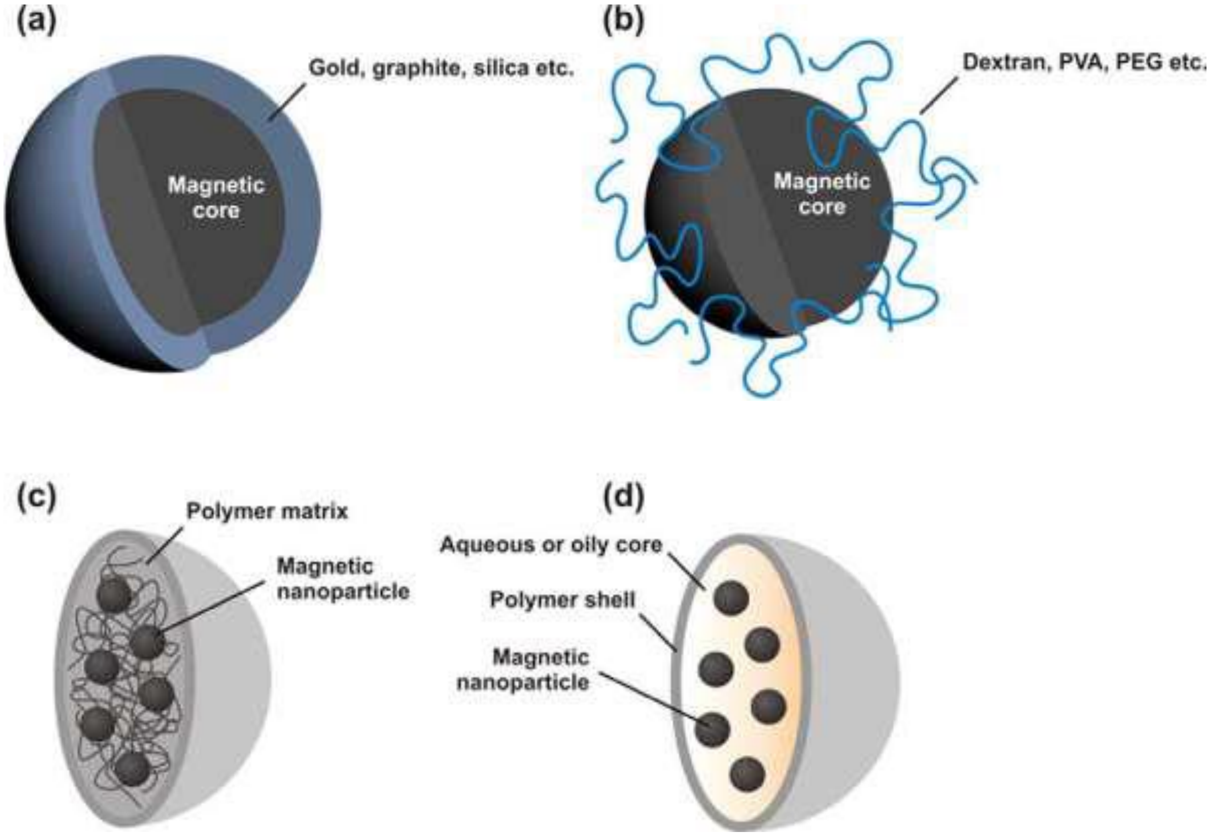


Fig-15: Response of nanomaterial to magnetic field.

METAL NANOCLUSTERS:

Metal nanoclusters consist of a small number of atoms, at most in the tens. These nanoclusters can be composed either of a single or of multiple elements, and typically measure less than 2 nm. Diameter is less than 100 Å. Such nanoclusters exhibit attractive electronic, optical, and chemical properties compared to their larger counterparts.

NANO CLUSTER SYNTHESIS & MAGIC NUMBERS

SYNTHESIS

- **The metal nanoclusters are made using the laser vaporization technique.**
- **This technique involves focusing a laser beam onto a metal sample.**
- **Metal atoms evaporate and are cooled with a flow of inert gas.**
- **As they cool the atoms combine into nanoclusters of varying sizes.**
- **They are then expanded through a nozzle into a vacuum to further cool them.**
- **Spectrometer gives information about the cluster formed.**

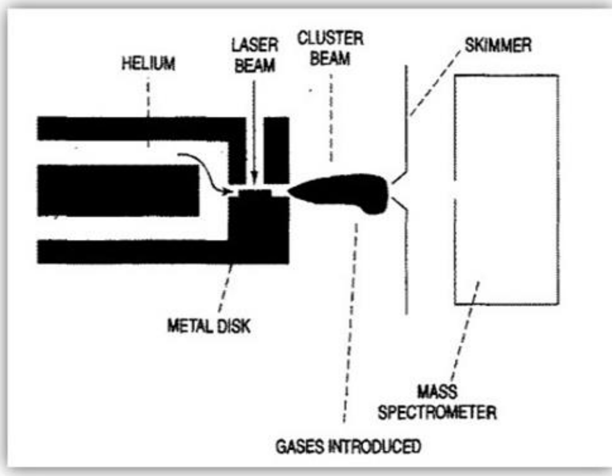


Fig 16 Apparatus to make nanoparticles by laser induced evaporation of atoms from the surface of metal

MAGIC NUMBERS

- **ELECTRONIC MAGIC NUMBER**

  Ionization potential

  It is the energy that is necessary to remove the outer electron from the atom.

- Maximum ionization potential occurs for the rare gases, because their outer orbital is completely filled.
- Peaks are observed at clusters having two and eight atoms.
- These numbers are referred as electronic magic number.

- **STRUCTURAL MAGIC NUMBER**

  For larger clusters the stability is determined by structure and magic number is called as Structural Magic Number.

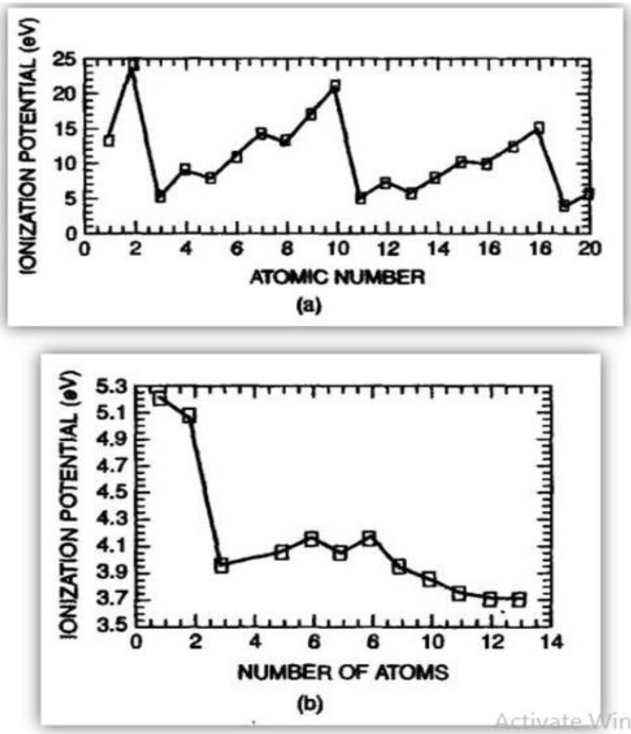


Fig 17 Plot of ionization potential verses (a)Atomic number (b) Number of atom in cluster

Theortical Modeling of Nanoparticles

JELLIUM MODEL

- It envisions cluster as a large atom.
- Positive nuclear charge of each Cluster is assume to be uniformly distributed over a sphere the size of the cluster.
- Interaction of electron with positive sphere is described as a spherically symmetric potential well.
- Energy levels can be obtained by solving Schrodinger equation.

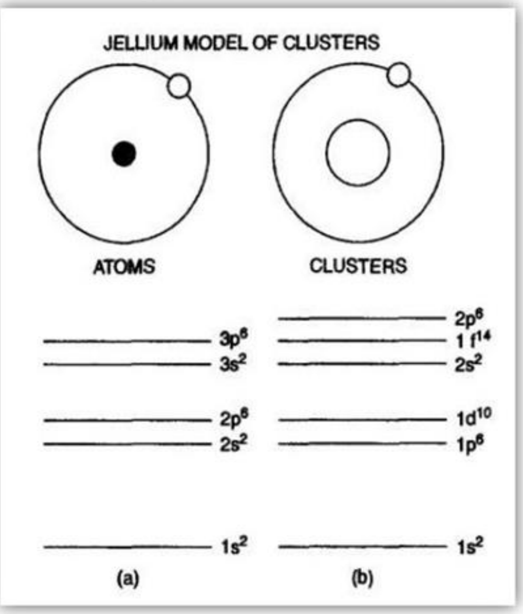


Fig 18 A comparison of energy levels of hydrogen atom and Jellium model of clusters

STRUCTURES

GEOMETRICAL STRUCTURE

- Crystal structure of large nanoparticles have same structure with somewhat different lattice as bulk.
  - e.g.
    80 nm aluminum has FCC unit cell as bulk aluminum have.

- Small particles having diameter <5 nm may have different structure.
  - e.g.
    Gold nanoparticles of 3-5 nm have an icosahedral structure rather than the bulk FCC

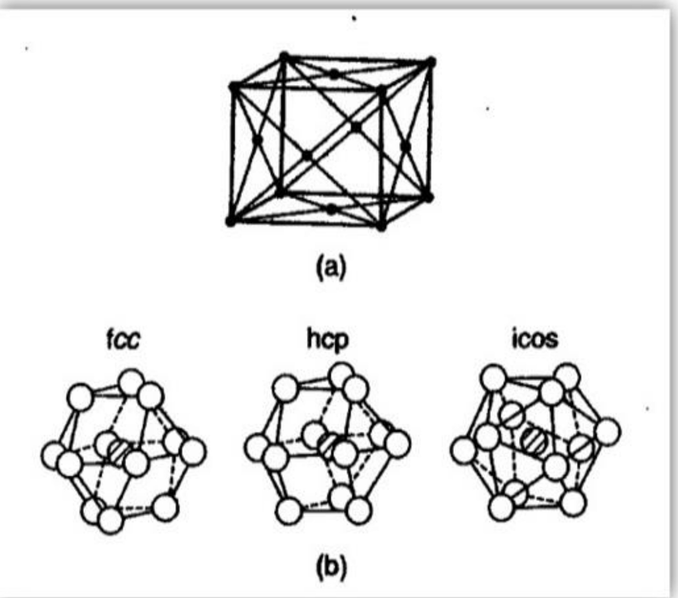
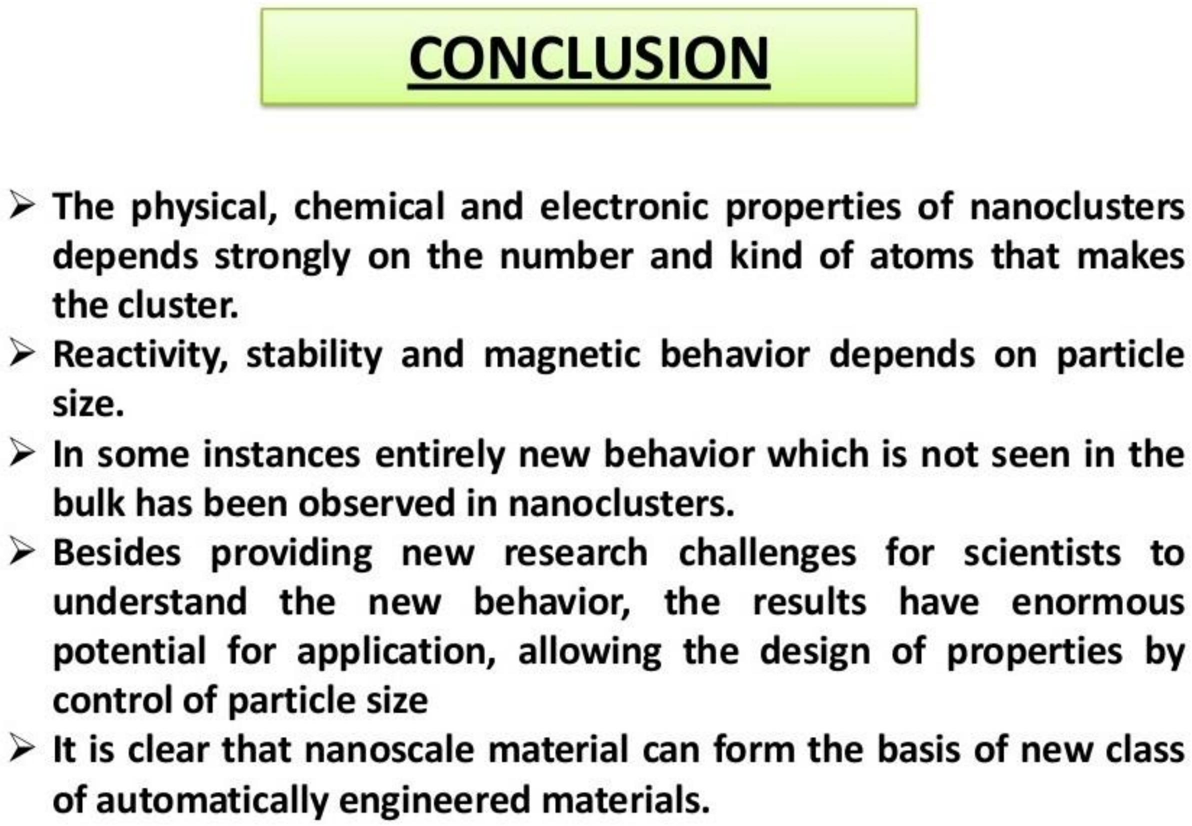


Fig 19 the unit cell of bulk aluminum (b) three possible structure of Aluminum FCC, HCP, ICOS



CONCLUSION

- The physical, chemical and electronic properties of nanoclusters depends strongly on the number and kind of atoms that makes the cluster.
- Reactivity, stability and magnetic behavior depends on particle size.
- In some instances entirely new behavior which is not seen in the bulk has been observed in nanoclusters.
- Besides providing new research challenges for scientists to understand the new behavior, the results have enormous potential for application, allowing the design of properties by control of particle size
- It is clear that nanoscale material can form the basis of new class of automatically engineered materials.

SEMICONDUCTOR NANOPARTICLES:

- Nanocrystalline materials are single or multi-phased polycrystalline solids with a grain size of a few nanometers, typically less than 100 nm.
- Consequently, nanocrystalline materials exhibit properties that are significantly different from and often improved over their conventional coarse-grained polycrystalline counterparts
- The electronic and optical properties of II-VI compound semiconductor nanoparticles have been extensively investigated in view of a wide variety of applications.
- With change in the particle size, dramatic modifications of their electronic and optical properties take place due to the three-dimensional quantum confinement of electrons and holes when the size of the particle approaches the Bohr radius of an exciton
- In addition to the change in electronic and optical properties, the structural behavior also exhibits changes with change in particle size.
- Semiconductors with widely tunable energy band gap are considered to be the materials for next generation flat panel displays, photovoltaic, optoelectronic devices, laser, sensors, photonic band gap devices, etc.

DOPED II-VI SEMICONDUCTOR NANOPARTICLES:

- Doping is very important not only to control the transport properties of the semiconductors but also to modify their optical properties.
- Hence, they find applications in display screens of computer monitors, screens of cathode ray tubes (CRT), fluorescent lamps, X-ray detectors, light emitting diodes (LED), laser materials, etc.
- Semiconductors used in such applications are doped with metal ions, especially transition, or rare earth metal ions.
- Depending upon the size and charge on the ion, substitutional doping of impurity ions can produce either excess electrons or holes in a semiconductor or just lattice distortion can take place.
- This gives rise to localized levels in the band gap of a semiconductor.
- Such states are responsible for transport properties, photo luminescence, electro luminescence and other optical properties in these semiconductors.

NANOCOMPOSITES:

- Nanocomposite is a multiphase solid material where one of the phases has one, two or three dimensions of less than 100 nanometers (nm) or structures having nano-scale repeat distances between the different phases that make up the material.
- The idea behind Nanocomposite is to use building blocks with dimensions in nanometre range to design and create new materials with unprecedented flexibility and improvement in their physical properties.
- Continuous phase is called as "matrix" whereas discontinuous phase is called as "reinforcement"

Classification Of Nanocomposites:

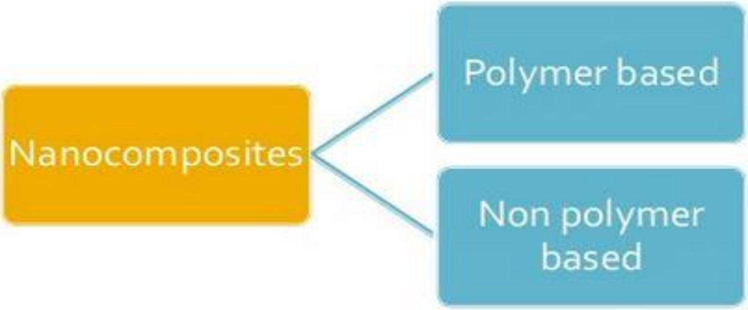


Fig-20: Classification of nanocomposites

NON-POLYMER BASED NANOCOMPOSITES:

- **Metal/Metal nanocomposites**

  (either in the form of alloy or core-shell structure)

  Eg. Pt-Ru

- **Metal/Ceramic nanocomposites**

  (either in the form of nanotube or complicated nanostructure)

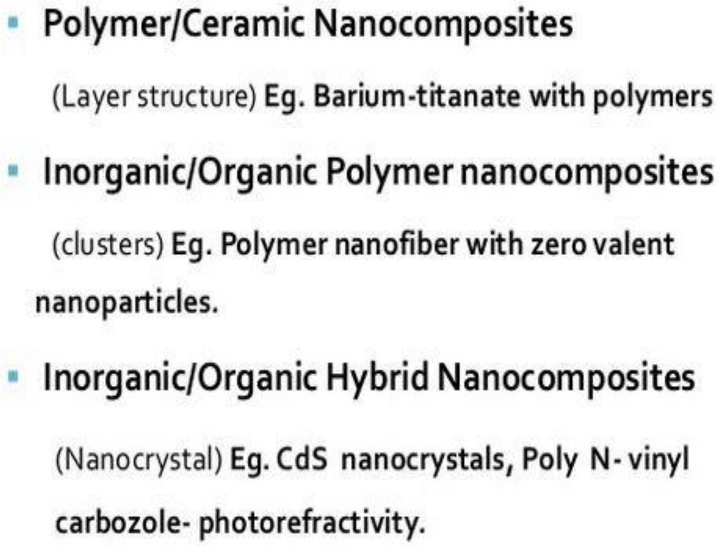
  Eg. Polysilazane/polysiloxane

- **Ceramic/Ceramic nanocomposites**

  (alloy or ceramic)

  Eg. Zirconia-toughened alumina

POLYMER BASED NANOCOMPOSITES



- **Polymer/Ceramic Nanocomposites**

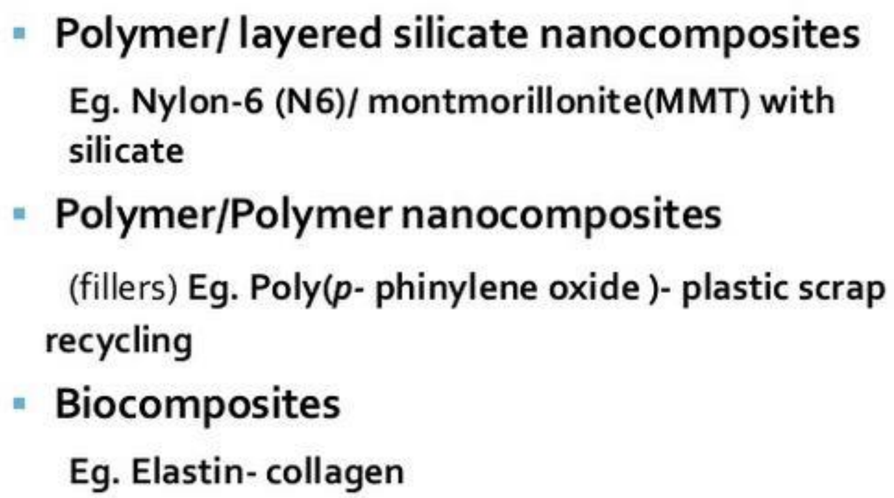
  (Layer structure) **Eg. Barium-titanate with polymers**

- **Inorganic/Organic Polymer nanocomposites**

  (clusters) **Eg. Polymer nanofiber with zero valent nanoparticles.**

- **Inorganic/Organic Hybrid Nanocomposites**

  (Nanocrystal) **Eg. CdS nanocrystals, Poly N- vinyl carbozole- photorefractivity.**



- **Polymer/ layered silicate nanocomposites**

  Eg. Nylon-6 (N6)/ montmorillonite(MMT) with silicate

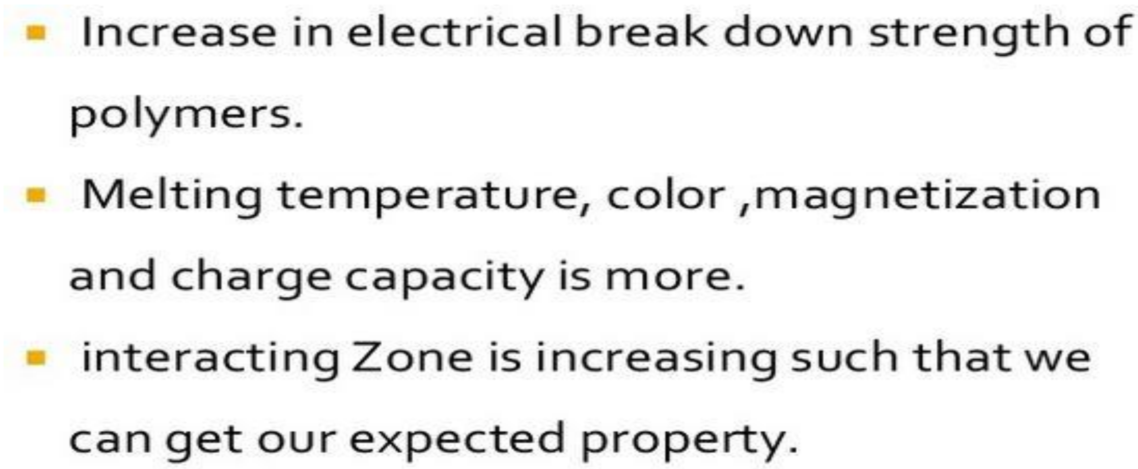
- **Polymer/Polymer nanocomposites**

  (fillers) **Eg. Poly(*p*- phinylene oxide)- plastic scrap recycling**

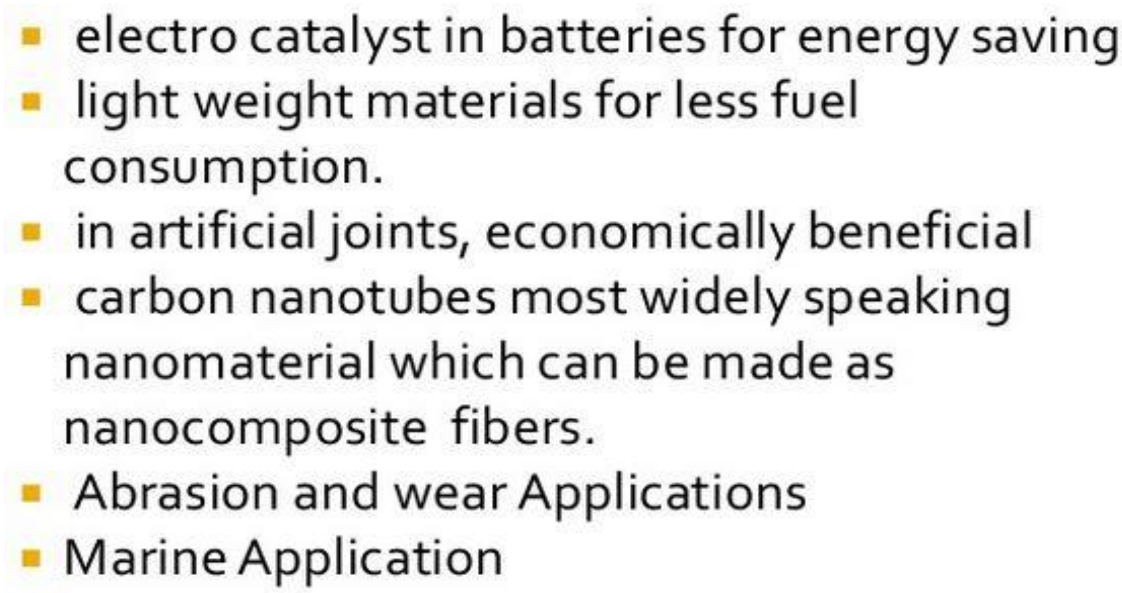
- **Biocomposites**

  Eg. Elastin- collagen

Why nanocomposites are unique?



- Increase in electrical break down strength of polymers.
- Melting temperature, color ,magnetization and charge capacity is more.
- interacting Zone is increasing such that we can get our expected property.



- electro catalyst in batteries for energy saving
- light weight materials for less fuel consumption.
- in artificial joints, economically beneficial
- carbon nanotubes most widely speaking nanomaterial which can be made as nanocomposite fibers.
- Abrasion and wear Applications
- Marine Application

Applications:

❖ **Gas Barrier:**

- The gaseous barrier property improvement that can result from incorporation of relatively small quantities of nanoclay materials is shown to be substantial.
- Data provided from various sources indicates oxygen transmission rates for polyamide-organoclay composites which are usually less than half that of the unmodified polymer.
- Further data reveals the extent to which both the amount of clay incorporated in the polymer, and the aspect ratio of the filler contributes to overall barrier performance.
- Such excellent barrier characteristics have resulted in considerable interest in nanoclay composites in food packaging applications, both flexible and rigid.
- Specific examples include packaging for processed meats, cheese, confectionery, cereals and boil-in-the-bag foods, also extrusion-coating applications in association with paperboard for fruit juice and dairy products, together with co-extrusion processes for the manufacture of beer and carbonated drinks bottles.

❖ **Oxygen Barriers:**

▪ Honeywell have also been active in developing a combined active/passive oxygen barrier system for polyamide-6 materials.

- ▪ Passive barrier characteristics are provided by nanoclay particles incorporated via melt processing techniques whilst the active contribution comes from an oxygen scavenging ingredient (undisclosed).
- ▪ Oxygen transmission results reveal substantial benefits provided by nanoclay incorporation in comparison to the base polymer (rates approximately 15-20% of the bulk polymer value, with further benefits provided by the combined active/passive system).

❖ **Fuel TANKS:**

- The ability of nanoclay incorporation to reduce solvent transmission through polymers such as polyamides has been demonstrated.
- Data provided by De Bievre and Nakamura of UBE Industries reveals significant reductions in fuel transmission through polyamide–6/66 polymers by incorporation of a nanoclay filler.
- As a result, considerable interest is now being shown in these materials as both fuel tank and fuel line components for cars.
- Of further interest for this type of application, the reduced fuel transmission characteristics are accompanied by significant material cost reductions.

INTRODUCTION TO CARBON NANOSTRUCTURE:

- Carbon is perhaps the most important element on earth because without it the life as we know it would not be possible.
- Carbon forms the backbone of the organic and biological molecules
- Many biological molecules have dimensions in the nanometer range so that an important area of nanotechnology deals with biological molecules and their manipulation to yield newer applications and products.
- Diamonds, graphite fibers, amorphous carbon filters, plastics, paints and lubricants, all contain inorganic carbon.
- The smallest dimension for the inorganic carbon structures was limited to about a micron until the discovery of fullerene in 1985.

- The next carbon nanostructured material to be discovered in laboratory was the carbon nanotubes (CNT) which are single walled or multiwalled hollow cylinders of carbon.
- The graphite structure is made of sheets of carbon atoms stacked one above the other, atoms in each sheet being arranged in a hexagonal arrangement. Each such sheet is called a *graphene sheet.*

Structure of carbon nanostructure-Graphite:

- As mentioned nanostructures of carbon are arranged one above the other.
- Carbon is the sixth element in the periodic table. Its electronic structure is $1s^2 2s^2 2p^2$.
- The two core electrons in the 1s orbital are strongly bound to the nucleus while the four electrons in the *2s* and 2*p* orbitals are weakly bound.

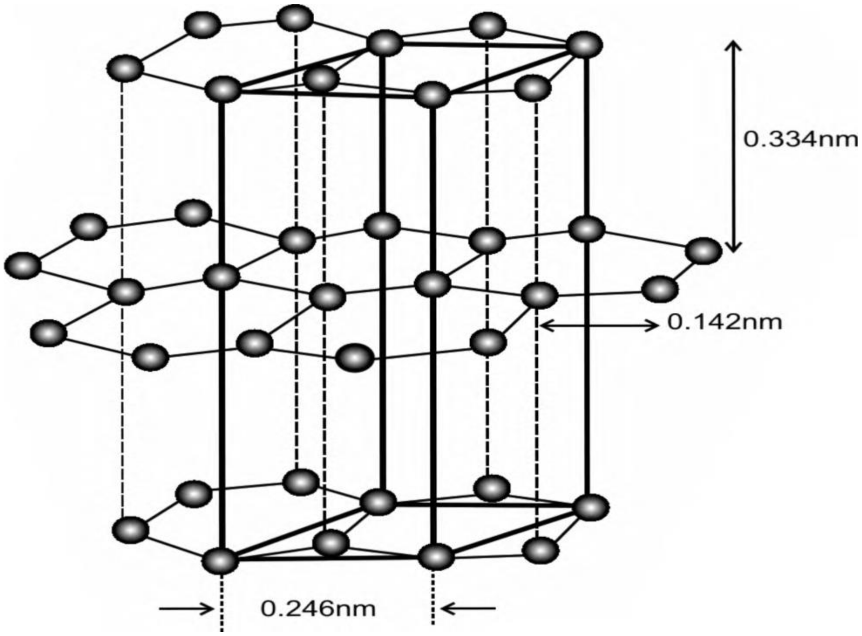


Fig-21: A schematic showing the relative positions of the alternate layers in the graphite structure; the unit cell of graphite has been outlined

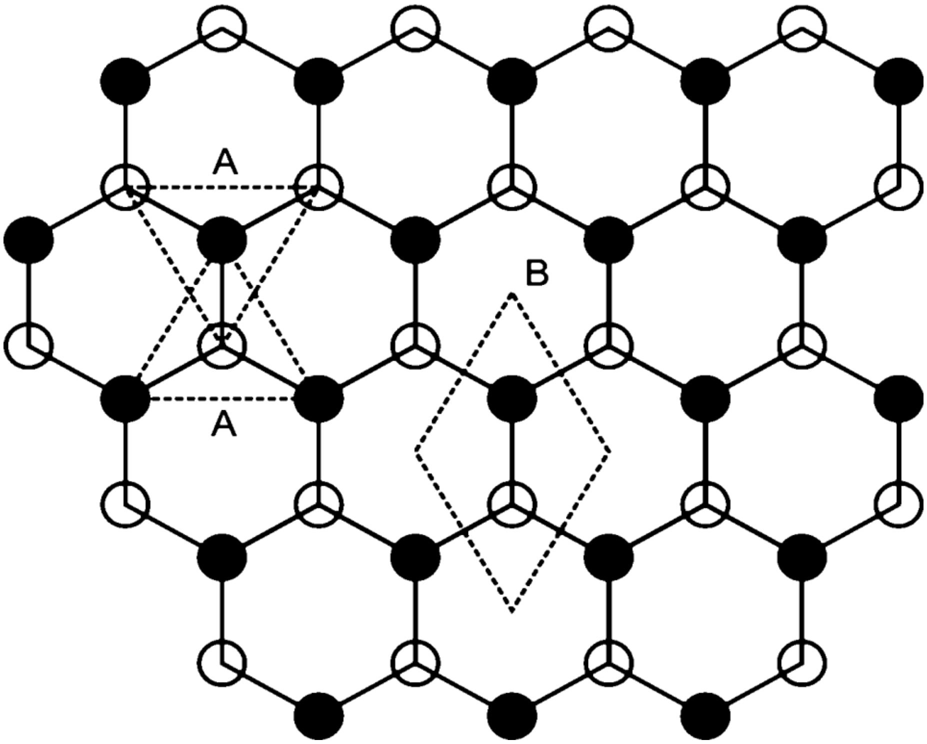


Fig-22: The structure of graphene consists of carbon atoms located at the corners of hexagons.

Carbon Nanotubes Application:

- Carbon is the 15th most abundant element in the Earth's crust, and the fourth most abundant element in the universe by mass after hydrogen, helium & oxygen.
- It is reactive non metal.

Allotropes of carbon:

Allotropy is the property of some chemical elements to exist in two or more different forms, or allotropes, when found in nature. There are several allotropes of carbon.

- a)Diamond,
- b)Graphite,
- c)Lonsdaleite,
- d)C60 (Buckminsterfullerene or buckyball),
- e)C540,
- f)C70,
- g)Amorphous carbon, and

- h)single-walled carbon nanotube, or buckytube

FULLERENCES:

- Fullerenes are a family of carbon allotropes.
- They are molecules composed entirely of carbon.
- They are in the form of a hollow sphere, ellipsoid, or tube.

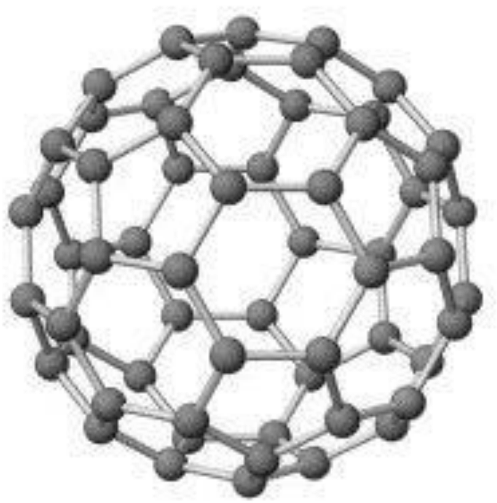


Fig-23:Fullerences

- Carbon nanotubes are tubular forms of carbon that can be envisaged as graphene sheets rolled into cylindrical form.
- These nanotubes have diameters of few nanometers and their lengths are up to several micrometers.
- Each nanotube is made up of a hexagonal network of covalently bonded carbon atoms.
- Carbon nanotubes are of two types: single-walled and multi-walled.
- A single-walled carbon nanotube (SWNT) consists of a single graphene cylinder whereas a multi-walled carbon nanotube (MWNT) comprises of several concentric graphene cylinders.

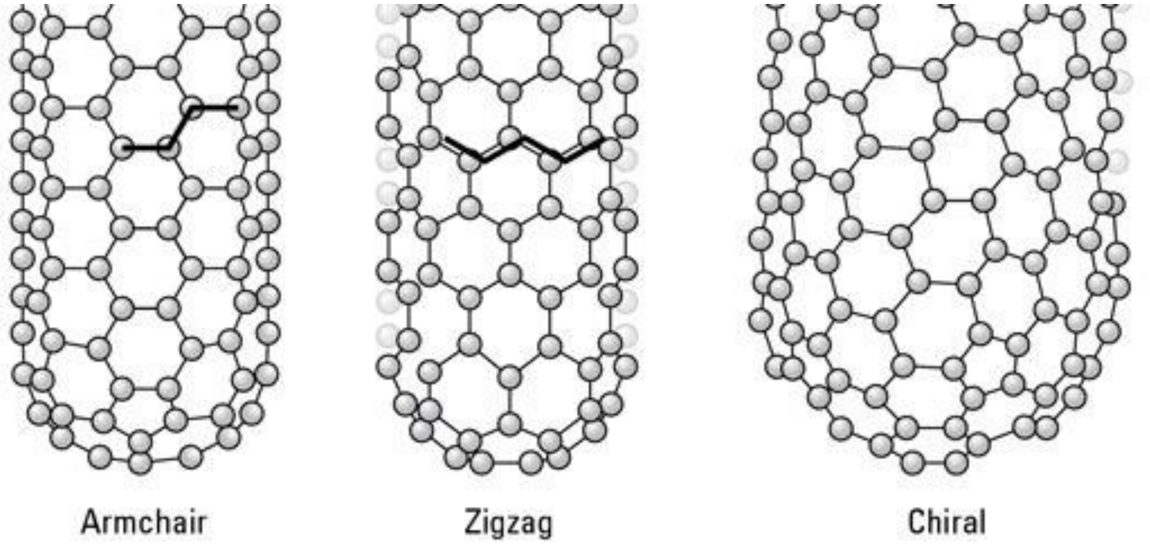


Fig-24: Different structure of carbon nanotube

Carbon nanotubes are of two types :

- 1.Single wall carbon nanotube (SWNT)
- 2.Multiple wall carbon nanotube (MWNT)

Single wall nanotube (SWNT):

- It consist of one cylinder. It is made of single graphene sheet rolled up into cylinder closed by two caps (semi fullerenes). The SWNTs have diameter in the range of 0.5-2.0 nm.
- The length is in the range of 50-150μmlength.
- Electronic properties of SWNTs are governed by two factors, tube diameters and helicity, which further depend on the way graphene layer is rolled up, arm chair or chiral.
- Electrical conductivity, surface curvature and presence of inner cavity in CNTs make the metal –support interaction different compared to that in activated carbon or graphite support.
- Mechanically bent SWNTs present kink sites that are chemically more active.

Multiwall (MWNT) nanotubes:

- It consist of many nested concentric SWNTs cylinders with increasing successive radii. The concentric walls are spaced regularly at 0.34 nm similar to inter graphene distance.
- MWNTs have outer diameter in range of 2 –100 nm depending on number of coaxial tubes present.

- The most common characterization techniques of these materials are electron microscopy, Raman spectroscopy, TGA , IR and UV-Vis.

Mechanical Properties:

- The strength of the carbon–carbon bond gives rise to the extreme interest in the mechanical properties of nanotubes.
- Theoretically, they should be stiffer and stronger than any known substance.
- Simulations and experiments demonstrate a remarkable "bend, don't break" response of individual SWNT to large transverse deformations; an example from Yakobson's simulation is shown in Figure

Fig-25: Carbon Nanotube subjected to bending

Thermal properties:

- All nanotubes are expected to be very good thermal conductors along the tube, but good insulators are placed laterally to the tube axis.
- It is predicted that carbon nanotubes will be able to transmit up to 6000 watts per meter per Kelvin at room temperature; compare this to copper, a metal well-known for its good thermal conductivity, which transmits 385 watts per meter per K.
- The temperature stability of carbon nanotubes is estimated to be up to 2800^{o}C in vacuum and about 750^{o}C in air.
- If the nanotube structure is armchair then the electrical properties are metallic

- If the nanotube structure is chiral then the electrical properties can be either semiconducting with a very small band gap, otherwise the nanotube is a moderate semiconductor
- In theory, metallic nanotubes can carry an electrical current density of 4×10^9A/cm^{2}which is more than 1,000 times greater than metals such as copper

Electrical Properties:

- If the nanotube structure is armchair then the electrical properties are metallic.

- If the nanotube structure is chiral then the electrical properties can be either semiconducting with a very small band gap, otherwise the nanotube is a moderate semiconductor
- In theory, metallic nanotubes can carry an electrical current density of 4×10^9A/cm^{2}which is more than 1,000 times greater than metals such as copper

Magnetic Properties:

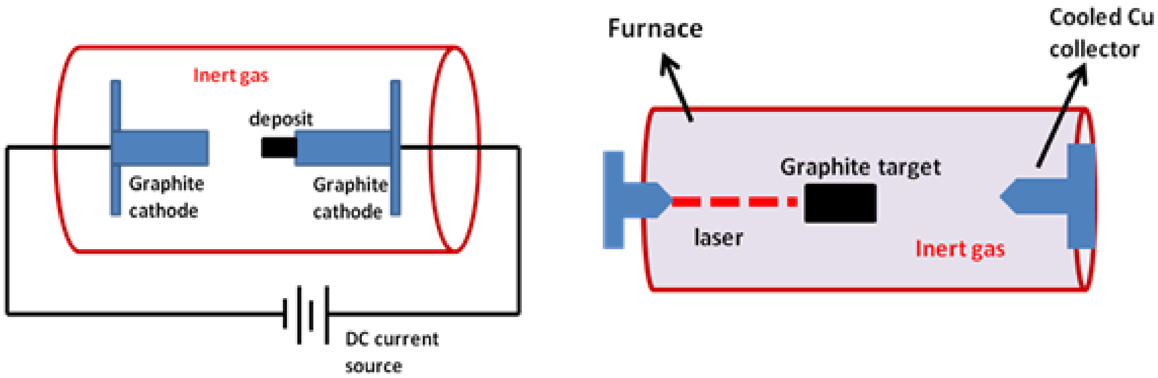
- It has been observed that there is no bulk magnetism in a clean multi-wall-nanotube sample.
- On the other hand, when these are placed on a flat ferromagnetic substrate, fringing fields can be observed by magnetic force microscopy.
- Therefore the prospect for “contact-induced magnetism” and the application of carbon nanotubes to nano scale spintronic devices remain open.
- Magnetic contrast is observed for carbon nanotubes placed on cobalt or magnetite substrates, but is absent on silicon, copper, or gold. Spin transfer of about 0.1 μB per contact carbon atom is obtained.

Synthesis of CNTs:

  - There are two main methods for preparation of CNT:

1. Sublimation of graphite with subsequent desublimation
    - -Arc Discharge Method
    - -Laser ablation
2. Decomposition of carbon containing compounds
    - -Chemical Vapor Deposition(CVD)

Sublimation of graphite with subsequent desublimation:



Arc discharge

Laser ablation

Fig-26: Schematics for CNT formation by sublimation of graphite with subsequent desublimation

- This method involves condensation of carbon atoms generated from evaporation of solid carbon sources of graphite. The sublimation of the solid can be done using electric arc or laser ablation where the temperature reaches to 2500°C -3500°C.

Decomposition of carbon containing compounds:

- The most used method to prepare CNT is pyrolysis of hydrocarbon gases or vapors such as propane, butane, hexane, benzene, toluene etc. The method is also known as chemical vapor deposition (CVD) process.

- By chemical vapordeposition CNTs can be produced in large quantities. The process temperature can vary from 500°C –1300°C. The hydrocarbon precursors include CH_4, C_2H_2, C_6H_6, alcohols etc.

$$\text{Hydrocarbon} + \text{Fe} / \text{Co} / \text{Ni catalysts} \xrightarrow{550-1000^{0}\,C} \text{CNT}$$

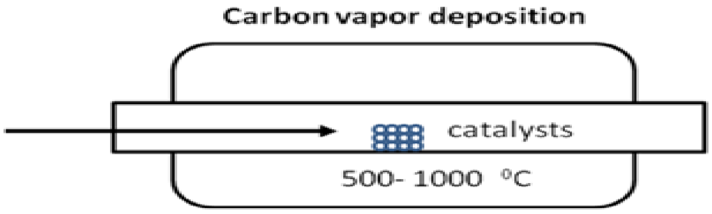


Fig-27: Schematics for carbon vapour deposition method

Applications of Carbon Nanotubes:

The unique nature of carbon combines with the molecular perfection of single-wall CNTs to endow them with extraordinary material properties, such as very high thermal and electrical conductivity, stiffness, strength, and toughness. It is the only element in the periodic table which bonds to itself in an extended network with the strength of the carbon-carbon bond. The delocalized pi-electron donated by each atom is free to move about the whole structure, instead of remaining with its donor atom, resulting in the first known molecule with metallic-type electrical conductivity. Moreover, an intrinsic thermal conductivity higher than even diamond is offered by the high-frequency carbon-carbon bond vibrations.

In most materials, however, due to the occurrence of defects in their structure, the actual observed material properties such as strength, electrical conductivity, and so on are degraded very significantly. For example, high-strength steel typically fails at only around 1% of its theoretical breaking strength. However, CNTs achieve values very near to their theoretical limits owing to their molecular perfection of structure. This aspect is part of the unique story of CNTs. CNTs are examples of true nanotechnology: they are only about a nanometer in diameter, but are molecules that can be manipulated physically and chemically in very useful ways. They find an incredible range of applications in electronics, materials science, energy management, chemical processing, and many other fields.

REFERENCES:

1. Tai Ram Hsu, Mems and Microsystems, Design and Manufacture, TMH, 2008.
2. Mohammedhad-el-hak, MEMS Introduction & Fundamentals, CRC Press, 2005.
3. Marc J. Madou, Fundamentals of Microfabrication and Nanotechnology, 3rd Edition, 2011, CRC Press. ISBN
9780849331800
4. Harsingh Nalwa, Encyclopedia of Nanoscience and Nanotechnology, American Scientific Publishers, 2007.
5. Neelina Malsch, Biomedical Nanotechnology. CRC, 2005
6. Richard Booker and Earl Boysen, Nanotechnology for Dummies, John Wiley & Sons, 2011

QUESTION BANK:

1) What is the effect of nanotechnology.?

2) With few examples illustrate the methods of nanofying electronics.?

3) Explain the properties of nanomaterials in detail.?

4) What are metal nano clusters. Explain the operation of metal nanoclustures with applications.?

5) What are semiconductor nanoparticles.?

6) Describe the working and applications of nanocomposites.

7) What is a carbon nanostructure.? Explain in detail the operation of carbon nanostructure with neat sketch

8) What are carbon nanotubes.? Illustrate with neat sketch with example.

SATHYABAMA
INSTITUTE OF SCIENCE AND TECHNOLOGY
(DEEMED TO BE UNIVERSITY)
Accredited "A" Grade by NAAC | 12B Status by UGC | Approved by AICTE
www.sathyabama.ac.in

SCHOOL OF BIO & CHEMICAL ENGINEERING

DEPARTMENT OF BIOMEDICAL ENGINEERING

UNIT – V – MEMS in Healthcare – SBMA7007

NANOTECHNOLOGY AND BIOMEDICINE:

"Nanotechnology" is the creation of very small particles, devices and systems; the technology takes place at a very minute level. One nanometer is one billionth of a meter, the width of about 5 atoms. These materials and devices can be designed to interact with cells and tissues at a molecular (i.e. subcellular) level with high degree of functional specificity, thus allowing integration between the device and biological system, not previously attainable1. The emerging field of nanotechnology is not a single scientific discipline but it involves scientists from many different areas including physicists, chemists, engineers and biologists. In this review, the emerging technology being developed for medical application for diagnostic and therapeutic purposes has been reviewed.

Challenges associated with nanotechnology:

Today, Nanotechnology is gaining importance in biology due to its small size and targeted effects. Nanoscale devices are 100-10,000 times smaller than the human cell. Because of their small size and larger surface area relative to their volume, nanoscale devices can readily interact with biomolecules (such as enzymes and receptors) on both, the surface of the cell and inside the cell. By gaining access to various areas of the body, nanoparticles have the potential to detect disease at the micro level and deliver treatment. Work is currently being conducted to find ways to safely move these new research tools into clinical practice (Fig.1). Nanoparticles, for example can have multiple functionalities that can provide detailed information on the progression of disease.

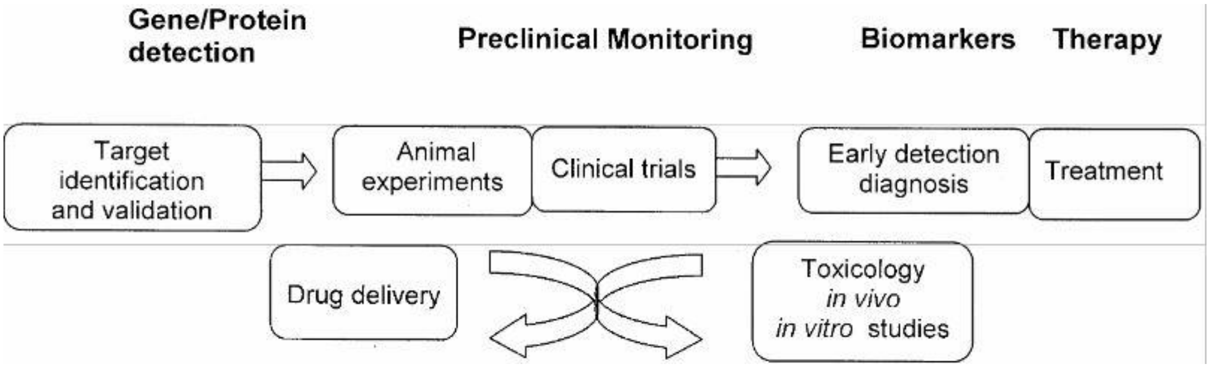
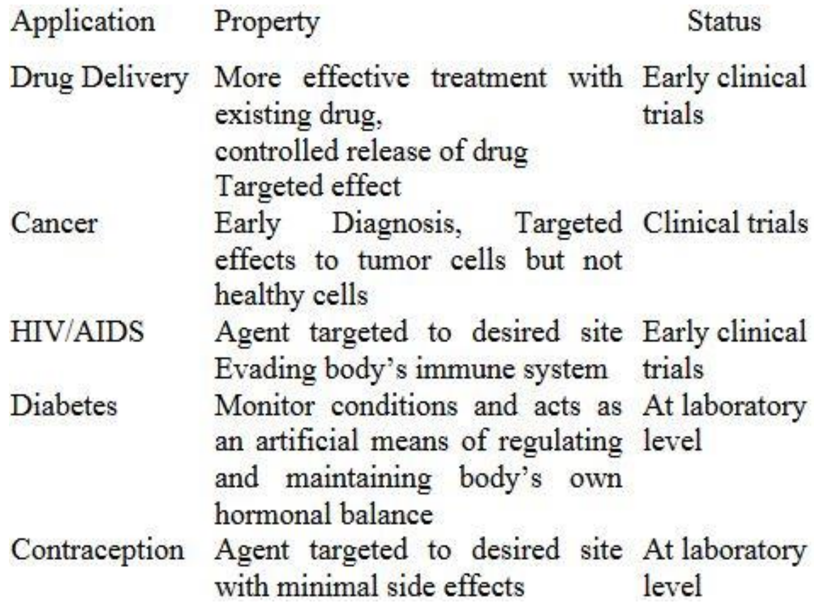


Fig-1: Nanotechnology: multiple applications

Nanoparticles can be made from a vast range of materials, such as metals (gold, silver), metal oxides, [e.g. titanium dioxide (TiO_2), Silicon dioxide (SiO_2)], inorganic materials (carbon nanotubes, quantum dots), polymeric materials and lipids2. The other new sets of tools is available in nanotechnology are nanocrystals, cantilevers, dendrimers, nanoshells and nanowires. These particles can range from few to several hundreds of nanometers in diameter. Products made from each of these tools can be used for diagnosis (as biomarkers) and therapy.

As reported by Service nanotechnology in just 5 years has developed from being a specialty of physicists and chemists to a worldwide scientific and industrial enterprise. Currently most of the research work focuses on the use of nanoparticles to treat diseases such as cancer, HIV and diabetes and as carrier for drug delivery (Table 1).

Table-1: Use of nanoparticles in medicine



Application	Property	Status
Drug Delivery	More effective treatment with existing drug, controlled release of drug Targeted effect	Early clinical trials
Cancer	Early Diagnosis, Targeted effects to tumor cells but not healthy cells	Clinical trials
HIV/AIDS	Agent targeted to desired site Evading body's immune system	Early clinical trials
Diabetes	Monitor conditions and acts as an artificial means of regulating and maintaining body's own hormonal balance	At laboratory level
Contraception	Agent targeted to desired site with minimal side effects	At laboratory level

Nanotechnology and its application to cancer:

Cancer, a major killer disease is a complex sequence starting from diagnosis till therapy. Currently detection and diagnosis of cancer usually depends on changes in cells and tissues which occur at the nanoscale level inside the cells and are detected either by physical examination or imaging expertise. Scientists would now like to make it possible to detect cancer when the earliest molecular changes occur. Detecting cancer at an early stage before it spreads, completely changes the scenario for treatment of most cancer. Nanotechnology offers a wealth of tools that provide cancer researchers with new and innovative ways to diagnose and treat cancer.

National Cancer Institute (NCI) US is working on Nanotechnology in Cancer. NCI has also established the nanotechnology characterization laboratory, which will develop a cascade of assays for further product development and regulatory review. Dr. Gregory Downing, Director of NCI has described how nanotechnology can help in product development from ‘bench to bedside’ and improve drug discovery efforts by addressing the complexities of cancer. Nanoscale devices can deliver multiple therapeutic agents to a tumor in order to simultaneously attack multiple points in the pathway involved in cancer. Similarly, nanotechnology generates in vivo biosensors that have the capability of detecting and pointing the location of tumor and metastatic changes that are smaller than those detectable using conventional technologies.

Diagnosis:

Nanodevices such as nanowires and cantilevers can provide rapid and sensitive detection of cancer related molecules by enabling scientists to detect molecular changes even when they occur only in a small percentage of cells. This would help in early detection of cancer. The attachment of nanomaterials to the molecule of interest can be used as diagnostic markers.

The cantilever is one tool with potential aid in cancer diagnosis. Nanoscale cantilevers-tiny bars anchored at one end can be engineered to bind to molecules associated with cancer. When the cancer associated molecule binds to the cantilevers, it changes the surface tension causing the cantilever to bend. By monitoring whether the cantilevers are bent and to what extent, scientists can assess, whether the cancer molecules are present. One tool Quantum dot can detect early DNA changes in the body. Quantum dots are tiny crystals that glow when they are stimulated by ultraviolet light. The wavelength or color of the light depends on the size of the crystal. Latex beads filled with these crystals can be designed to bind to specific DNA sequences. When the crystals are stimulated by light, the colors they emit act as dyes that light up the sequences of interest. By combining different size quantum dots within a single bead, researchers can create probes that release a spectrum of various colors and intensities of light serving as spectral bar code. To detect cancer, one can design beads containing quantum dots to bind to the sequence of DNA that is associated with cancerous cells. Research is underway to find out innovative ways at the nanoscale level which could be useful to detect early mutagenic changes.

Therapy:

After diagnosis when it is time to treat cancer, nanoscale devices have the potential to improve cancer therapy other than the existing conventional (chemotherapy, radiotherapy) techniques and also to discover new therapeutic agents. It is useful for developing ways to eradicate cancer cells without harming healthy, neighboring cells. Scientists hope to use this technology to create therapeutic agents that can target specific cells and deliver toxins in a controlled, time released manner6. The ultimate goal of researchers is to find out agents of these nanoparticles which can circulate through the body, detect cancer associated molecular changes, assist in imaging, release a therapeutic agent and then monitor the effectiveness of the intervention. It can reduce the unpalatable side-effects that accompany many current cancer therapies.

One such molecule with potential to link treatment with detection and diagnosis is known as dendrimer. A useful feature of dendrimer is their branching shape, which provides a vast surface area so that scientists can attach therapeutic agents or other biological molecules. A single dendrimer can carry a molecule that can recognize cancer cells, a therapeutic agent that kills these cells and a molecule that recognizes the signals of cell death.

Application of nanotechnology in drug delivery:

Currently, the most promising consequence of the application of nanotechnology, with respect to medicine, is of drug delivery. The major problem with most of the new chemical entities is their insolubility. Therefore the first principal aim of nanotechnology is to improve their solubility and bioavailability. The second is to enhance the release rate of the drug. Due to these reasons nanotechnology has focused on targeted drug delivery and controlled drug release. A targeted drug delivery system can convey drugs more effectively, increase patient compliance and extend product life cycle. According to Dubin, drugs tend to perform more effectively in nanoparticulate form and with fewer side-effects. Further, specific nanosized receptors present on the surface of a cell can recognize the drug and elicit an appropriate response, by delivering and releasing therapy exactly wherever needed.

Thus drugs can be loaded via encapsulation, surface attachment or entrapping. The architecture of nanoparticles, material, drug type and targeted location can determine the attachment technique. Encapsulated drugs can be protected from degradation. The drug may be in particles with coating only a few nanometers in thickness. Drugs are normally ingested or implanted and designed to deliver a controlled release of drug, which may last for many months and can be activated at different sites in the body. Nanopores can act as tiny particles for releasing drugs. By making the nanopores only slightly larger than the molecules of drugs, they can control the rate of diffusion of the molecules, keeping it constant, regardless of the amount of drug remaining inside a capsule. Drugs in such a nanocrystalline form can be administered in smaller doses because they can be delivered directly to the tissue and in controlled doses.

Drug synthesis and delivery:

Nanoparticle drug delivery systems are engineered technologies that use nanoparticles for the targeted delivery and controlled release of therapeutic agents. The modern form of a drug delivery system should minimize side-effects and reduce both dosage and dosage frequency. Recently, nanoparticles have aroused attention due to their potential application for effective drug delivery. Nanomaterial's exhibit different chemical and physical properties or biological effects compared to larger-scale counterparts that can be beneficial for drug delivery systems. Some important advantages of nanoparticles is their high surface-area-to-volume ratio, chemical and geometric tunability, and their ability to interact with biomolecules to facilitate uptake across the cell membrane.

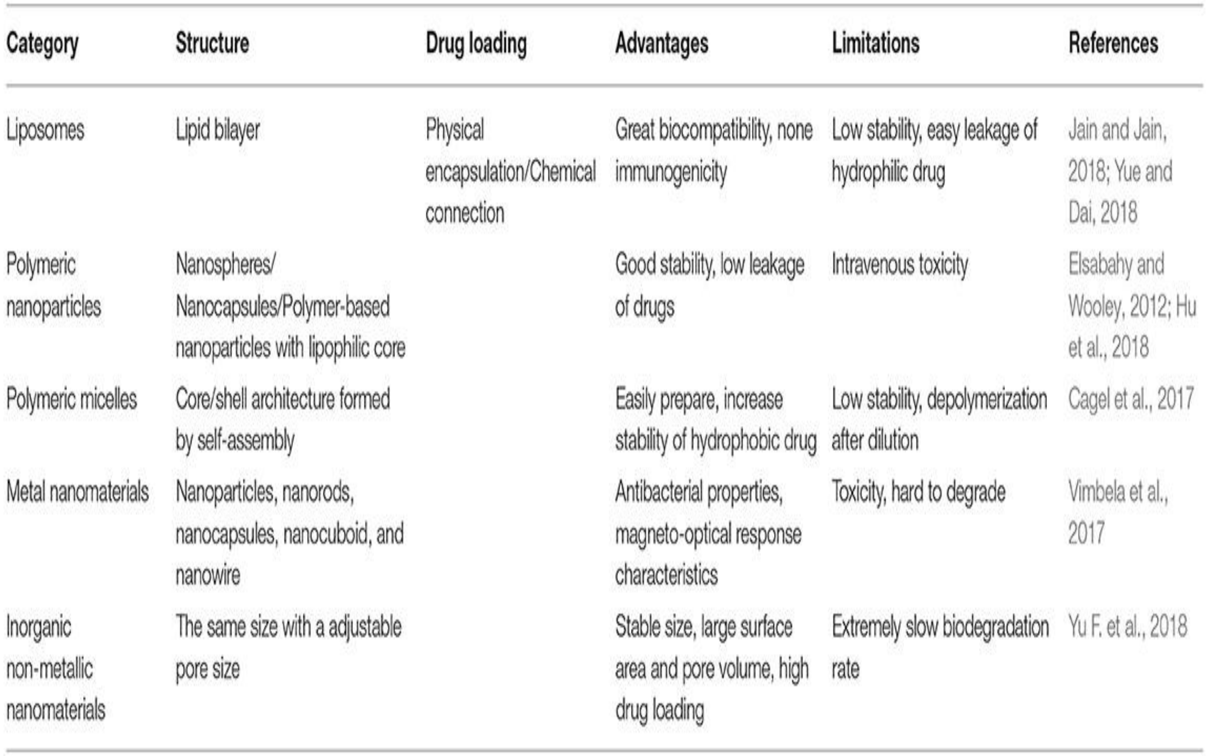
The large surface area also has a large affinity for drugs and small molecules, like ligands or antibodies, for targeting and controlled release purposes. Nanoparticles refer to a large family of materials both organic and inorganic. Each material has uniquely tunable properties and thus can be selectively designed for specific applications. Despite the many advantages of nanoparticles, there are also many challenges, including but not exclusive to: nontoxicity, bio-distribution and accumulation, and the clearance of nanoparticles by human body. The National Institute of Biomedical Imaging and Bioengineering has issued the following prospects for future research in nanoparticle drug delivery systems:

1. crossing the blood-brain barrier (BBB) in brain diseases and disorders;
2. enhancing targeted intracellular delivery to ensure the treatments reach the correct structures inside cells;
3. combining diagnosis and treatment.

An ideal drug delivery system should have effective targeting and controlled release. The two main targeting strategies are passive targeting and active targeting. Passive targeting depends on the fact that tumors have abnormally structured blood vessels that favor accumulation of relatively large macromolecules and nanoparticles. This so-called enhanced permeability and retention effect (EPR) allows the drug-carrier be transported specifically to the tumor cells. Active targeting is, as the name suggests, much more specific and is achieved by taking advantage of receptor-ligand interactions at the surface of the cell membrane. Controlled drug release systems can be achieved through several methods. Rate-programmed drug delivery systems are tuned to the diffusivity of active agents across the membrane. Another delivery-release mechanism is activation-modulated drug delivery, where the release is triggered by environmental stimuli. The stimuli can be external, such as the introduction of a chemical activators or activation by light or electromagnetic fields, or biological - such as pH, temperature, and osmotic pressure which can vary widely throughout the body.

Nano drug delivery is used for treating cardiovascular diseases. Cardiovascular diseases (CVDs) have become a serious threat to human life and health. Though many drugs acting via different mechanism of action are available in the market as conventional formulations for the treatment of CVDs, they are still far from satisfactory due to poor water solubility, low biological efficacy, non-targeting, and drug resistance. Nano-drug delivery systems (NDDSs) provide a new drug delivery method for the treatment of CVDs with the development of nanotechnology, demonstrating great advantages in solving the above problems.

Table-2: Nano Drug Carriers:



Category	Structure	Drug loading	Advantages	Limitations	References
Liposomes	Lipid bilayer	Physical encapsulation/Chemical connection	Great biocompatibility, none immunogenicity	Low stability, easy leakage of hydrophilic drug	Jain and Jain, 2018; Yue and Dai, 2018
Polymeric nanoparticles	Nanospheres/ Nanocapsules/Polymer-based nanoparticles with lipophilic core		Good stability, low leakage of drugs	Intravenous toxicity	Elsabahy and Wooley, 2012; Hu et al., 2018
Polymeric micelles	Core/shell architecture formed by self-assembly		Easily prepare, increase stability of hydrophobic drug	Low stability, depolymerization after dilution	Cagel et al., 2017
Metal nanomaterials	Nanoparticles, nanorods, nanocapsules, nanocuboid, and nanowire		Antibacterial properties, magneto-optical response characteristics	Toxicity, hard to degrade	Vimbela et al., 2017
Inorganic non-metallic nanomaterials	The same size with a adjustable pore size		Stable size, large surface area and pore volume, high drug loading	Extremely slow biodegradation rate	Yu F. et al., 2018

On the basis of passive targeting, using the special pathological features of CVDs to develop an active targeting strategy for CVDs can improve the targeted delivery efficiency of drugs to the lesions of CVDs, which aroused researchers strong interest. Active targeting is primarily directed to functional modification of NDDSs with one or more targets to allow the drug to reach a particular site (Figure) That is to say, introducing a functional group or active substance that specifically interacts with diseased tissues or cells into the surface of the nano-drug carrier will enhance carriers targeting.

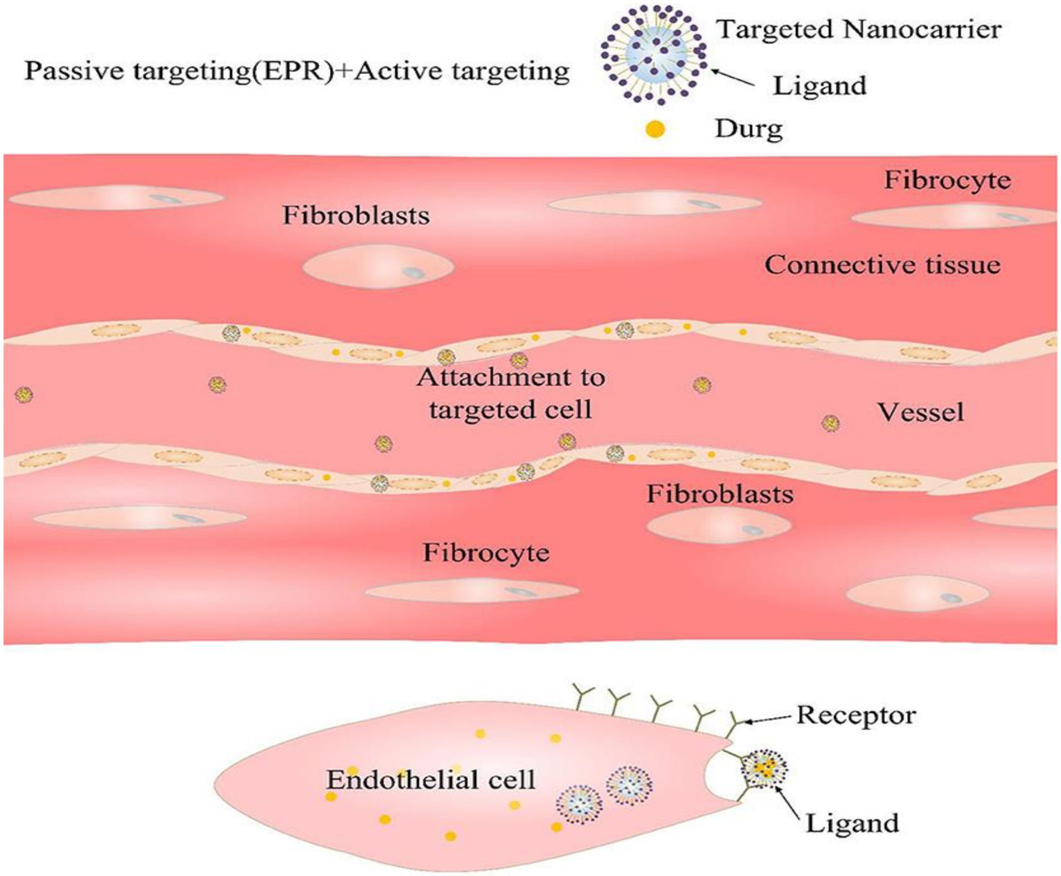


Fig-2: Diagrammatic sketch of active targeting. The surface of the nano-carrier is grafted with a targeting ligand, which is strongly bound to the selective cell surface by ligand-receptor binding.

NANO FABRICATION METHODS:

The terms nanofabrication and nanomanufacturing are often used interchangeably for making one-, two-, or three-dimensional nanostructures in various contexts (medical, photonics, electronics, energy, etc.), with a relatively high degree of functionality and structural complexity and hierarchy. These terms cover a host of different materials, devices, products, and processes and are simply too broad to cover in detail in a short article.

One possible approach to distinguish between the terms is by using the criterion of economic viability: the connotations of industrial scale and profitability associated with the word manufacturing imply that nano manufacturing is an economic activity with industrial production facilities with more or less fully automated assembly lines. By contrast, nanofabrication is more of a research activity based on developing new materials and processes – it's more a domain of skilled craftsmen and not of mass production.

Today, the only industry where nanoscale manufacturing technologies are employed on a large scale is the semiconductor industry, where device structures have reached the single nanometers scale. Of course, the chemical industry has long been working with nanoscale particles and pigments, but this falls more into the realm of chemistry rather than nanomanufacturing.

Here the term nanofabrication is used for simplicity, which can have a whole range of meanings: making small features on larger objects, (e.g., integrated circuit fabrication):

- – making nanoscale objects with special properties (e.g., quantum dot synthesis);
- – assembling nanoscale objects into more complex structures (e.g., DNA origami-directed assembly);
- – incorporating nanoscale objects into larger objects to enable special functionality (e.g., graphene into electronic or sensor devices);
- – and using nanotechnology to manufacture nanoscale structures (e.g., dip-pen nanolithography).

There are different ways of fabricating functional nanostructures. The two notions you hear most are top-down and bottom-up methods.

Top-down versus bottom-up nanofabrication:

This is the nanotechnology equivalent of lithography – predominantly photolithography, which is the standard workhorse employed in today's semiconductor industry, and nanoimprint lithography (NIL) for the large-scale production of nanoparticles for diagnostic and therapeutic applications – and other top-down methods where we start by taking a block of material and remove the bits and pieces you don't want until we get the shape and size we do want.

In the process we spend (relatively much) energy, use (sometimes very toxic) chemicals, produce (often quite a bit of) waste, need a lot of patience (these processes are relatively slow) and often the results are quite unique and not easily replicable.

Optical lithography and NIL are the dominant top-down nanomanufacturing methods, although there are a large number of other nanofabrication approaches available. Electron beam lithography (EBL) for instance can generate sub-10 nm features, over large areas, with good placement and overlay, but because of its relatively low throughput, it is limited commercially to the production of masks for use in photo- and nanoimprint lithography and device development.

In contrast to the deterministic nature of top-down processes, bottom-up processes are driven by a combination of thermodynamics and kinetics which then determines the yield of the desired structure. Bottom-up nanofabrication processes typically don't need expensive tooling to create nanoscale structures, and scaling to large volumes is potentially straightforward. With the application of the tools of chemical synthesis, quantum dots, plasmonically active particles, carbon nanotubes, metallic nanowires, and multifunctional particles for medical applications have been successfully produced in manufacturing quantities.

Efforts to develop purely bottom-up self-assembly methods to create more complex devices typically rely on engineering the interactions between the various components, placing them in a simple environment and then letting the system evolve to a final state.

To make things a bit more complicated, there are two fundamentally different ways of fabricating things from the bottom up. And this is where a lot of the confusion about the different nanotechnology terminology comes from.

One bottom-up method is nature's way: self-assembly. Self-organizing processes are common throughout nature and involve components from the molecular (e.g. protein folding) to the planetary scale (e.g. weather systems) and even beyond (e.g. galaxies).

The other way of doing bottom-up nanotechnology is man's way: molecular assembly. It sounds like self-assembly but it is a very different concept. This is the vision that proponents or revolutionary nanotechnology put forward: molecular assembly as a factory concept, assembly lines and all, just scaled down to the nano level.

The notion of 'self-assembly' becomes relevant in this context with regard to 'self-replicating' nanomachines, i.e. machines that self-assemble themselves; but this is very different from the type of self-assembly found in nature. There is one – very big – catch though:

BIOMIMETIC NANODEVICES:

Biomimetics, also known as bionics, biognosis, or biomimicry, is the use and implementation of concepts and principles from nature to creating new materials, devices and systems. This adaptation of methods and systems found in nature into synthetic constructs is desirable because evolutionary pressure typically forces natural systems to become highly optimized and efficient. Nature provides a database of several solutions that already work and thus serve as models of inspiration for synthetic paradigms.

Biomimetics, in fact, has its origins back in the times when the Wright brothers modeled their planes on the structure of bird wings; when Joseph Paxton used the design of a lily pad to structure the Crystal Palace and when Leonardo da Vinci was working on his flying machines and ships. However the field was only given its official name and definition by Jack Steele of the U.S. Force in the 1960's

Biomimmicry only recently begun to reach is full potential since the invention of Velcro, the biomimetic-equivalent of hooks in natural burrs created by George de Mestral in 1948. Since then, many facets have evolved and can be broadly categorized under two main topics:

- Mimicking mechanisms found in nature

e.g. water-proof glue developed with parallel mechanisms found in the study of adhesives produced by mollusks

- Utilizing or incorporating nature itself into novel devices

e.g. new strong but light materials have come from studying the structure of bone Velcro.

Confluence of Nanotechnology and Biomimetics

Most of the applications developed in the past have been created on the macromolecular level. Only recently has Biomimetics begun to approach the micro and sub-micro molecular level of matter. At the turn of the century, however, the interests of scientists and researchers have shifted towards thinking of matter at the atomic level hence the field Nanotechnology.

NANOMATERIALS IN HUMAN BODY - TOXICITY IN NANOMATERIALS:

The biological effect of materials or substances depends on their ability of reaching the body or rather the organs and cells inside the body. Detection of the uptake in the respective organism is an essential factor in evaluating nanomaterials and nanoparticles. Like in the case of other substances, nanomaterials are taken up depending on how they occur in the environment: as free particles, bound in another substance e.g., as reinforcements in plastics; distributed in a liquid e.g., as constituents of lubricants or oils.

Basically, there are three pathways for all substances, including free nanoparticles, to get into the human body

1. via the air during inhalation - inhalative uptake
2. via the digestive tract - oral uptake
3. via the skin - dermal uptake

Once the particles have reached the blood stream they already bypassed the "classical barriers". In this context new so far unaffected tissue barrier tissues are becoming more important, e.g. the placental barrier between mother and child.

In principle, the same conditions apply for the uptake of nanoparticles to humans and environmental organisms.

Inhalaing uptake:

Nanoparticles are very lightweight particles that do not deposit easily and rather tend to remain in the air. In view of many experts, the lung, therefore, is the main uptake organ. Basically, finest particles can get through to the deepest regions of the lung to reach the alveoles. As a basic rule all particles smaller than 3 µm in diameter - that is 20 times smaller than the diameter of a human hair, rank among the finest particles. Since this is the part of the lung where the vital gas exchange takes place, deposition of airborne particles in that area can be problematic depending on the dose that has been taken up

Oral uptake:

Any substance that is not needed by the body is transported to the bowels to be disposed of before reaching any other parts of the body. Consequently, particles that are taken up via the food are excreted via the stool.

There are three large body barriers: The skin, the lung, and the mucous membrane of the bowels. Nanoparticles of natural or synthetic origin are basically assumed to be able to overcome the intestinal barrier via one or the other pathway (endocytosis via the M cells, persorption: Uptake via dead cells at the tip of the villus). The transport rate or bioavailability is rated very low (rarely more than 1 % of the respective dose). However, it may increase due to inflammatory diseases that disturb the function of the intestinal barrier. As a matter of fact, there is a certain demand for nanotoxicological studies of the pathway of oral absorption via the intestinal mucous membrane in addition to studies of the skin or the lung.

Dermal Uptake:

Substances can also be taken up through the skin, for example through drug patches. The skin, therefore, is another gate though which nanoparticles may enter.

The European research project NANODERM has investigated these issues comprehensively and has analysed nanostructured Titanium dioxide and Zinc oxide that are contained in many sun creams as a protection against carcinogenic UV light. The project has shown that in spite of the smallness of the particles or agglomerates, the skin is a very good barrier that leaves no particles/agglomerates through to the deeper layers. Since the skin is covered with up to twelve layers of dead corneal cells, no living cells can come into contact with the nanostructured particles.

Uptake through the placenta:

The placental tissue is a tightly regulated tissue, which regulates the gas exchange between mother and the foetus and keeps the two circulations separated from each other.

First indications that nano-sized materials may cross the placental tissue came from animal studies done with mice or rats. However these data cannot be extrapolated to humans because anatomy and physiology of the human placenta are unique. With the human ex-vivo placenta perfusion model a controlled system for studying the transplacental transport was shown that nanoparticles may have the potential to cross the human placental barrier. The underlying mechanism how the particles find their way across the human placenta is still part of the on-going research.

Uptake - Environmental Organisms:

In principle, the same conditions apply for the uptake of nanoparticles to humans and environmental organisms but because of their diversity of there are much more possibilities for an uptake by organisms. Thus additional routes like gills, the respiratory organs of aquatic organisms, have to be taken into account. Depending on the preferred habitat of the organism nanoparticles are absorbed from the water, the ground or the air.

It has been detected in laboratory experiments that pumpkin plants can absorb these nanoparticles from the water through their roots. When small crabs were held in water containing carbon nanotubes, bundles of these nanotubes became apparent in their digestive tract after some time. There is also some evidence that nanoparticles can be harmful without being taken up into a cell, so for example on bacteria.

REFERENCES:

1. Tai Ram Hsu, Mems and Microsystems, Design and Manufacture, TMH, 2008.

2. Mohammedhad-el-hak, MEMS Introduction & Fundamentals, CRC Press, 2005.

3. Marc J. Madou, Fundamentals of Microfabrication and Nanotechnology, 3rd Edition, 2011, CRC Press. ISBN 9780849331800

4. Harsingh Nalwa, Encyclopedia of Nanoscience and Nanotechnology, American Scientific Publishers, 2007.

5. Neelina Malsch, Biomedical Nanotechnology. CRC, 2005

6. Richard Booker and Earl Boysen, Nanotechnology for Dummies, John Wiley & Sons, 2011

QUESTION BANK:

1) Explain how nanotechnology is applied in biomedicine in the fields of Drug synthesis and drug delivery

2) What are the nano fabrication methods.? Explain with suitable steps and figures.?

3) What are biomimetic nanodevices.?

4) Justify on how nanomaterials provide toxicity in human beings.