NEHRU COLLEGE OF ENGINEERING AND RESEARCH CENTRE
(NAAC Accredited)
(Approved by AICTE, Affiliated to APJ Abdul Kalam Technological University, Kerala)

DEPARTMENT OF MECHATRONICS ENGINEERING

COURSE MATERIALS

MR 409 MICRO ELECTRO MECHANICAL SYSTEM

VISION OF THE INSTITUTION

To mould true citizens who are millennium leaders and catalysts of change through excellence in education.

MISSION OF THE INSTITUTION

NCERC is committed to transform itself into a center of excellence in Learning and Research in Engineering and Frontier Technology and to impart quality education to mould technically competent citizens with moral integrity, social commitment and ethical values.

We intend to facilitate our students to assimilate the latest technological know-how and to imbibe discipline, culture and spiritually, and to mould them in to technological giants, dedicated research scientists and intellectual leaders of the country who can spread the beams of light and happiness among the poor and the underprivileged.

ABOUT DEPARTMENT

- Established in: 2013
- Course offered: B.Tech Mechatronics Engineering
- Approved by AICTE New Delhi and Accredited by NAAC
- Affiliated to the University of Dr. A P J Abdul Kalam Technological University.

DEPARTMENT VISION

To develop professionally ethical and socially responsible Mechatronics engineers to serve the humanity through quality professional education.

DEPARTMENT MISSION

1) The department is committed to impart the right blend of knowledge and quality education to create professionally ethical and socially responsible graduates.

2) The department is committed to impart the awareness to meet the current challenges in technology.

3) Establish state-of-the-art laboratories to promote practical knowledge of mechatronics to meet the needs of the society

PROGRAMME EDUCATIONAL OBJECTIVES

I. Graduates shall have the ability to work in multidisciplinary environment with good professional and commitment.

II. Graduates shall have the ability to solve the complex engineering problems by applying electrical, mechanical, electronics and computer knowledge and engage in lifelong learning in their profession.

III. Graduates shall have the ability to lead and contribute in a team with entrepreneur skills, professional, social and ethical responsibilities.

IV. Graduates shall have ability to acquire scientific and engineering fundamentals necessary for higher studies and research.

PROGRAM OUTCOME (PO'S)

Engineering Graduates will be able to:

PO 1. Engineering knowledge: Apply the knowledge of mathematics, science, engineering fundamentals, and an engineering specialization to the solution of complex engineering problems.

PO 2. Problem analysis: Identify, formulate, review research literature, and analyze complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences, and engineering sciences.

PO 3. Design/development of solutions: Design solutions for complex engineering problems and design system components or processes that meet the specified needs with appropriate consideration for the public health and safety, and the cultural, societal, and environmental considerations.

PO 4. Conduct investigations of complex problems: Use research-based knowledge and research methods including design of experiments, analysis and interpretation of data, and synthesis of the information to provide valid conclusions.

PO 5. Modern tool usage: Create, select, and apply appropriate techniques, resources, and modern engineering and IT tools including prediction and modeling to complex engineering activities with an understanding of the limitations.

PO 6. The engineer and society: Apply reasoning informed by the contextual knowledge to assess societal, health, safety, legal and cultural issues and the consequent responsibilities relevant to the professional engineering practice.

PO 7. Environment and sustainability: Understand the impact of the professional engineering solutions in societal and environmental contexts, and demonstrate the knowledge of, and need for sustainable development.

PO 8. Ethics: Apply ethical principles and commit to professional ethics and responsibilities and norms of the engineering practice.

PO 9. Individual and team work: Function effectively as an individual, and as a member or leader in diverse teams, and in multidisciplinary settings.

PO 10. Communication: Communicate effectively on complex engineering activities with the engineering community and with society at large, such as, being able to comprehend and write effective reports and design documentation, make effective presentations, and give and receive clear instructions.

PO 11. Project management and finance: Demonstrate knowledge and understanding of the engineering and management principles and apply these to one's own work, as a member and leader in a team, to manage projects and in multidisciplinary environments.

PO 12. Life-long learning: Recognize the need for, and have the preparation and ability to engage in independent and life-long learning in the broadest context of technological change.

PROGRAM SPECIFIC OUTCOME(PSO'S)

PSO 1: Design and develop Mechatronics systems to solve the complex engineering problem by integrating electronics, mechanical and control systems.

PSO 2: Apply the engineering knowledge to conduct investigations of complex engineering problem related to instrumentation, control, automation, robotics and provide solutions.

COURSE OUTCOME

After the completion of the course the student will be able to

SUBJECT CODE: C405	
COURSE OUTCOMES	
CO 1	Understand the basic knowledge about micro electro mechanical systems
CO 2	Acquire knowledge on micro manufacturing techniques
CO 3	Describe about micro fabrication and special machining
CO 4	Interpret about mechanical micromachining
CO 5	Explain about micro sensors and micro actuators
CO 6	Acquire knowledge on the application of MEMS in various industries

CO VS PO'S AND PSO'S MAPPING

CO Vs PO													
SUBJECT													
COURSE COUTCOME	**PO1**	**PO 2**	**PO 3**	**PO 4**	**PO 5**	**PO 6**	**PO 7**	**PO 8**	**PO 9**	**PO1 0**	**PO1 1**	**PO1 2**	PSO 1	PSO 2
C0 1	3	-	3	-	-	-	-	-	-	-	-	2	2	3
C0 2	3	-	3	-	3	-	-	-	-	-	-	2	2	3
C0 3	3	-	3	-	2	-	-	-	-	-	-	2	2	3
C0 4	3	-	3	-	2	-	-	-	-	-	-	2	2	3
C0 5	3	-	3	-	2	-	-	-	-	-	-	2	2	3
C0 6	3	-	3	-	2	-	-	-	-	-	-	2	2	3

Note: H-Highly correlated=3, M-Medium correlated=2, L-Less correlated=1

SYLLABUS

Module	Contents
I	Micro electro mechanical system: MEMS and microsystems – evolution of microfabrication – microsystems and miniaturization-Materials for MEMS - Microsystems packaging.
II	Micro Manufacturing Techniques: Photolithography- chemical Vapour Deposition – Physical Vapour Deposition- Etching Processes-Bulk micro manufacturing- surface micro manufacturing-LIGA process.
III	Micro-fabrication special machining: Laser beam micro machining-Electrical Discharge Machining- Ultrasonic Machining- Electro chemical Machining- Electron beam machining. Clean room-New Materials
IV	Mechanical micromachining: Theory of micromachining-Chip formation-size effect in micromachining-microturning-micromilling- microdrilling- Precision Grinding : Partial ductile mode grinding- Binderless wheel-Free form optics.
V	Microsensors:acoustic- biomedical- chemical- optical- pressure-thermal- Microactuation : actuation using thermal forces- shape memory alloys- piezo electric crystals-electrostatic forces. MEMS with micro actuators: microgrippers - micromotors-microvalves-micropumps.
VI	Laws of scaling- Applications of MEMS in various industries : Automobile- defence- healthcare- Aerospace- industry- Future of MEMS

QUESTION BANK

MODULE I

Q:NO:	QUESTIONS	CO	KL	PAGE NO:
1	Write a short note on MEMS?	CO1	K2	15
2	What are the types of MEMS switch technology?	CO1	K3	9
3	What are the materials used for MEMS manufacturing?	CO1	K2	45
4	Explain any two MEMS Basic Process?	CO1	K3	46
5	What is etching? What are the different types of etching?	CO1	K2	15
6	Define Physical deposition?	CO1	K2	18
7	Define Chemical deposition?	CO1	K5	43
8	Write a short note on microsystem packaging?	CO1	K2	18
	MODULE II			
1	Write a short note about Photolithography?	CO2	K2	99
2	What are the various steps involved in Photolithography?	CO2	K2	61
3	Write a short note about Plasma-enhanced chemical vapor deposition?	CO2	K2	104

4	Write a short note about Write a short note about?	CO2	K1	67
5	What are the steps involved in physical vapor deposition? Explain with neat diagram?	CO2	K1	90
6	Illustrate ion implantation with neat sketch?	CO2	K3	85
7	Explain wet etching process with suitable diagram?	CO2	K2	101
8	Explain the difference between anisotropic and isotropic etching?	CO2	K2	91
9	Explain reactive ion etching?	CO2	K2	97
10	What are the advantages and disadvantages of dry etching process?	CO2	K3	74
MODULE III				
1	Illustrate Laser Beam Micro machining with a neat sketch?	CO3	K3	113
2	What are the major parts of a Laser Beam Micro Machining?	CO3	K3	111
3	Explain Ultrasonic Machining with neat diagram?	CO3	K2	115
4	Illustrate Electrical Discharge Machining	CO3	K3	111
5	Explain the working of Electrical Discharge Machining?	CO3	K5	111
6	Write a short note about Ultrasonic Machining?	CO3	K3	113
7	State faraday’s law?	CO3	K2	111
8	Explain Electro Chemical Machining with neat sketch?	CO3	K1	115
9	Discuss about the applications of Electro Chemical Machining?	CO3	K1	111
10	Illustrate the working of Electron Beam Machining?	CO3	K2	119

11	Write a short note about the advantages and disadvantages of Electron Beam Machining?	CO3	K1	131
12	Illustrate the electron gun construction of an Electron Beam Machining apparatus? .	CO3	K2	133
13	Illustrate the working of Electron Beam Machining?	CO3	K1	135
	MODULE IV			
1	Write a short note about chip formation?	CO4	K2	142
2	Explain about the various methods used for chip control?	CO4	K1	159
3	Discuss about the various types of chips?	CO4	K2	139
4	Write a short note about micro milling, with neat sketch?	CO4	K3	165
5	illustrate micro turning process with proper explanation? .	CO4	K1	155
6	Write a short note about micro drilling?	CO4	K2	167
	MODULE V			
1	Illustrate acoustic wave sensor with proper explanation?	CO5	K2	180

2	Evaluate the difference between biosensor and biomedical sensor?	CO5	K2	180
3	Evaluate the difference between biosensor and biomedical sensor?	CO5	K3	184
4	Write a short note about the types of chemical sensor?	CO5	K2	185
5	Illustrate the different types of optical sensors?	CO5	K3	180
6	Explain the concept of pressure sensor, with a neat sketch?	CO5	K2	196
7	Discuss about the various types of micro actuation techniques, with neat diagram?	CO5	K2	181
8	Write a short note about thermal sensor, with clear illustration?	CO5	K3	196
9	Illustrate micro grippers with proper explanation?	CO5	K3	190
10	Evaluate the difference between the working of a micro valve and a micro pump?	CO5	K2	188
11	Discuss about the concept of micro motors, with neat diagram?	CO5	K2	184
	MODULE VI			
1	Discuss about the various application of MEMs in Automobile Industry?	CO6	K1	
2	Evaluate the different applications of MEMS in Healthcare field?	CO6	K2	
3	Explain the applications of MEMS in Defense Industry?	CO6	K2	
4	Discuss about the applications of MEMS in new generation automobiles?	CO6	K3	

5	Evaluate the Applications of MEMS in aerospace Industry?	CO6	K2	
6	Write a short note about the importance of MEMS in Industrial field?	CO6	K2	

APPENDIX 1

CONTENT BEYOND THE SYLLABUS

S:NO;	TOPIC	PAGE NO:
1	ION IMPLANTATION	14
2	PARAMETERS OF ETCHING	27

MODULE I

MEMS

- MEMS refers to technology that allows mechanical structures to be miniaturized and thoroughly integrated with electrical circuitry, resulting in a single physical device that is actually more like a *system*, where "system" indicates that mechanical components and electrical components are working together to implement the desired functionality. Thus, it's a micro (i.e., very small) electrical and mechanical system.

Mechanical to Electrical to (Micro) mechanical

- Mechanical components and systems are generally considered to be less technologically advanced than comparable solutions based primarily on electrical phenomena, but this doesn't mean that the mechanical approach is universally inferior.
- The mechanical relay, for example, is far older than transistor-based devices that provide similar functionality, but mechanical relays are still widely used.
- Nevertheless, typical mechanical devices will always have the disadvantage of being hopelessly bulky in comparison to the electronic components found in integrated circuits.
- The space constraints of a given application may cause electrical components to be favored or required, even when a mechanical implementation would have resulted in a simpler or higher-performance design.
- MEMS technology represents a conceptually straightforward solution to this dilemma: if we modify the mechanical devices such that they are not only very small but also fully compatible with integrated-circuit manufacturing processes, we can, to a certain extent, have the "best of both worlds."

**** WRITTEN NOTES ON THE END OF THIS DOCUMENT**

MODULE 2

PHOTOLITHOGRAPHY

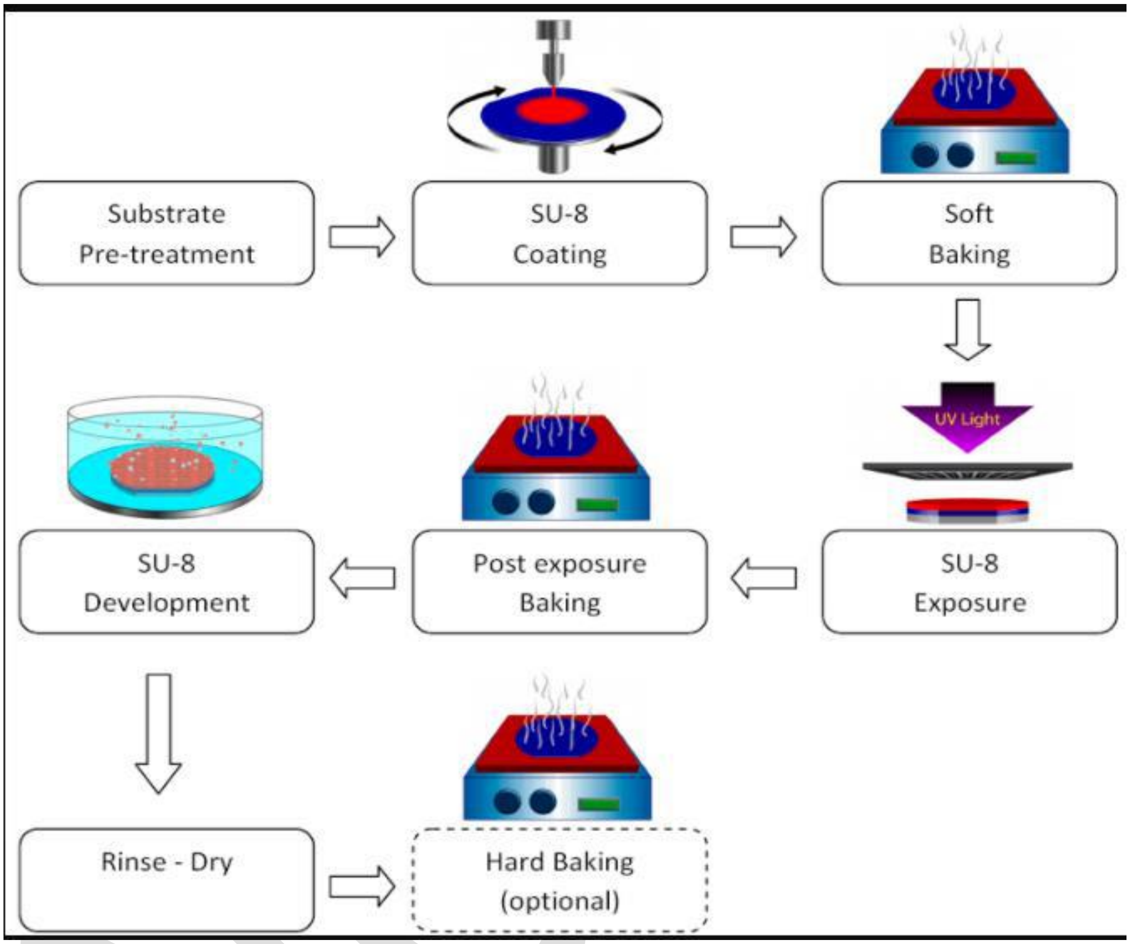
- Photolithography, also termed optical lithography or UV lithography, is a process used in microfabrication to pattern parts of a thin film or the bulk of a substrate.
- Using optical image and a photosensitive film to produce patterns in a subtract

Substrate

•Silicon dioxide (sio2)

Photolithography used in ……..

- Bulk micro manufacturing
- Surface micro manufacturing
- IC manufacturing
- Sensors and actuators



Spin Coating

- A viscous, liquid solution of photoresist is dispensed onto the wafer, and the wafer is spun rapidly to produce a uniformly thick layer.
- The spin coating typically runs at 1200 to 4800 rpm for 30 to 60 seconds, and produces a layer between 0.5 and 2.5 micro meters thick.

Soft baking

- The photo resist-coated wafer is then prebaked to drive off excess photoresist solvent, typically at 90 to 100 C for 30 to 60 seconds on a hotplate.

Exposure to UV Light

- After prebaking, the photoresist is exposed to a pattern of intense light.
- The exposure to light causes a chemical change that allows some of the photoresist to be removed by a special solution
-

Positive photoresist

- the most common type, becomes soluble in the developer when exposed

Negative Photoresist

- Unexposed regions are soluble in the developer.

Post-Exposure Bake

- Post-exposure bake is performed before developing, typically to help reduce standing wave phenomena caused by the destructive and constructive interference patterns of the incident light

Development

- The develop chemistry is delivered on a spinner, much like photoresist. Developers originally often contained sodium hydroxide.

Hard-baking in development

- The resulting wafer is then hard-baked "if a non-chemically amplified resist was used, typically at 120 to 180 C for 20 to 30 minutes.
- The hard bake solidifies the remaining photoresist, to make a more durable protecting layer in future ion implantation, wet chemical etching, or plasma etching.

Etching

- a liquid or plasma ("dry") chemical agent removes the uppermost layer of the substrate in the areas that aren't protected by photoresist

Stripping

•After a photoresist is no longer needed, it must be removed from the substrate.

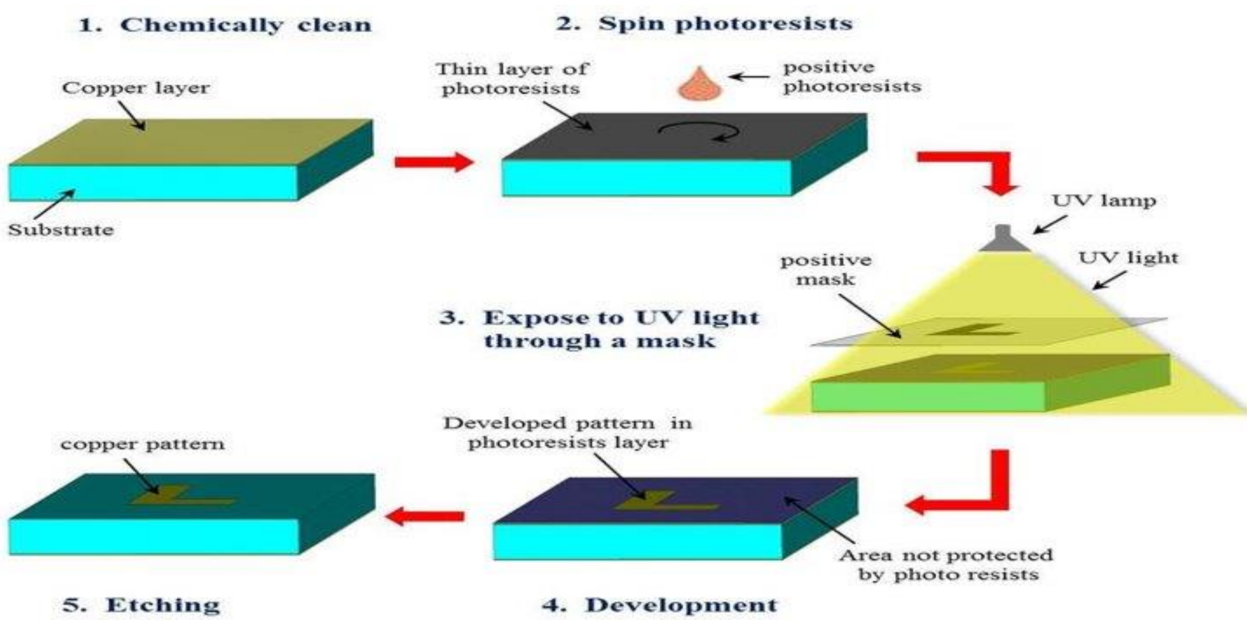
- This usually requires a liquid "resist stripper", which chemically alters the resist so that it no longer adheres to the substrate.
- Alternatively, photoresist may be removed by a plasma containing oxygen, which oxidizes it. This process is called **ashing,** and resembles dry etching.
-

Class 10 clean room

- Based on air quality
- Number of dust particle of 5nm in a cubic foot is less than 10

Light source

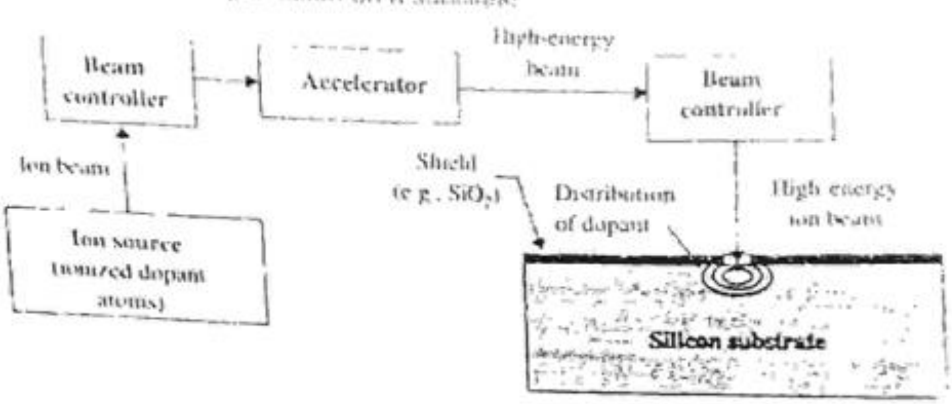
- Mercury vapor lamb
- Wavelength spectrum from 310 t0 440 nm
- For high resolution x ray are used.



ION IMPLANTATION

- **Ion implantation** is a low-temperature process by which **ions** of one element are accelerated into a solid target, thereby changing the physical, chemical, or electrical properties of the target.
- **Ion implantation** is used in semiconductor device fabrication and in metal finishing, as well as in materials science research.
- Acceleration and kinetic energy is very important.

Figure 8.4 | Ion implantation on a substrate



Applications

- Used mainly in semiconductor based industry
- Application in surface treatment process

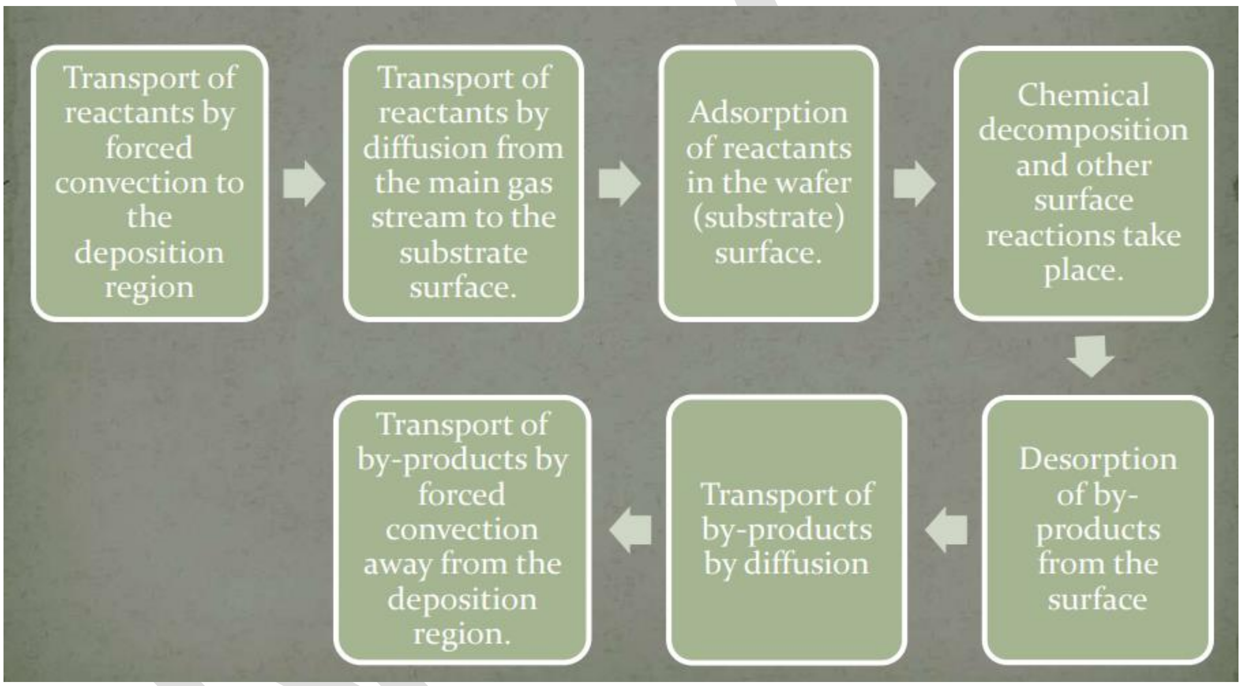
Biomedical application

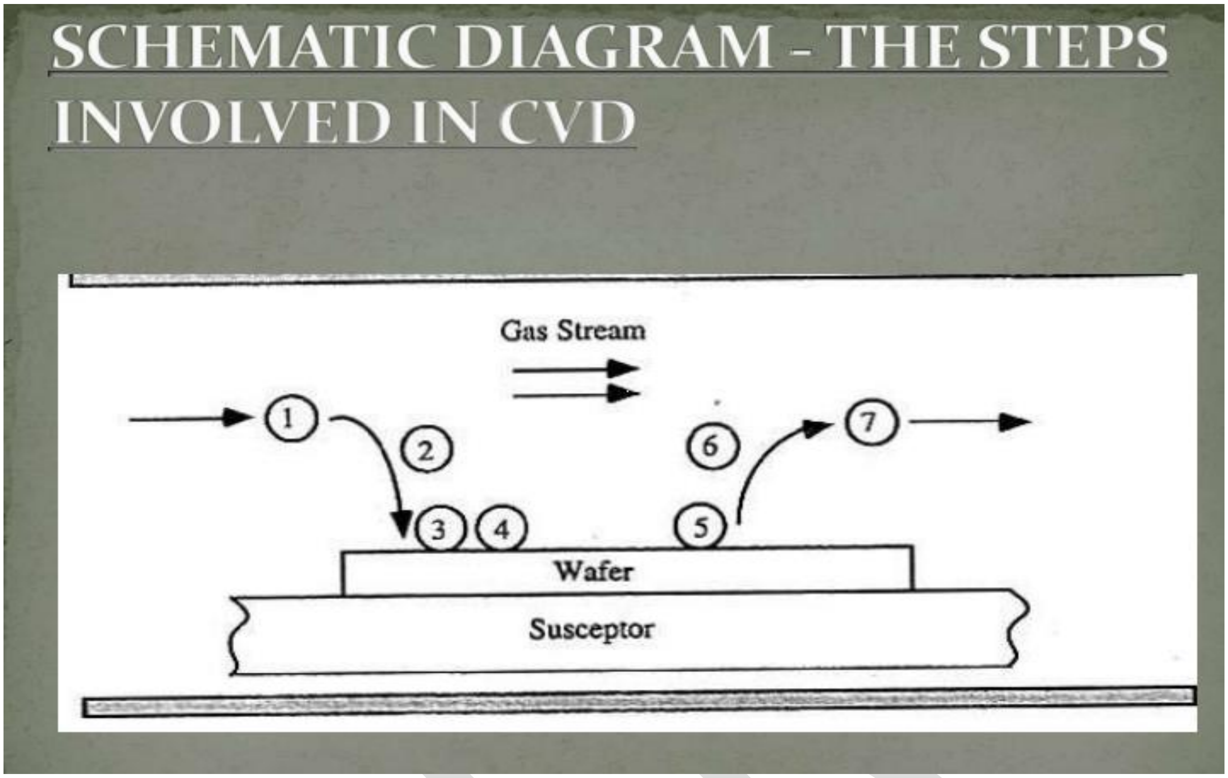
- Metal parts of heart valves are ion implanted by using carbon to make them bio – compactable
- Radio isotopes are implanted in artificial body parts for radio therapy

MODULE 2

CHEMICAL VAPOUR DEPOSITION

- Chemical Vapour Deposition (CVD) is a chemical process used to produce high purity, high performance solid materials.
- In a typical CVD process, the substrate is exposed to one or more volatile precursors which react and decompose on the substrate surface to produce the desired deposit.
- During this process, volatile by-products are also produced, which are removed by gas flow through the reaction chamber.





- CVD's are classified into two types on the basis of Operating Pressure.

1) Atmospheric Pressure CVD

2.) Low Pressure CVD

  - Plasma Enhanced CVD
  - Photochemical Vapour Deposition —
  - Thermal CVD

Atmospheric Pressure CVD

- **CASE 1 : HIGH TEMPERATURE**
- This process is used to deposit Silicon and compound films or hard metallurgical coatings like Titanium Carbide and Titanium Nitride**.**
- **CASE 2 : LOW TEMPERATURE**
- Many insulating film layers such as Silicon dioxide need to be deposited at low temperatures for effective deposition

- Aluminum oxide films are deposited by this method from aluminium trichloride, argon and oxygen gas mixtures at temperatures ranging from 800-1000 degree Celsius
- The films have low chlorine content, which continue to decrease with increasing temperature.

Limitation of APCVD

- Film thickness uniformity cannot be maintained.
- Large number of pinhole defects can occur.
- Wafer (Substrate) throughput is low due to low deposition rate.
- The deposits get contaminated very easily since it takes place at atmospheric pressure.
- Maintaining stoichiometry is extremely difficult.

Low Pressure CVD

- The deposition of Silicon carbide thin film is performed using low pressure CVD of Dichlorosilane / Acetylene / Hydrogen reaction system.
- The Silicon carbide film deposited at three different temperatures has three different properties.
- 1023 K------- AMORPHOUS
- 1073 K -------MICROCRYSTALLINE
- 1173 K-------- PREFERENTIALLY ORIENTED

Advantage and Disadavtages of LPCVD

- This technique permits either horizontal or vertical loading of the wafers into the furnace and accommodates a large number of wafers for processing.
- The process results in the deposition of compounds with excellent purity and uniformity.
- However the technique requires higher temperatures and the deposition rate is low.

Plasma-enhanced chemical vapor deposition (PECVD)

- Plasma-enhanced chemical vapor deposition (PECVD) is a process used to deposit thin films from a gas state (vapor) to a solid state on a substrate.
- Chemical reactions are involved in the process, which occur after creation of a plasma of the reacting gases.

- The plasma is generally created by RF (AC) frequency or DC discharge between two electrodes, the space between which is filled with the reacting gases.
- The helping hand of the Plasma helps in increasing the film quality at low temperature and pressure.
- PECVD uses electrical energy which is transferred to the gas mixture.
- This transforms the gas mixture into reactive radicals, ions, neutral atoms and molecules, and other highly excited species.
- These atomic and molecular fragments interact with a substrate and, depending on the nature of these interactions, either etching or deposition processes occur at the substrate. —

Some of the desirable properties of PECVD films are good adhesion, low pinhole density and uniformity

Photochemical vapour deposition

- Aluminium thin films are deposited via photochemical vapour deposition on catalytic layers of Ti, TiO_2 , and Pd, using dimethyl aluminum hydride.
- Deposition is carried out at low gas pressures to induce a surface reaction based on adsorption and subsequent decomposition of adsorbates.
- Of these three layers Ti is so effective as a catalyst that the Al films are thermally deposited even at a low substrate temperature of 60°C with a growth rate of 0.5 nm/min.
- The UV light generated by a deuterium lamp helped increase the growth rates. On the other hand, Al could be deposited on TiO_2 layers only under irradiation at a substrate temperature of 120°C It takes several minutes to cover the TiO_2 surface with Al and initiate the Al film's growth.
- Here, the UV light inhibited the Al growth on the surface, whereas the films are deposited thermally.

Thermal CVD

- In thermal CVD process, temperatures as high as 2000 degree Celsius is needed to deposit the compounds.
- There are two basic types of reactors for thermal CVD.

1. Hot wall reactor

2. Cold wall reactor

- A hot wall reactor is an isothermal surface into which the substrates are placed. Since the whole chamber is heated, precise temperature control can be achieved by designing the furnace accordingly.
- A disadvantage of the hot wall configuration is that deposition occurs on the walls of the chamber as well as on the substrate.
- As a consequence, hot wall reactors must be frequently cleaned in order to reduce contamination of substrates.
- In a cold wall reactor, only the substrate is heated.
- The deposition takes place on the area of the highest temperature, since CVD reactions are generally endothermic.
- The deposition is only on the substrate in cold wall reactors, and therefore contamination of particles is reduced considerably.
- However, hot wall reactors have higher throughput since the designs can easily accommodate multiple wafer (substrate) configurations.

Advantages of CVD

- Variable shaped surfaces, given reasonable access to the coating powders or gases, such as screw threads, blind holes or channels or recesses, can be coated evenly without build-up on edges.
- Versatile –any element or compound can be deposited.
- High Purity can be obtained.
- High Density – nearly 100% of theoretical value.
- Material Formation well below the melting point
- Economical in production, since many parts can be coated at the same time.

Applications of CVD

- CVD has applications across a wide range of industries such as:
- Coatings – Coatings for a variety of applications such as wear resistance, corrosion resistance, high temperature protection, erosion protection and combinations thereof.

- Semiconductors and related devices – Integrated circuits, sensors and optoelectronic devices

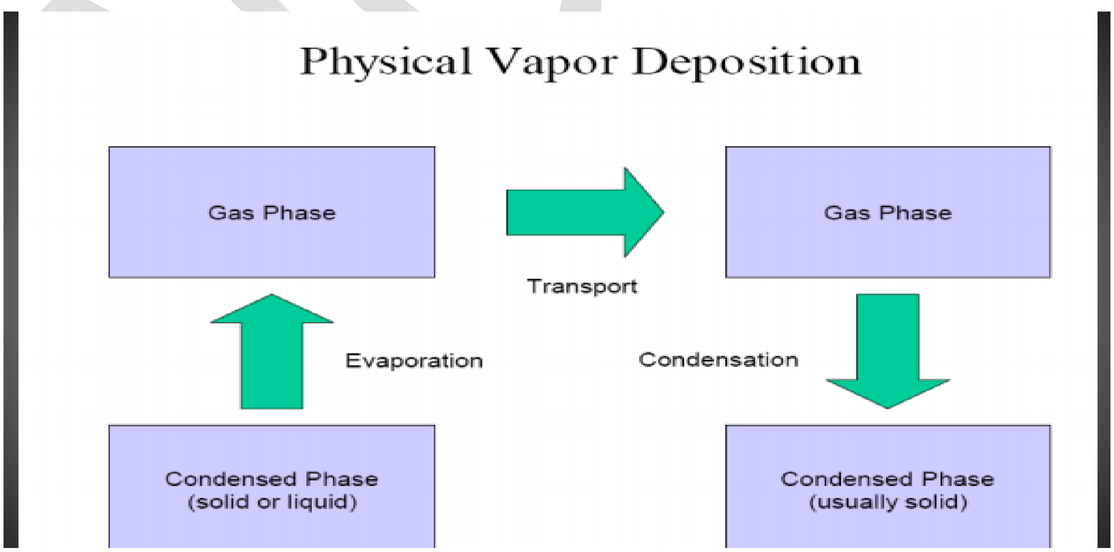
PHYSICAL VAPOUR DEPOSITION

- Physical Vapour Deposition (PVD) is fundamentally a vaporization coating technique, involving transfer of material on an atomic level.
- It is an alternative process to electroplating Ø
- The process is similar to chemical vapour deposition (CVD) except that the raw materials/precursors
- i.e. the material that is going to be deposited starts out in solid form, whereas in CVD, the precursors are introduced to the reaction chamber in the gaseous state.
- Working Concept PVD processes are carried out under vacuum conditions.

The process involved four steps:

- 1.Evaporation
- 2.Transportation
- 3.Reaction
- 4.Deposition

PHYSICAL VAPOUR DEPOSITION

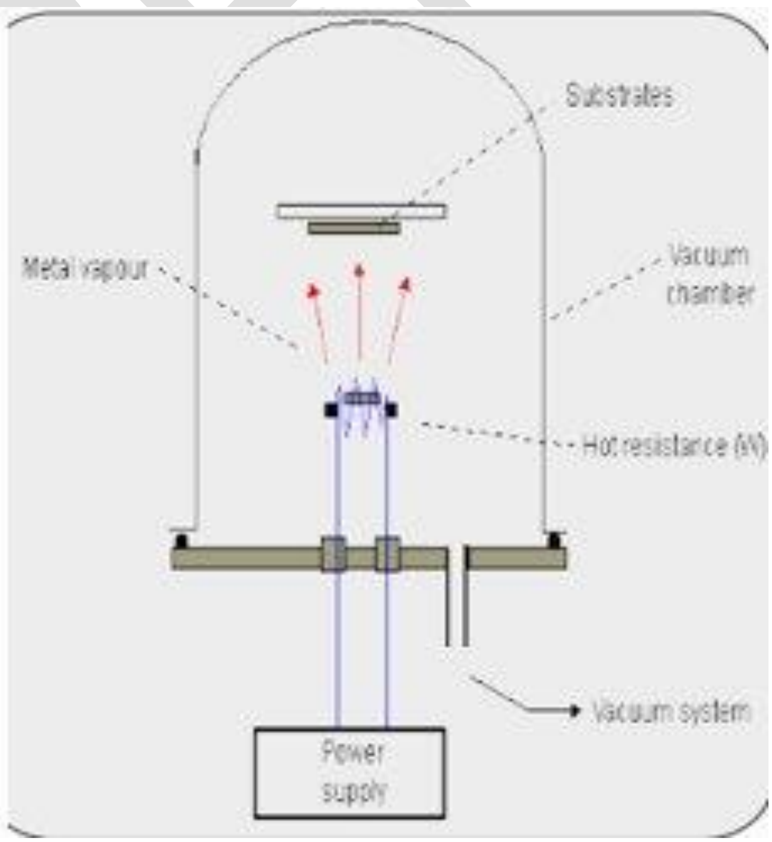


Types of PVD

- **Evaporative deposition**
- **Sputter deposition**
- **Ion induced deposition**
- **Cathode Arc Deposition**

EVAPORATIVE DEPOSITION

- Resistive heating method is used.
- deposition is performed at high temperature & low vacuum
- Vacuum decreases the content of Contamination
- Voltage & current is manually controlled.
- Material is kept in boats.

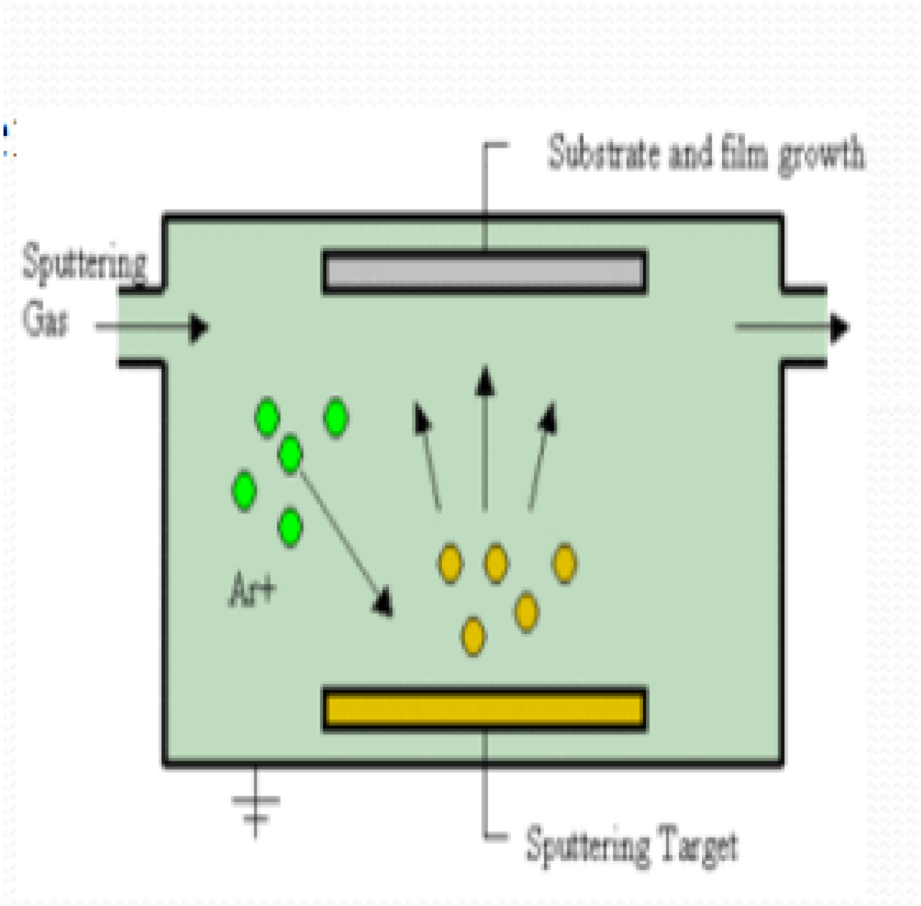


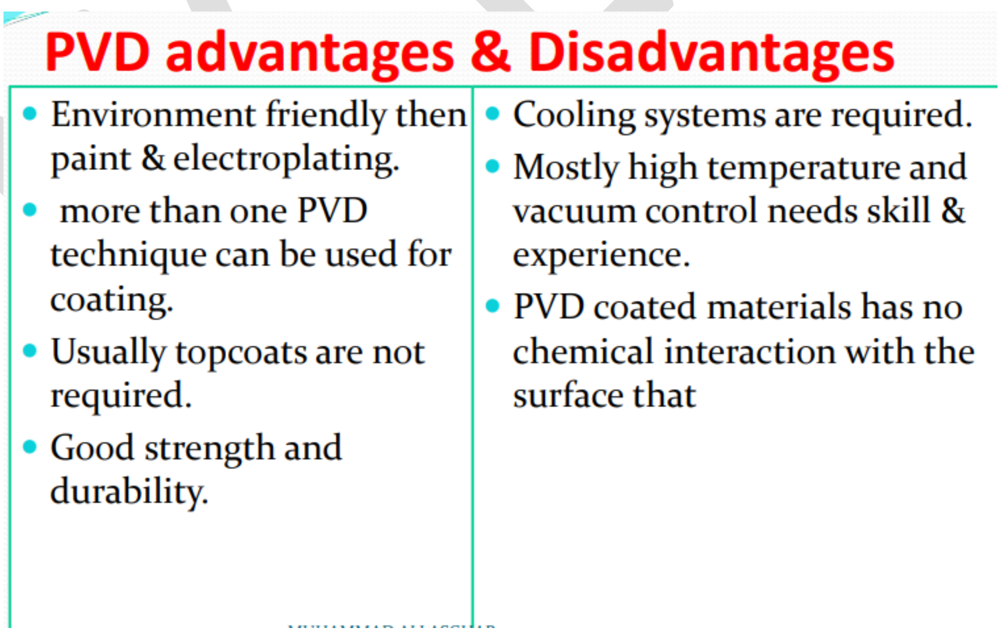
SPUTTER DEPOSITION

- Sputtering works on the bases of momentum principle, formed by the collision of the atoms and molecules.
- Plasma glow, ion accelerator or radioactive emitting is used to evaporate material.
- argon gas is used for inert atmosphere.

Types of sputtering

- Chemical and etching sputtering
- Electronic sputtering
- Potential sputtering

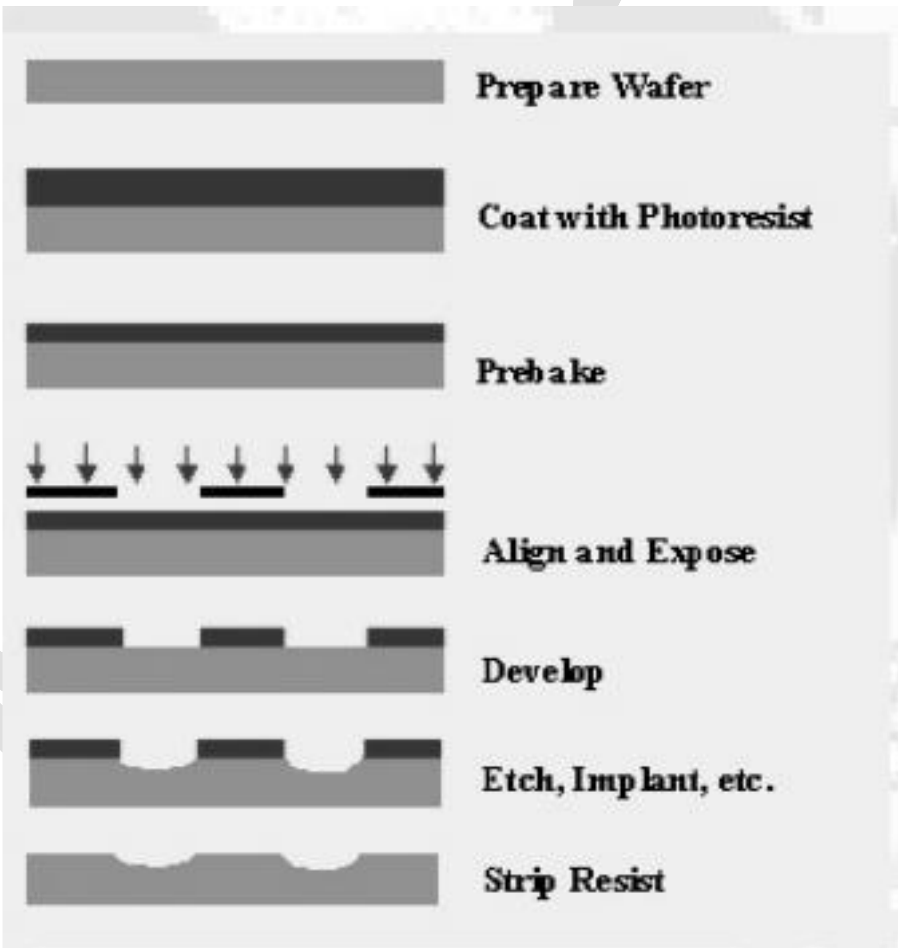

Substrate and film growth
Sputtering Gas
Ar+
Sputtering Target


PVD advantages & Disadvantages
Environment friendly then paint & electroplating.
more than one PVD technique can be used for coating.
Usually topcoats are not required.
Good strength and durability.
Cooling systems are required.
Mostly high temperature and vacuum control needs skill & experience.
PVD coated materials has no chemical interaction with the surface that

ETCHING PROCESS

- Etching is the one of the most important process in microfabrication
- It involves the removal of material in desired area by physical or chemical means
- Definition: Etching is traditionally the process of using strong acid or mordant to cut into the unprotected parts of a metal surface to create a design in the metal

A mordant or dye fixative is a substance used to set dyes on fabrics by forming a coordination complex with the dye, which then attaches to the fabric (or tissue).



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

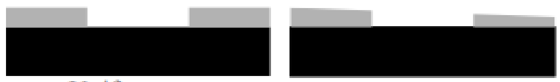
1) Chemical etching (Wet etching) where the material is dissolved when immersed in a chemical

solution.

2) Physical Etching (Dry etching) where the material is sputtered or dissolved using reactive ions or a vapor phase etchant.

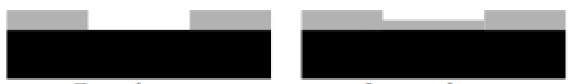
Goals (Uniformity, Control and Selective)

- Uniformity:
  - is defined as the percentage change in etch rate across the entire etched region



Uniform   Non-Uniform

- Etch Control:
  - Etch rate is defined as the amount of the film etched in a given time.
  - Possible problems



Complete   Incomplete

Too short an etch time
The presence of a surface layer that slows the etching process
A lowered temperature or weakened etch solution

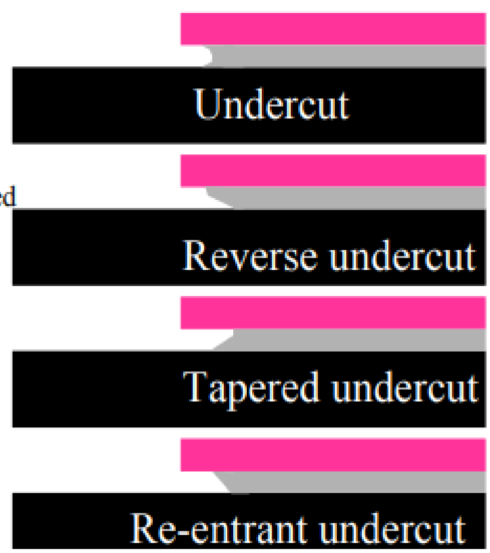
- Problem: Over-etch and undercutting

In any etch process there is always some degree of overetch planned into the process

One way to quantify the undercut is the undercut distance per side. For e.g. a particular etching process may produce 0.8 µm line when the patterned resist line is 1 µm width. Thus, the undercut is 0. 1 µm per side.

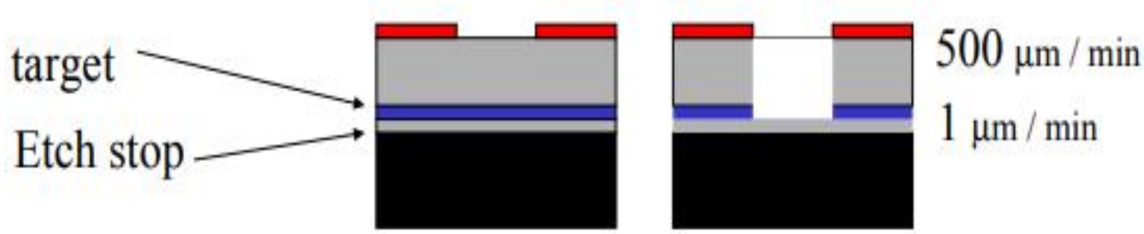
<u>Severe undercutting takes place when</u>

1. Excessive etch time
2. High temperature
3. Strong etchant solution
4. Adhesion between resist and wafer is weak….



- Etch Selectivity
  - One goal in etching step is the preservation of the surface underlying the etched layer.
  - The protected layer is too thin and important. Etch rate is too fast
  - Etch Selectivity (S) is expressed as the ratio of the etch rate of the layer material (r_n) to the etch rate of the underlying surface (r_s)

    – $S = r_n/r_s$



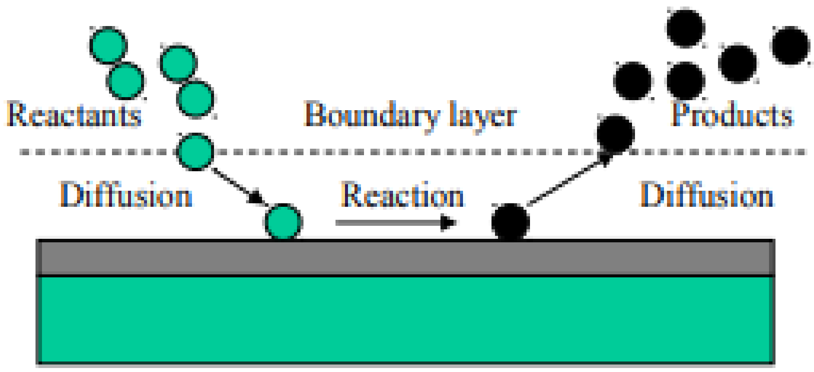
Chemical Etching (Wet Etching)

- This is the simplest etching technology. All it requires is a container with a liquid solution that will dissolve the material in question.
- Liquid solution contains mixture of oxidizing agent and reducing agent whereby etching reactions involve oxidation-reduction mechanisms.
- Oxidizing agent will oxidize the wafer material and the reducing agent will dissolve the oxide product.
- Rate of etching depends in :
  - Substrate material to be etched.
  - Concentration of the chemical reactants in the solution.
  - Temperature of the solution**.**

Three major process stages:

- The diffusion of the reacting ions or molecules from etchant solution towards the exposed film on the wafer surface through the boundary layer.
- The formation of a soluble or/and gaseous by-products through the chemical reaction between the etchant and the exposed film.

- The diffusion of the reaction by-product from the surface of the wafer through boundary layer into the bulk of the etchant solution.



Advantage of a wet etch process

- Damage-free finish to wafer surface where surface morphology is typically smooth and shiny
- fast etch rate especially for blanket etch
- simple and direct etching process since simple resist can be used as etch mask
- process occur at atmospheric environment
- cheaper cost
- high etch selectivity easily available for etchants, resist and etched materials
- Good etch uniformity across wafer.

Disadvantages:

- isotropic etching
- No control for precision etching
- Excessive particle contamination is possible
- Bubbles can grow during etching that act as localized mask
- 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.

- **Isotropic etching**

- Same etch rate in different direction in a material

- **Anisotropic etching**
- in contrast to isotropic etching means different etch rates in different directions in the material.
- The result is a pyramid shaped hole instead of a hole with rounded sidewalls with a isotropic etchant

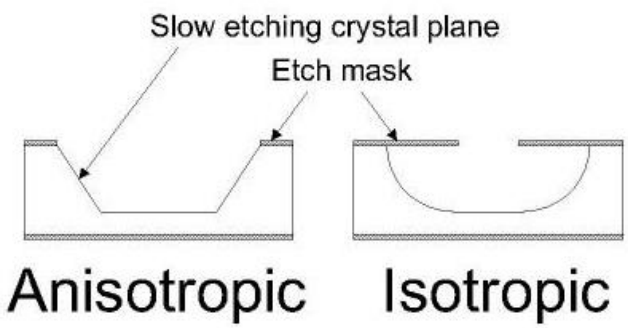


Figure 1: *Difference between anisotropic and isotropic wet etching.*

Plasma Etching (Dry Etching)

Dry Etching : Material removal reactions occur in the gas phase

Types of Dry Etching: Non-plasma/Plasma based

1) Reactive ion etching (RIE)

2) Sputter etching

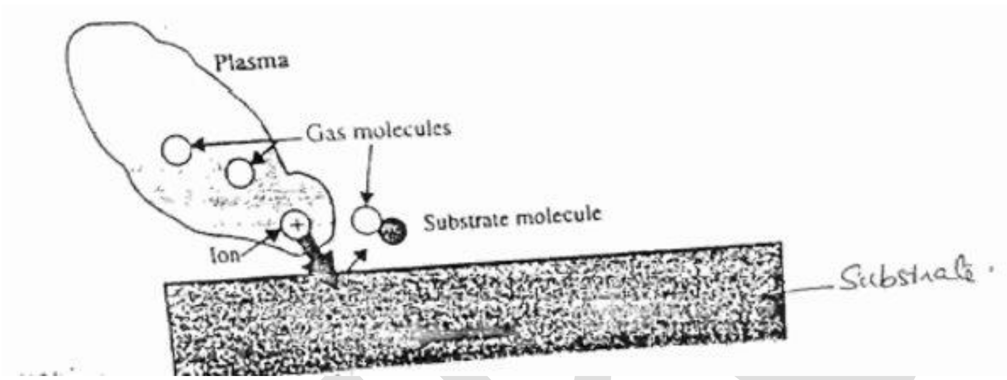
3) vapor phase etching

Reactive ion etching (RIE)

- 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



Dry Etching Advantages

- Eliminates handling of dangerous acids and solvents
- Uses small amounts of chemicals
- Isotropic or anisotropic etch profiles
- Directional etching without using the crystal orientation of Si
- High resolution and cleanliness
- Less undercutting
- No unintentional prolongation of etching
- Better process control
- Ease of automation

Dry Etching Advantages

- Some gases are quite toxic and corrosive
- Re-deposition of no volatile compounds
- Need for specialized expensive equipment

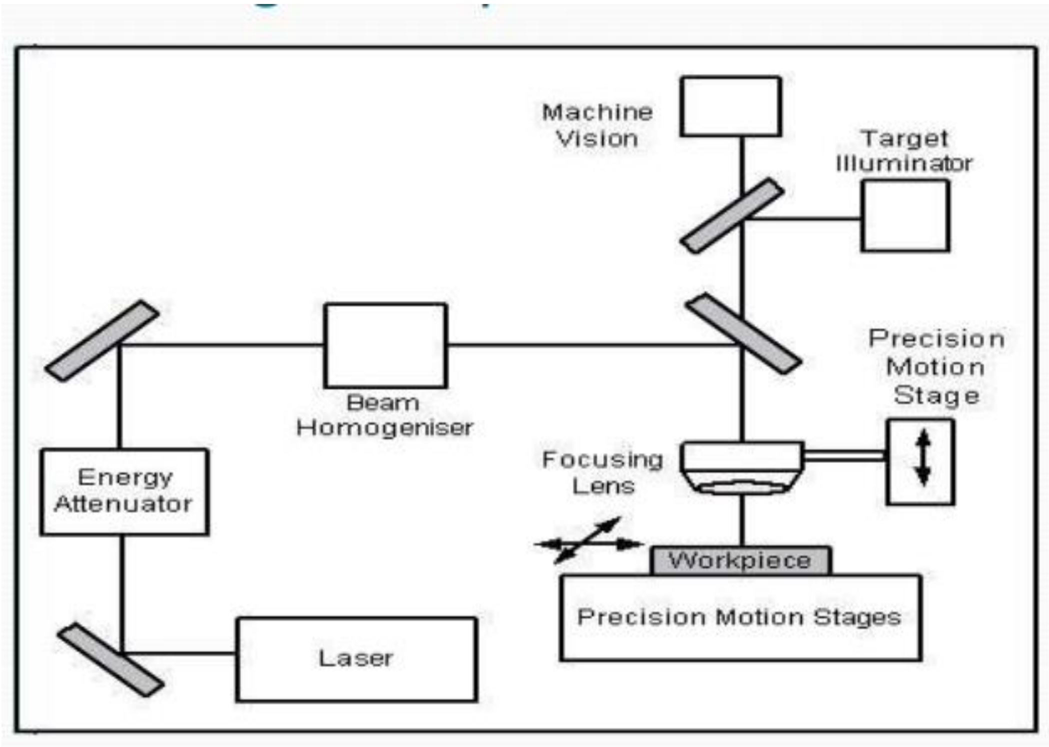
Module 3

Micro-Fabrication Special Machining

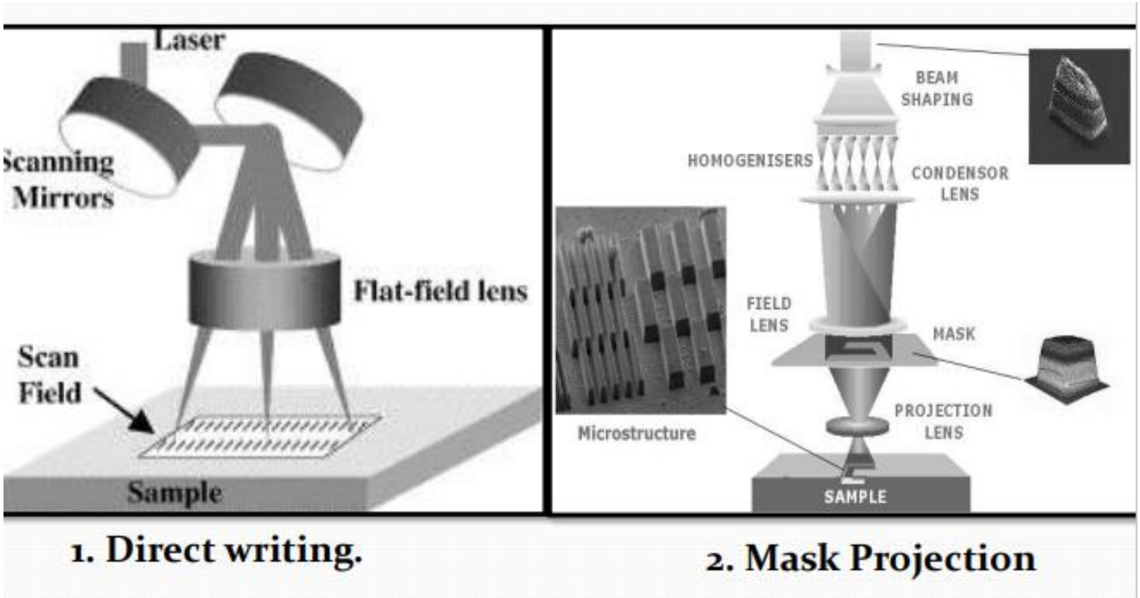
- Several conventional, non-IC-related technologies that do not use photolithography are also capable of forming features of relatively small dimensions.
- These include mechanical machining, ultrasonic machining, electro discharge machining, and laser machining.
- In some applications, such as ink-jet printer nozzles and automobile fuel-injection nozzles, photolithographic fabrication methods have been used, but proved less economical than the more established methods.

Laser Machining

- Laser micromachining: cutting, drilling, welding, or other modification in order to achieve small features.
- Micro machining implies that parts are made to the size of 1 to 999 µm. However Micro also means very small in the fields of machining, manufacture of small parts are not easy.
- Lasers have been in use in various industrial sectors such as the automotive and aerospace industries for many years performing cutting, welding and materials processing tasks.
- Focused pulses of radiation, typically 0.1–100 ns in duration, from a high-power laser can ablate material (explosively remove it as fine particles and vapor) from a substrate.
- Incorporating such a laser in a CNC system enables precision laser machining. Metals, ceramics, silicon, and plastics can be laser machined.
- Holes as small as tens of microns in diameter, with aspect ratios greater than 10:1, can be produced.
- Laser machining is most often a serial process, but with mask-projection techniques, it becomes a parallel process.
- it has successfully competed with KOH etching and with electroplating in the production of ink-jet nozzles.
- Due to its speed, low cost, and rapid turn-around time, laser machining is one of the preferred methods of creating trenches and cuts in plastics.

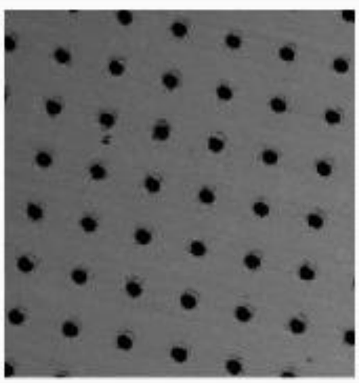


- A laser machine consists of the laser, mirrors for beam guidance, a focusing optic and a positioning system.
- The laser beam is focused onto the work piece and can be moved relative to it.
- The laser machining process is controlled by switching the laser on and off, changing the laser pulse energy and other laser parameters and by positioning either the work piece or the laser focus.
- Laser is emitted from the source is passed through the energy attenuator. After it is passed through the beam homogenizer to homogenize the beam.
- The target illuminator and machine vision controls the beam to the focusing lens. The lens is moved by precision motion stages. The beam is then falls on the work piece and the machining takes place.



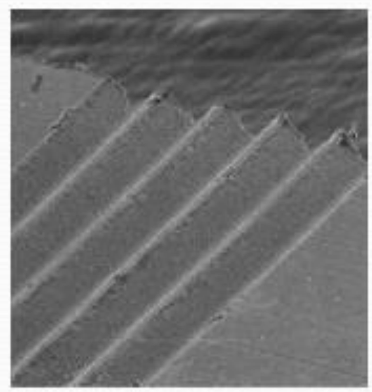
Applications

- For drilling micro holes, laser beam drilling technique is used.



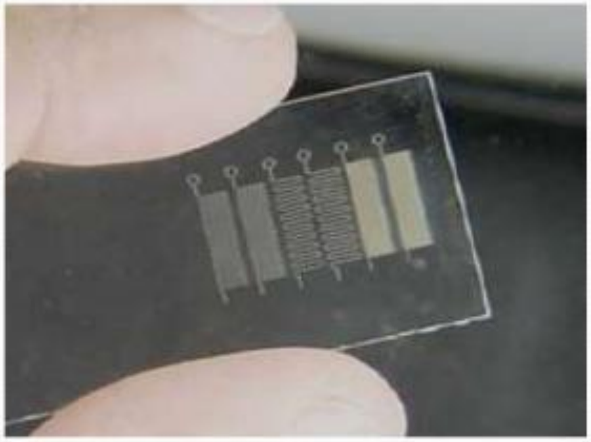
High speed drilling of 20μm holes in 50μm thick foil

Cutting of 1mm tube

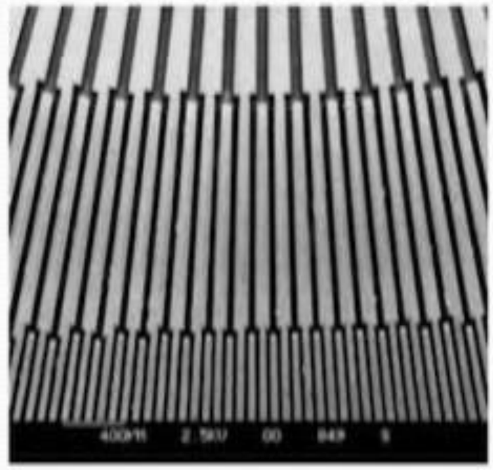


100μm wide v-grooves

- Laser Micro machining technique finds application in the manufacture of micro channels and micro holes in integrated chips and microchips



Micro holes on integrated chips



Micro channels on integrated chips

Advantages

- Easy capability of being automated •Straightforward process monitoring
- Forceless and contactless machining
- Minor heat-affected zone
- Marginal modifications to the microstructure •Machining free of burr and bulging
- High flexibility regarding design of tiny structures
- High machining speed
- High precision
- Constant machining quality
- No additional tooling costs by wear
- No solvent chemicals used
- Material removal rate controllable down to the nanometer scale

Disadvantages

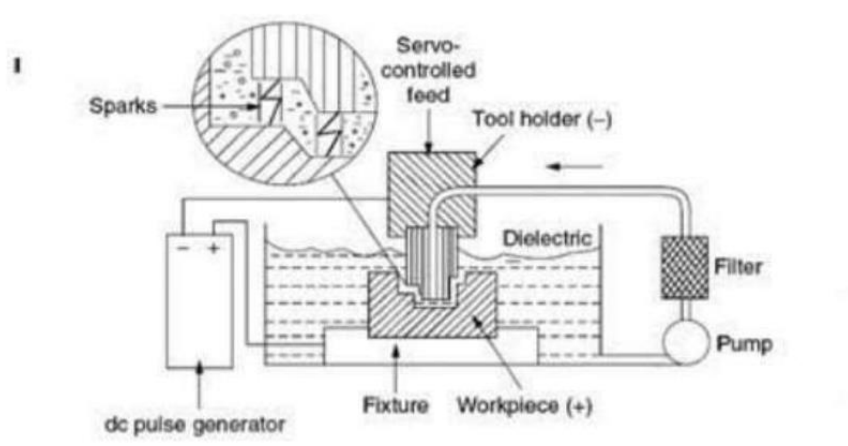
- The equipment required for micro machining is very costly than other cutting processes.
- Need highly skilled persons to operate micro machining systems.
- Material limitations (including crystalline and reflective materials)
- Reflected laser light can present a safety hazard

Electrical Discharge Machining

- Electro discharge machining, also called electrical-discharge machining or spark erosion machining (EDM) uses a series of electrical discharges (sparks) to erode material from a conductive work piece.

- High-voltage pulses, repeated at 50 kHz to 500 kHz, are applied to a conductive electrode, typically made of graphite, brass, copper, or tungsten.
- Electrodes as small as 40 µm in diameter have been used, limiting features to about the same size.
- Each discharge removes a small volume of material, typically in the range of 103 to 105 µm3, from the work piece.
- EDM is performed in a dielectric liquid such as mineral oil. Due to heating, a gas bubble is formed during each voltage pulse.
- After the pulse, the bubble collapses, flushing away debris from the blank and electrode.

Figure of Electrical Discharge Machining [EDM]



Working principle of EDM

- The EDM system consider tool as negative terminal (Cathode) and w/p as positive terminal (Anode) are connected to DC power supply to create a potential difference between the w/p and the tool.
- The tool and w/p are separated by gap, is called spark gap. This gap is filled by dielectric fluid.
- This process increase the concentration of electrons and ions in dielectric medium between the tool and the w/p at the spark gap**.**

- The electrical energy dissipated at the thermal energy of the spark. When the electrons and the ions reach the anode and cathode, they give up their kinetic energy in the form of heat.
- With a very short duration spark (2 to 2000 microsecond), The temperature of the electrodes can be raised more than their normal boiling point, about 10,000 C.
- A servo controlled electrode feeding mechanism is used to control gap between electrode and w/p. The spark gap used in EDM is about 0.0125 to 0.125 mm.
- There are two types of servo controlled system as electrical servo control and hydraulic servo system.

Electrodes:

- It should have good electrical conductivity and thermal conductivity.
- It should be easy to fabricate in any required shape.
- It should have high melting point.
- It should have low erosion rate.

Characteristics of Dielectric Fluid:

- The function of dielectric Fluid is to act as a flushing medium for the removal of the chips and to provide a cooling medium.
- It should have good cooling ability and low viscosity of dielectric produces smooth surfaces.
- It should be chemically neutral otherwise it reacts with electrode, w/p and container.
- It should not produce any toxic vapors during the process.

Applications of EDM :-

- EDM can be used make parts with complex, Precise and irregular shapes for forging, press tools, extrusion dies, cutting tool dies and mould.
- EDM for create accurate dimension holes, deep small diameter holes, narrow slots in turbine blades, difficult to internal shape.
- EDM can also used in aerospace and medical application.

- **Advantages of EDM**

- EDM Drilling to create very small holes.
- EDM Milling to machine complex shape with simple cylindrical electrodes.
- EDM process has ability to machine hard, difficult to machine materials.
- Thin and brittle components can be machined without distortion because there is no direct contact between the tool and w/p.

- No burrs are left in machined surface.

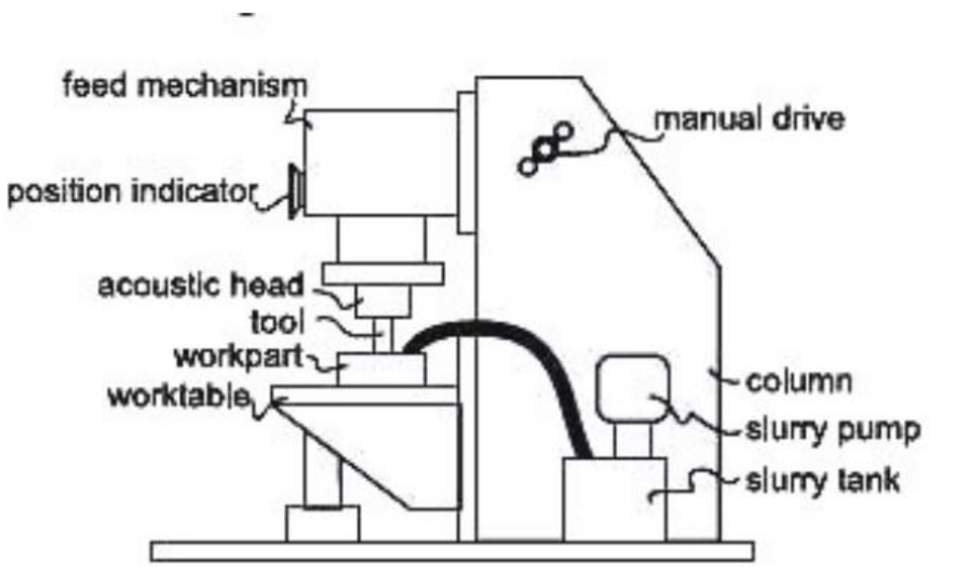
Limitations of EDM

- This process can only be employed in electrically conductive materials.
- Material removal rate is low and the process overall is slow compared to conventional machining process. Energy required for the operation is more than that of conventional machining.
- Rough surface finish when at high rates of material removal.
- Finishing cuts are needed at low MRR.
- Profile machining is complex contours is not possible at required tolerance.
- Produces slightly tapered holes, especially if blind

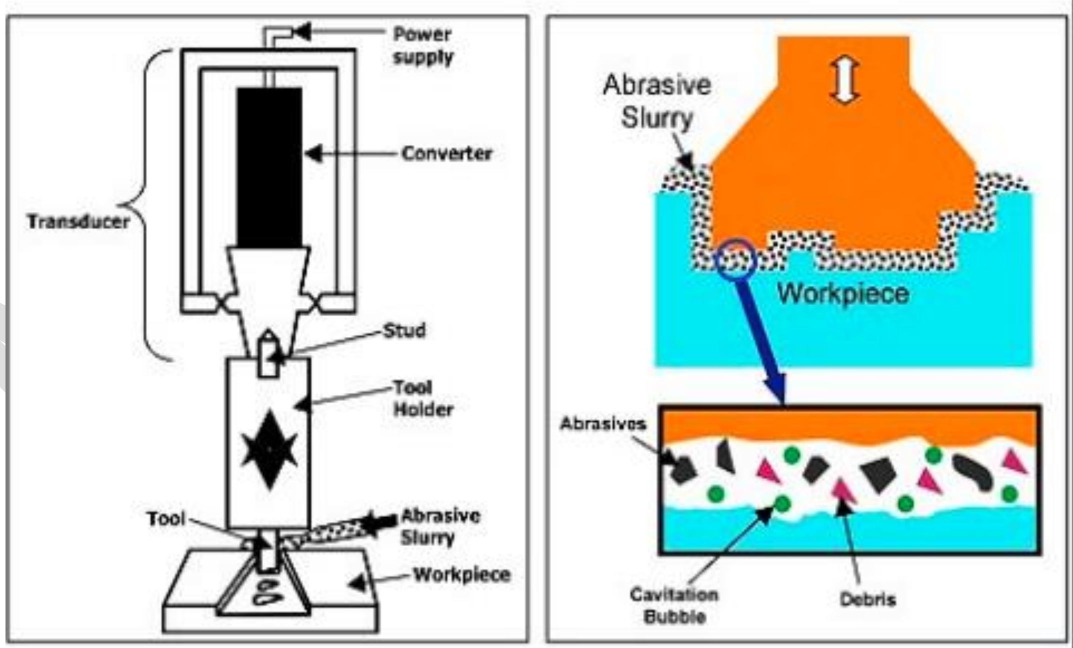
Ultrasonic Machining

- Also Known as Ultrasonic Impact Grinding.
- Vibrating tool at ultrasonic frequency.
- Use of abrasive slurry.
- Very little heat generated
- In ultrasonic machining, also known as ultrasonic impact grinding, a transducer vibrates a tool at high frequency (20–100 kHz).
- The tip of the tool is pushed against the work piece as a slurry of water or oil and abrasive particles, such as boron carbide, aluminum oxide, or silicon carbide, is flushed across the surface.
- There are several mechanisms for removal of material: The tool vibration directly hammers particles into the surface, as well as imparting a high velocity to other particles, both of which chip away at the work piece.
- Cavitation erosion and chemical action can also contribute. The microscopic chips are carried away by the slurry.
- As the tool moves slowly into the work piece, a hole with vertical sidewalls is created. An array of tips can drill many holes at the same time.
- Ultrasonic machining can be performed on hard, brittle materials such as glasses, ceramics, diamond, and silicon.
- The minimum hole diameter is about 150 µm. At the other extreme, holes over 100 mm have been machined.

Ultrasonic Machine Parts



Principal components of an ultrasonic machine.



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Advantages

- It can be used machine hard, brittle, fragile and nonconductive material.
- No heat is generated in work, therefore no significant changes in physical structure of work material.
- Non-metal (because of the poor electrical conductivity) that cannot be machined by EDM and ECM can very well be machined by USM.
- It is burr less and distortion less processes.
- It can be adopted in conjunction with other new technologies like EDM, ECG,ECM.

Disadvantages

- Low Metal removal rate.
- It is difficult to drill deep holes, as slurry movement is restricted
- Tool wear rate is high due to abrasive particles. Tools made from brass, tungsten carbide, MS or tool steel will wear from the action of abrasive grit with a ratio that ranges from 1:1 to 200:1.
- USM can be used only when the hardness of work is more than 45 HRC.

Applications

- Machining of cavities in electrically nonconductive ceramics.
- Used to machine fragile components in which otherwise the scrap rate is high.
- Used for multistep processing for fabricating silicon nitride (Si3N4) turbine blades.
- Used for machining hard, brittle metallic alloys, semiconductors, glass, ceramics, carbides etc.
- Used for machining round, square, irregular shaped holes and surface impressions.
- Used in machining of dies for wire drawing, punching and blanking operations.
- USM has been used for piercing of dies and for parting off and blanking operations.
- USM enables a dentist to drill a hole of any shape on teeth without any pain.
- Ferrites and steel parts , precision mineral stones can be machined using USM
- USM can be used to cut industrial diamonds
- USM is used for grinding Quartz, Glass, ceramics
- Cutting holes with curved or spiral center lines and cutting threads in glass and mineral or metallic-ceramics

Electro Chemical Machining

- Electrochemical Machining (ECM) is one of the newest and most useful non-traditional machining (NTM) process belonging to Electrochemical category.
- Electrochemical machining (ECM) is used to remove metal and alloys which are difficult or impossible to machine by mechanical machining process.

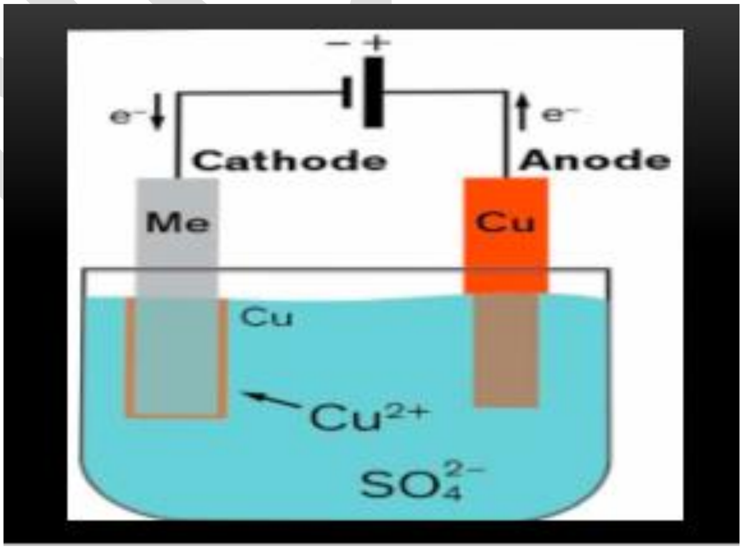
- The reverse of electroplating.
- This machining process is based Michael Faraday's classical laws of electrolysis, requiring basically two electrodes, an electrolyte, a gap and a source of D.C power of sufficient capacity.
- The working of ECM is based on Faraday's law of electrolysis.

<u>FARADAY'S LAW STATE THAT –</u>

- the amount of chemical change produced by current at an electrode-electrolyte boundary is proportional to the quantity of electricity used
- The amounts of chemical changes produced by the same quantity of electricity in different substances are proportional to their equivalent weights.
- In this machining process , tool is connected with the negative terminal of battery (work as cathodes)and work piece is connected with the positive terminal of battery (work as Anode) .
- They both are placed in a electrolyte solution with a small distance. When the DC current supplied to the electrode, metal removed from work piece .This is basic fundamental of electro chemical machining.
- ***Electrolyte:*** A Substance that dissociates into the ions in solution and acquires the capacity to a conduct electron.

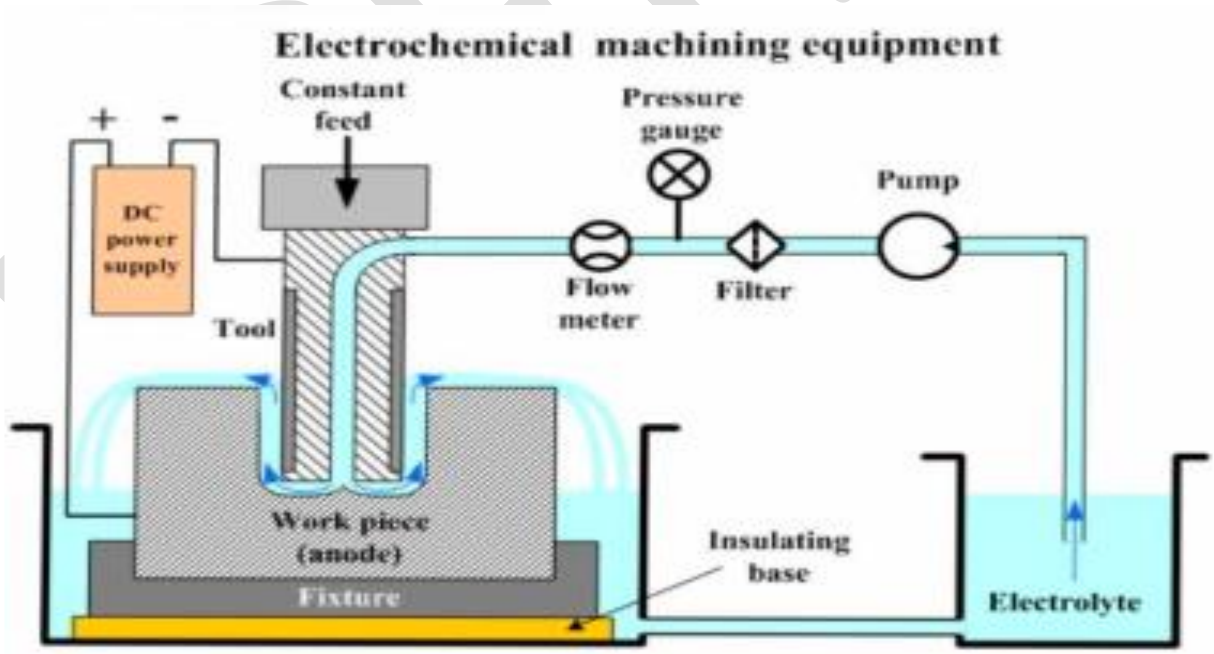
FUNCTION OF ELECROLYTE

- The current flow between the tool and w/p through electrolyte.
- The heat produced is dissipated by liquid electrolytic solution.
- The product of machining is removed by solution.



- Electro chemical machining works inverse as electroplating process.

- Metal is removed from Anode into electrolyte and slage form by reacting opposite ions available in electrolyte. This process works as follow.
- In ECM, the electrolyte is so chosen that there is no plating on tool and shape of tool remain unchanged.
- Generally **Nacl** into water takes as electrolyte.
- The tool is connected to negative terminal of battery and w/p is connected to positive terminal of battery.
- When the current passes through electrode, reaction occur at Anode or work piece and at the cathode or tool .
- Due to potential difference ionic dissociation take place in electrolyte.
- When the potential difference applied between the work piece and tool, positive ions move towards the tool and negative ions move towards the work piece.
- Thus the positive ion moves towards tool .As the positive reaches to the tool, it take some electron from it and convert into gas form .This gas goes into environment.
- The negative ions moves toward the work piece (Anode). This electrons removes material from the work piece and removed materials flowing through electrolyte and goes to the container.
- This machining process gives higher surface finishing because machining is done by atom.



APPLICATION

- ECM is used to machining disc or turbine rotor blades..
- The most common of application ECM is high accuracy finishing.

- It can be used for slotting very thin walled collets.

MERITS

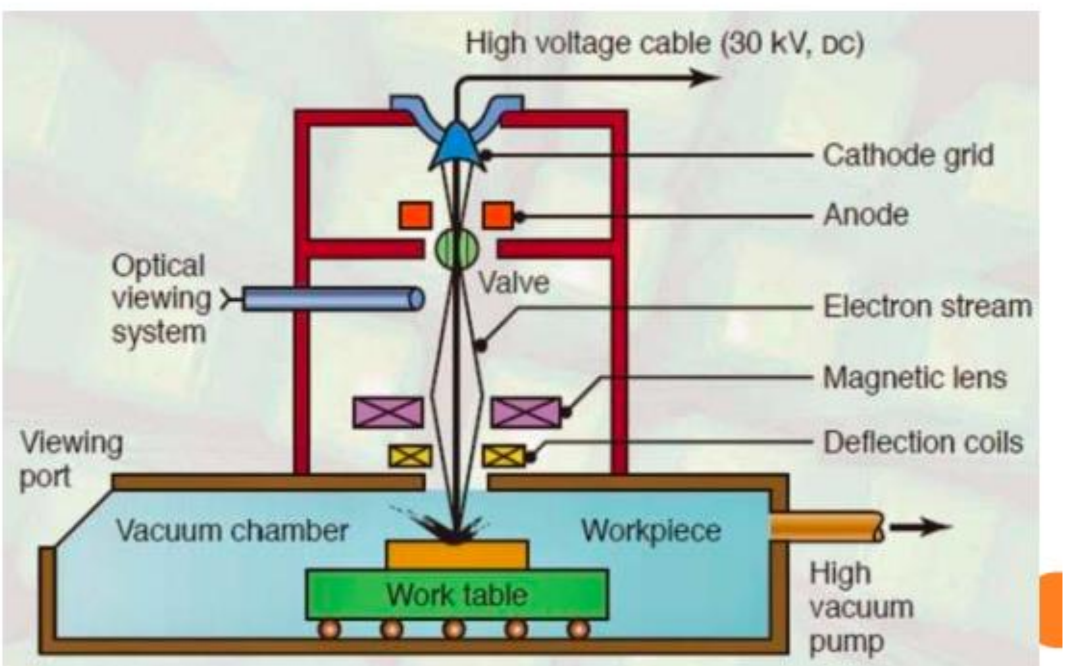
- It can be machine very complicated surface.
- It can machined harder metal than the tool.
- Better surface finish.
- A single tool can be used to machining large number of work piece or no tool wear occur

DEMERITS

- High initial cost of machine.
- Design and tooling system is complex.
- High energy consumption.
- Non conducting material cannot be machined.
- Blind hole cannot be machined by ECM.

Electron Beam Machining

EBM



BASIC PRINCIPLE

- This machining process works on basic principle of conversion of kinetic energy of electron into heat energy.
- When a high speed electron impinges on a work piece, they convert its kinetic energy into heat energy.
- This heat energy used to vaporize material at contact surface.
- This process is carried out in vacuum otherwise the electron will collide with air particle and loses its energy before impinging on work material.

EQUIPMENTS

Electron Gun:

- It is called heart of electron beam machining. It is used to generate electron.
- It is simply a cathode ray tube which generates electron, accelerate them to sufficient velocity and focus them at small spot size.
- In this gun cathode is made by tungsten or tantalum.
- This cathode filament heated up to 2500 degree centigrade vacuum in the chamber.

Annular bias grid

- It is next element of EBM. It is just after the electron gun.
- It is an anode which is connected by the negative bias so the electron generated by the cathode do not diverge from its path and approach to the next element.
- When the electrons leave this section, the velocity of electron is almost half the velocity of light.

Magnetic Lenses

- After the anode, magnetic lenses are provided which shape the beam and does not allow to diverge electron or reduce the divergence of beam.
- After the anode, magnetic lenses are provided which shape the beam and does not allow to diverge electron or reduce the divergence of beam.

Electromagnetic lens and deflection coil:

- Electromagnetic lens is used to focus the electron beam at a spot.
- They use to focus beam at a spot on work piece so a high intense beam reaches at work surface, which produces more heat and improve machining.
- The defecting coil does not allow to beam deflect and take care of all electrons moves in series thus form a high intense beam.

Work piece and work holding device:

- It can machine both metallic and non-metallic material.
- The work piece is hold by suitable fixture which is mounted on a CNC table.
- This table can be move in all three direction which control the shape of machining.

WORKING

- First electron gun produces high velocity electron particles. These electron particles move towards anode which is placed after cathode tube.
- Now this high intense electron beam passes through magnetic lenses. There are a series of lenses which take care of only convergent electron passes through it. It absorb all divergent electron and low energy electron. It provides a high quality electron beam.
- This electron beam now passes through electromagnetic lens and deflecting coil. It focus the electron beam at a spot.
- The high intense electron beam impinges on the work piece where kinetic energy of electrons convert into thermal energy.
- The material is removed from contact surface by melting and vaporization due to this high heat generated by conversion of kinetic energy into thermal energy. This whole process take place in a vacuum chamber otherwise these electron collide with air particle between path and loses its kinetic energy.

APPLICATION:

- It is used to produce very small size hole about 100 micro meters to 2 millimeter.
- It is used to produce holes in diesel injection nozzle.
- Used in aerospace industries for producing turbine blade for supersonic engines and in nuclear reactors

ADVANTAGES AND DISADVANTAGES

Advantages:

- It can be used for produce very small size hole in any shape.
- It can machining any material irrespective its hardness and other mechanical properties.
- It provides good surface finish. No any surface finishing process is require after EBM.
- Highly reacting material can be machine easily because machining is done under

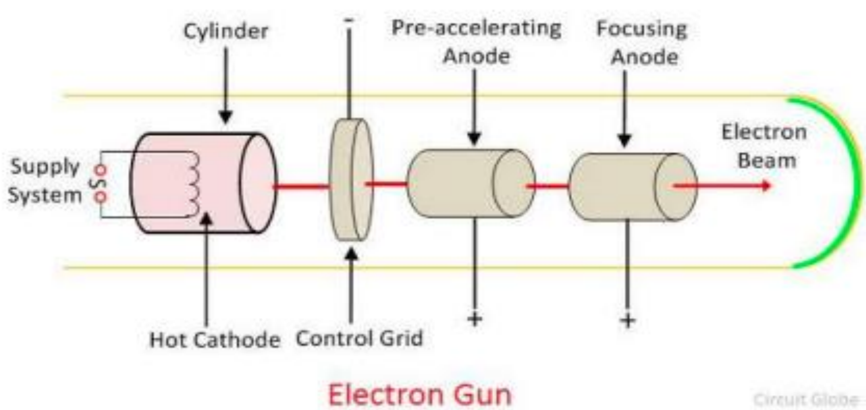
vacuum.

Disadvantages:

- High capital cost.
- High skill operator required.
- Regular maintenance is required
- Material removal rate is very low compare to other conventional process.
- It is difficult to produce perfect vacuum

ELECTRON GUN CONSTRUCTION

- Electron gun is defined as the source of focused and accelerated electron beam.
- It is a device used in Cathode Ray Tube for displaying the image on the phosphorous screen of CRT.
- The electron gun emits electrons and forms them into a beam by the help of a heater, cathode, grid, pre accelerating, accelerating and focusing anode.



CONSTRUCTION

Heater

- The heater converts the electric energy in the form of heat.
- It has a resistor which obstructs the flow of current and converts it into the thermal energy.

- The heater heats the cathode electrodes and emits the electrons.

Control Grid

- The control grid is a nickel cylinder. It is the metallic cup which has lower permeability steel.
- It is about 15 mm long and having the diameter of 15 mm. The hole of about 0.25 mm is drilled in the cap of the grid for the flow of the electron.
- The intensity of electron beam passing through the grid depends upon the emission of electrons.
- The control grid is negative biasing due to which it controls the flow of electrons.

Pre-Accelerating & Accelerating Anode

- The pre-accelerating and accelerating anode accelerated the beams passing through the gun.
- These anodes are connected to the high potential for accelerating the electrons.

Focusing Anode

- After passing through the pre-accelerating and accelerating electrodes, the electrons are passing through the focusing anode.
- The focusing anode produces the beams of sharply focus electrons.
- The electrons gun are placed inside the glass tube so that the electron beam did not interact with the air molecules.

MODULE 4

Theory Of micromachining

- Micromachining is the basic technology for fabrication of micro-components of size in the range of 1 to 500 µm.
- Their need arises from miniaturization of various devices in science and engineering, calling for ultra-precision manufacturing and micro-fabrication.
- Removal of material in the form of chips having the size in the range of microns.
- Creating micro features or surface characteristics (especially surface finish) in the micro/ Nano level.

WHY MICRO MACHINING?

- Final finishing operations in manufacturing of precise parts are always of concern owing to their most critical, labor intensive and least controllable nature.
- In the era of nanotechnology, deterministic high precision finishing methods are of utmost importance and are the need of present manufacturing scenario.
- The need for high precision in manufacturing was felt by manufacturers worldwide to improve interchangeability of components, improve quality control and longer wear/fatigue life.
- Present day High-tech Industries, Design requirements are stringent.
- Extraordinary Properties of Materials (High Strength, High heat Resistant, High hardness, Corrosion resistant etc.)

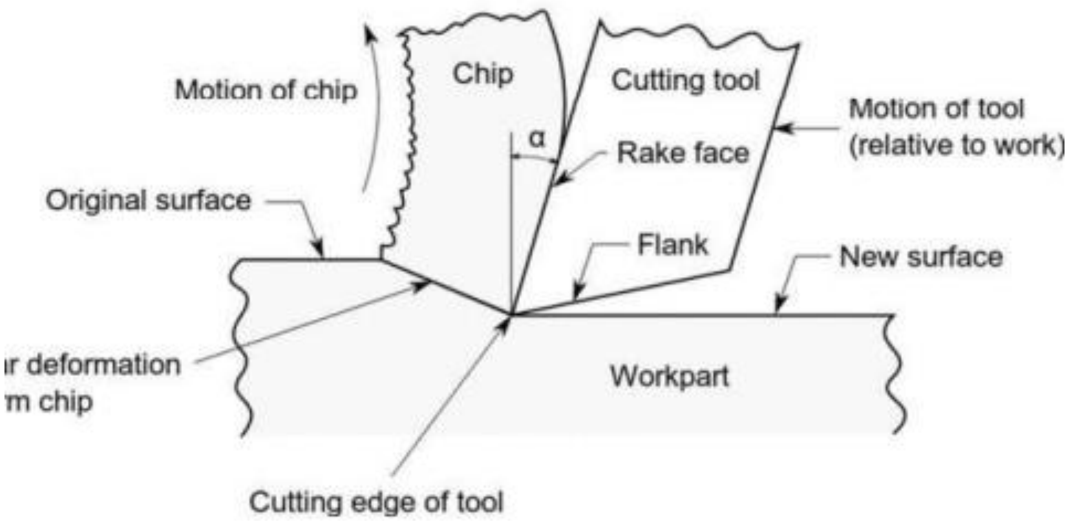
- Complex 3D Components (Turbine Blades)
- Miniature Features (filters for food processing and textile industries having few tens of microns as hole diameter and thousands in number)
- Nano level surface finish on Complex geometries (thousands of turbulated cooling holes in a turbine blade)
- Making and finishing of micro fluidic channels (in electrically conducting & non conducting materials, say glass, quartz, &ceramics)

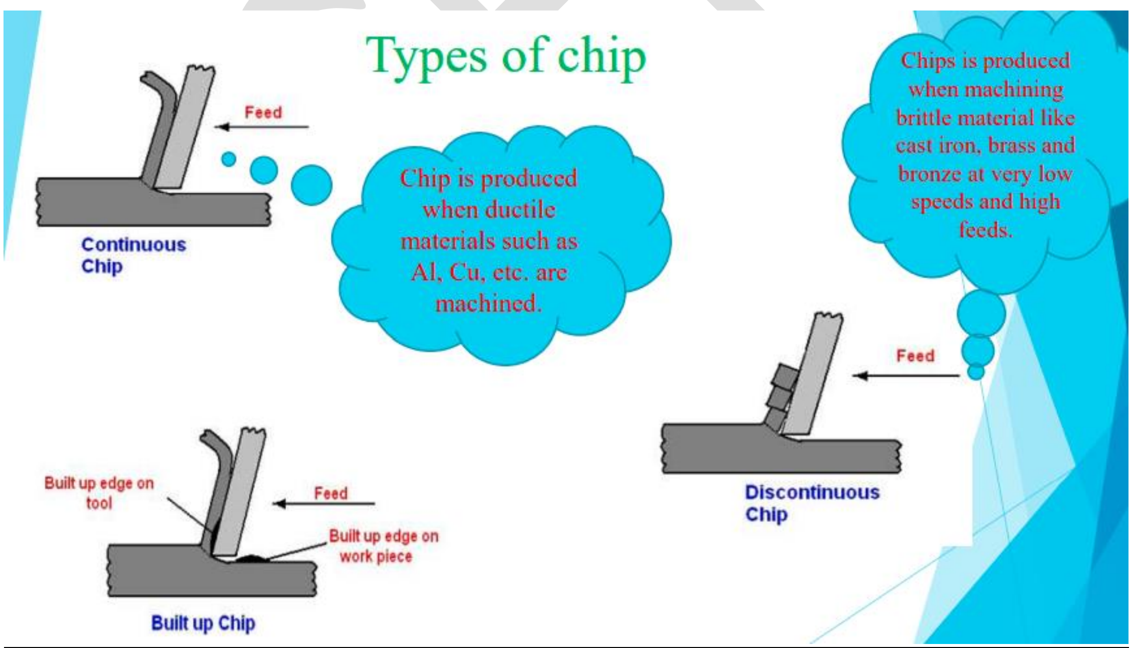
DIFFERENT MICROMACHINING TECHNIQUES

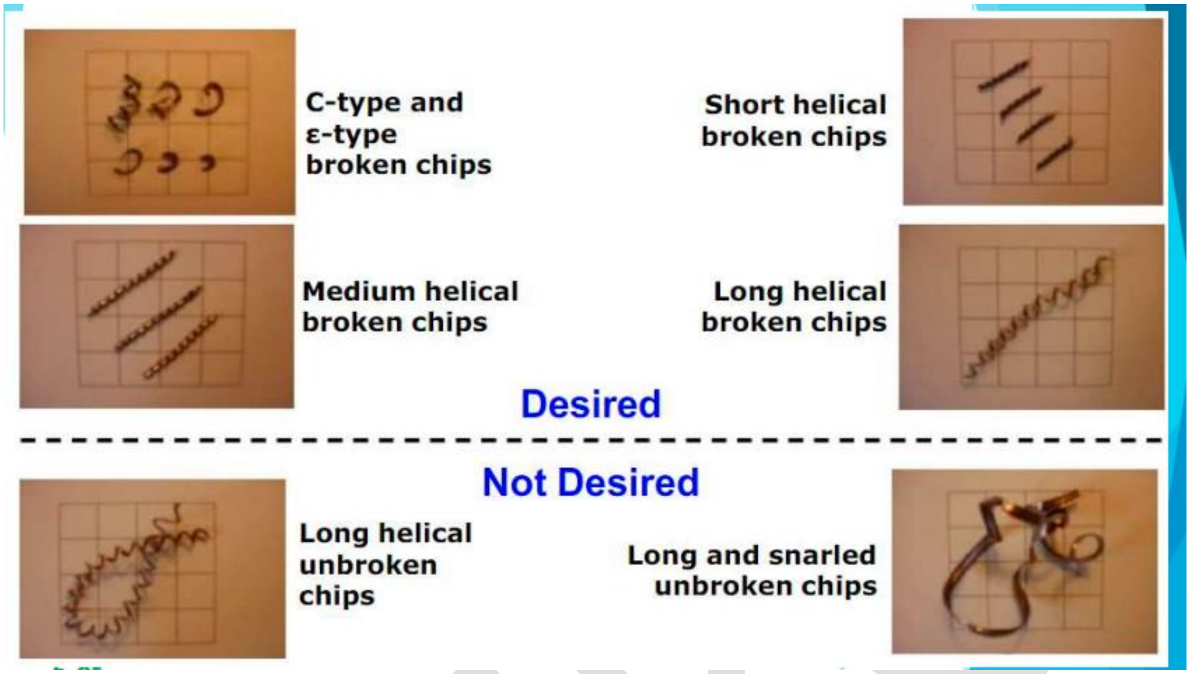
- Photolithography
- Etching
- Silicon Micromachining
- LIGA
- Mechanical Micromachining

CHIP FORMATION

- Chip formation is part of the process of cutting materials by mechanical means, using tools such as saws, lathes and milling cutters.
- An understanding of the theory and engineering of this formation is an important part of the development of such machines and their cutting tools.
- For all types of machining, including grinding, planing, turning, or milling, the phenomenon of chip formation is similar at the point where the tool meets the workpiece to remove the material as chip to reach the desired shape**.**


Chip
Cutting tool
Motion of chip
α
Rake face
Motion of tool
(relative to work)
Original surface
Flank
New surface
r deformation
m chip
Workpart
Cutting edge of tool


Types of chip
Feed
Continuous
Chip
Chip is produced when ductile materials such as Al, Cu, etc. are machined.
Chips is produced when machining brittle material like cast iron, brass and bronze at very low speeds and high feeds.
Feed
Discontinuous
Chip
Built up edge on tool
Feed
Built up edge on work piece
Built up Chip



Comparison between chip types

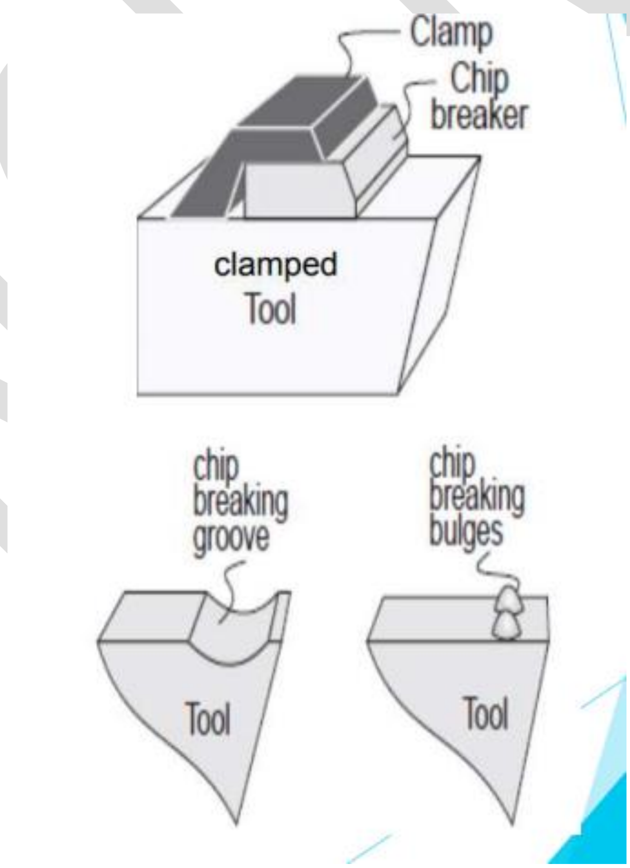
S. No.	Material type	Rack angle	Depth of cut	Cutting speed
Continuous Chips	Ductile	High	Small	High/medium
Discontinuous Chips	Brittle, Ductile but hard	Medium	High	Low
Continuous chips with built edge	Ductile	Low/Medium	Medium	Medium

CHIP CONTROL

- During machining high tensile strength materials chips has to be properly controlled.
- Carbide tip tools will be used for high speeds which leads to high temperature and produce continuous chips with blue color.
- There are two ways are employed to overcome all the previous drawbacks.
  1) Proper selection of cutting conditions.
  2) Chip breaker

Proper selection of cutting conditions

- Since the cutting speed influences to the great extend the productivity of machining and surface finish, working at low speeds may not be desirable.
- If the cutting speed is to be kept high, changing the feed and depth of cut is a reasonable solution for chip control.
- **External type, an inclined obstruction clamped to the tool face.**
- **Integral type, a groove ground into the tool face or bulges formed onto the tool face**



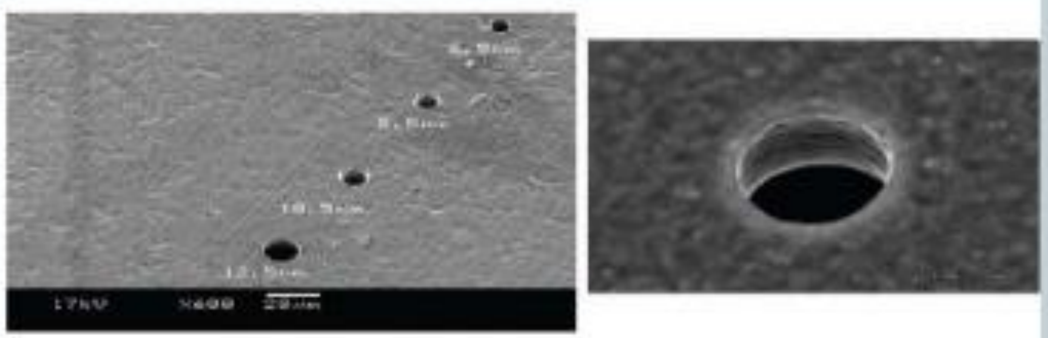
Conclusion

Discontinuous chips in ductile material give poor surface finish and slow machine. It is suitable form of chips of machining brittle material.

- Continuous chips are the most preferable type of chip due to following benefits:
  - It gives high surface finish of machining ductile material.
  - Due to low friction, friction loss minimize.
  - Due to low friction, tool life is high
  - Power consumption is low.

Micro Machining

- Removal of material at micron level.
- Macro/Micro or Nano components but material removal is at micro/nano level. (Ex. MEMS, NEMS).



6.5μm hole machined on 50μm stainless steel plate, probably the world's smallest hole with highest aspect ratio

Types of Micromachining Process

- There are two basic groups of micromachining process: mask based and tool based micromachining.
- The mask based technology has the limitations of fabricating 3D structures as it is applied only to two dimensional shapes.
- Processes using tools, especially those using solid tools, can specify the outlines of various 3D shapes owing to the clear border at the tool surface and the easily defined tool path.

Classification

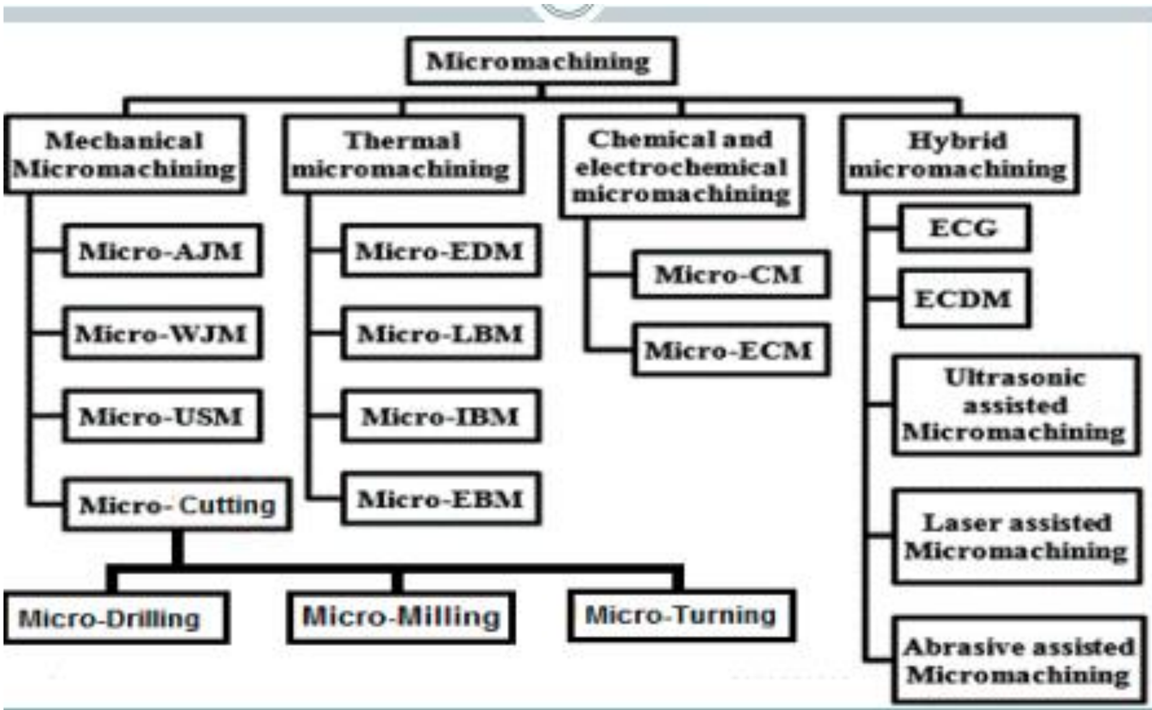
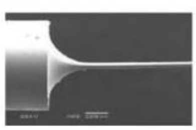
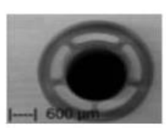
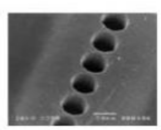
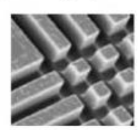


Table 1.2 Geometric characteristics of typical micro cutting operations

	Micro turning	Micro milling	Micro drilling	Micro grinding
Workpiece Shape	Rotational convex shape with large aspect ratio, such as micro shafts, micro pins, etc.	3D shape both convex and concave with high aspect ratios and high geometric complexity	Round holes through or blind	Hard and brittle materials; 3D convex and concave shape using micro grinding tips
				
Typical size	Down to ϕ5 μm, though 100 μm above more applicable	50 μm slots are practical applicable	ϕ50 μm holes are practical applicable	Micro structures down to 20 μm
Achievable surface roughness	0.1 μm Ra	Optical surface (<10 nm Ra) via diamond milling for non-ferrous materials	0.1 μm Ra	advantageous for brittle materials with optical surface finish (<10 nm Ra)

Micro Turning

- Micro turning is one of micromachining process which uses a solid tool and its material removal process to micron level in a turning operation.
- Used to create micro cylindrical or rotational symmetry parts by cutting away unwanted material.
- Requires a turning machine, work piece, fixture, and cutting tool.
- Bridges the gap between MEMS manufacturing and the capabilities of conventional machining.
- Material removal process is similar to conventional turning.
- Weather its Macro/Micro turning.!
- Range not exactly differentiated but mostly referred as: 0.5µm-999µm, Some reseachers suggest:
- 500µm-999µm J. Mc Geough,
- 0.5µm-499 µm Alberto Herrero

Fig. Shows example of simple micro pin

DRAWBACKS

- Turning micro parts can be difficult work.
- Secondary operations are often required for medical and aerospace parts.
- In addition to turning, this raises concerns about how to hold, mill, cross-drill, deburr and inspect the parts.
- Even finding the parts in the chip tray after cut off can be a challenge.

1.3.1 Micro Turning

Micro turning is an effective way to produce micro cylindrical or rotational symmetry components. Figure 1.5 shows examples of a simple micro pin with the diameter of 33µm. A micro part with the high aspect ratio can be achieved using the micro turning [23]. The most serious problem encountered during micro turning is the cutting force which tends to bend the workpiece, and the machining force influences machining accuracy and the limit of machinable size [24]. A detailed analysis on how size effect influences micro part rigidity and deflection is provided in Chapter 7. Micro turning is performed on either a conventional precision machine or a micro turning system.

Diamond turning of the micro structured surface can be regarded as another group of micro cutting. With the aid of fast tool servos (FTS), complex micro structured surfaces can be generated by diamond turning.

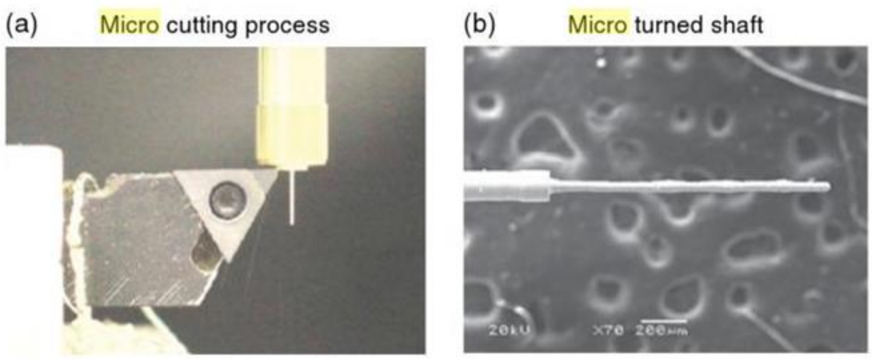
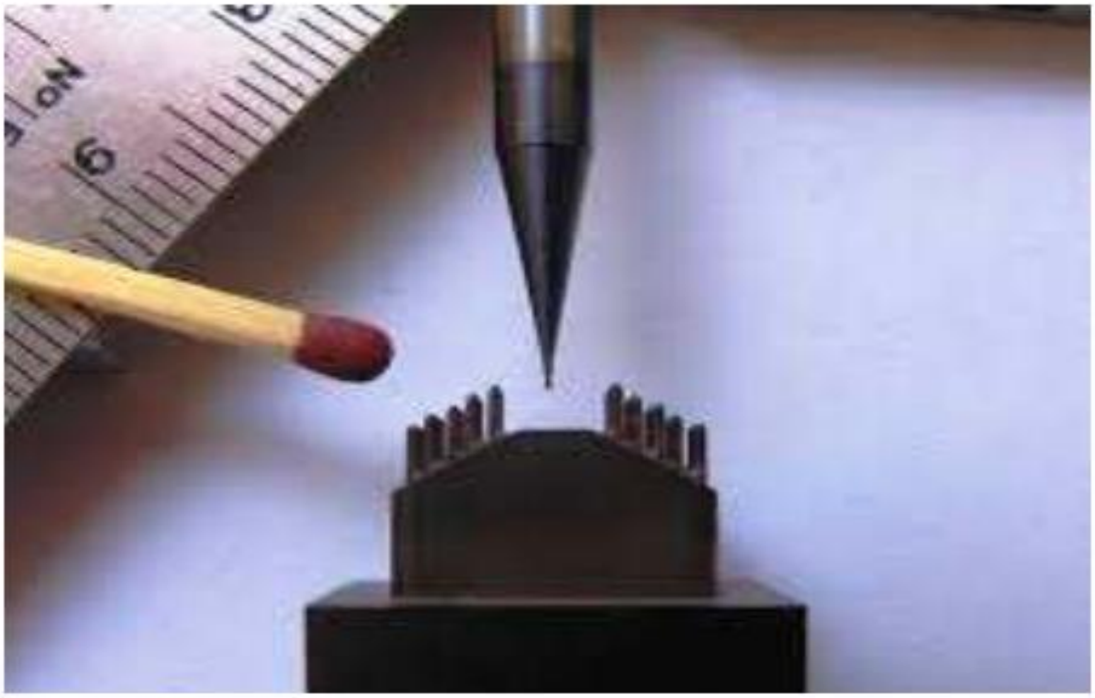


Figure 1.5 An example of micro-turned shaft (Reproduced from [23]). Reproduced with permission from [2]. Copyright 2007 Elsevier

Micro Milling



Micromachining capabilities					
	High Speed Milling	Sinker EDM	Wire EDM	X-ray Lithography	Ion Beam Machining
Minimum structure size (µm)	50	5 to 10	15-20	-	< 0.1
Surface finish Ra (µm)	1	0.2	0.05	-	0.04 to 0.15
Inner radius (µm)	50	< 10	~ 15	-	0.01
Aspect ratio	100-150	~ 20	100-150	100	10
Drawback	Heat fracture	Slow removal rates	Through shapes only	Learning curve to moldmakers	Learning curve to moldmakers

Table 4.2. *Listing of micromachining techniques and their capabilities in comparison to high-speed milling (HSM)*

- Complex 3-D mold cavities, chemical micro-reactors, fluidic parts, flow passages for micro compact heat exchangers, Lithography method complement.

- Micro-column arrays can be produced.
- Single crystal diamond – CER of 50nm- non ferrous – Brass, Al, Cu, electro less nickel.
- Tungsten Carbide tools – small CER – Rz
- This method allows us to produce V-shaped grooves with high shape accuracy without burrs and surface roughness of 48 nm (Rz).

Micro mills and tooling systems

- **Diamond tools – limited to non-ferrous**
- **Tungsten Carbide tool – grain size smaller than 600 nm.**

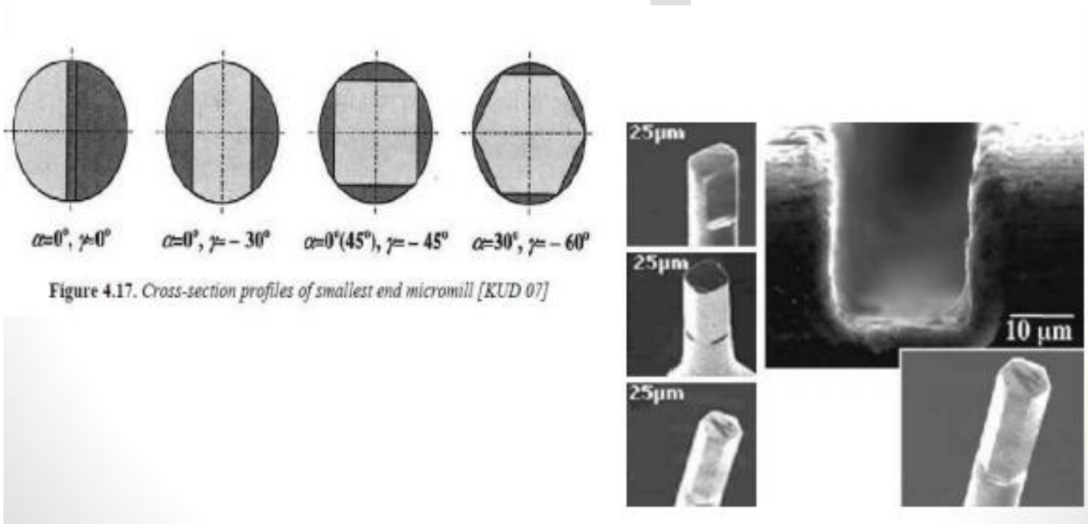
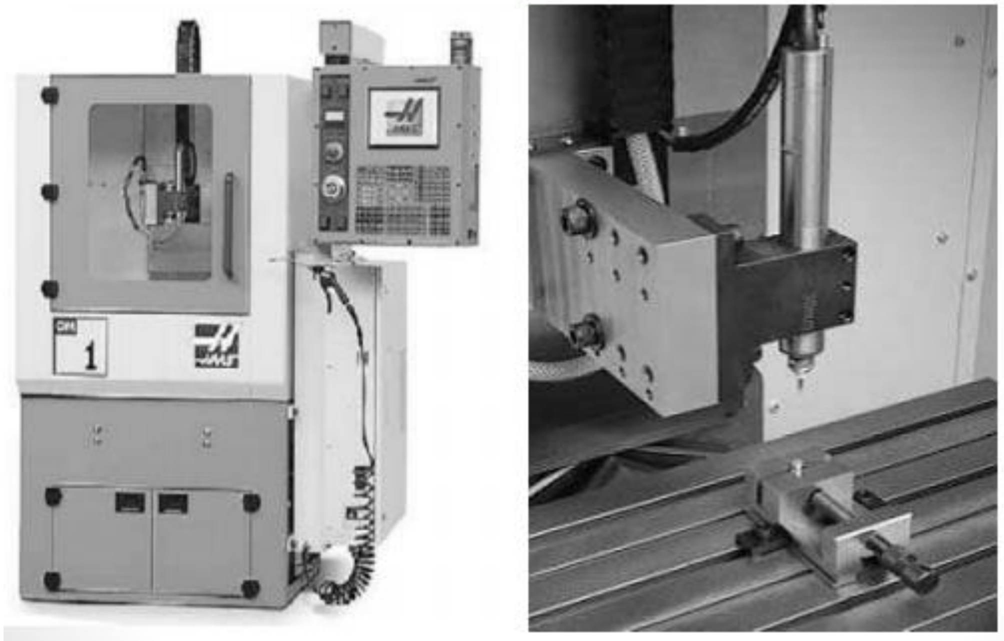


Figure 4.17. *Cross-section profiles of smallest end micromill [KUD 07]*

Machine Tools for Micro milling

- High speed machining
- 40,000 to 50,000 rpm – CAM programming.
- Stable Spindle – minimize vibration and thermal expansion.- small vibrations are amplified relative to tool diameter as it is reduced.
- CNC automated milling center – Ultra compact CNC mill.
- Direct change type spindle.
- Smart Machines – CNC operated.



1.3.2 Micro Milling

Micro milling is an emerging technology and is the most flexible and versatile micro cutting process. It is able to generate a wide variety of complex micro components and micro structures. In the past decade significant research has been carried out in micro milling modelling and experiments. Most of the micro components shown in Figure 1.3 were machined using micro milling technology.

Micro tooling is crucial to micro milling as it determines the feature size and also the surface roughness. Commercially available micro milling tools have the tool diameter ranging from 25–1,000 µm. Due to the limited rigidity of small diameter tools and difficulty in fabricating a micro tool, most of the micro milling tools have only two flutes, and some very small diameter tools (<100 µm), especially made from natural diamond or CVD, have only single flute or spade type tools. In terms of types of milling operations, micro end milling using either flat end or ball-nosed end mills dominates micro milling applications, and peripheral milling in macro milling is uncommon for micro milling. One of the challenges in micro milling is premature tool chipping and breakage. There are limited choices for micro tool fabrication. Coated micro grain tungsten carbide tools are widely employed, and natural

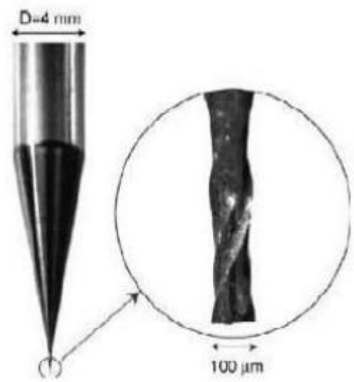
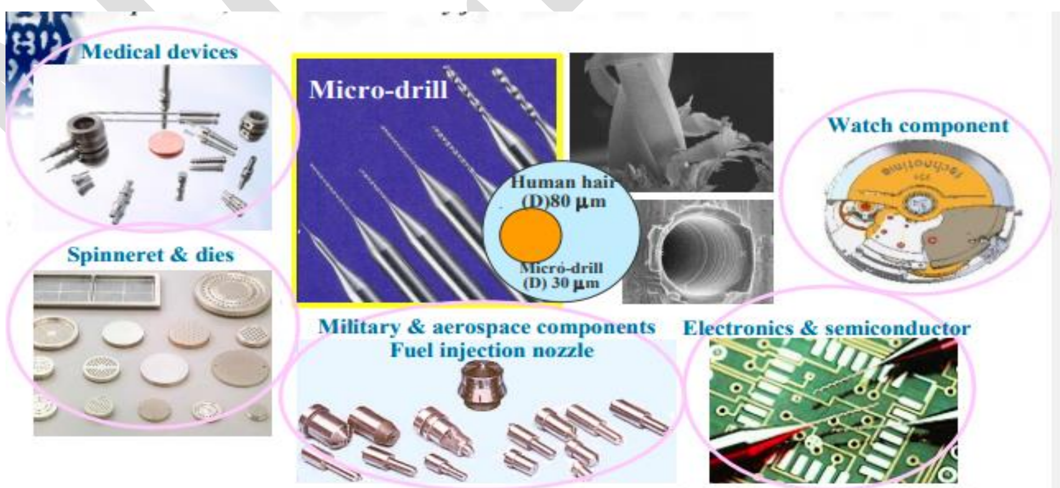


Figure 4.19. *Tungsten carbide micro-endmill with two flutes [FLE 04]*

Micro-drilling

- Micro-drilling is regarded as useful process technology to make tiny holes and widely used at electronic, semiconductor, medical, fuel injection, watch, spinneret, dies related industry fields.
- It became a common understanding that it is necessary for machining tiny holes smaller than 100 µm in diameter to apply the laser systems .
- However, it is also true that laser systems have several disadvantages compared to conventional mechanical drilling.
- And the mechanical system could be competitive against the laser system, if they can have micro drilling capabilities.

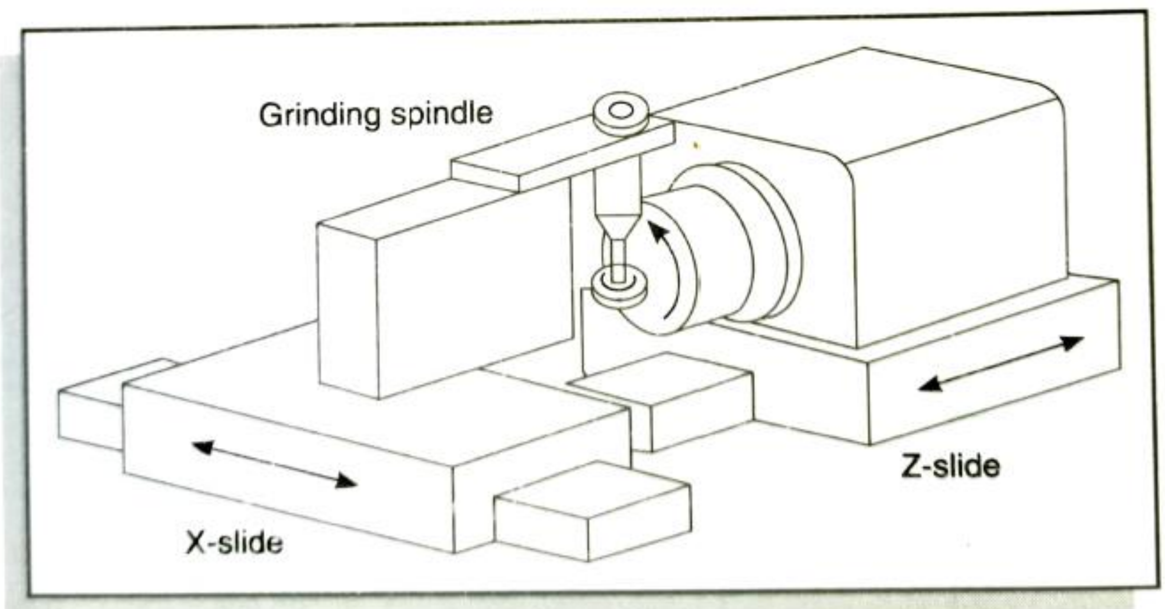


- Thus, many manufacturers have been making efforts to retry the traditional mechanical precision drilling machine for machining tiny holes with high productivity.
- Recently, creative precision has complete micro hole drilling capabilities for holes down to 30 µm in diameter

- But conventional micro-drilling has also several problems such as excessive forces, tool breakage, chatter, burr formation in metals.

PRECISION GRINDING

- Precision grinding ranks in between diamond turning and polishing in many respects.
- In this, a set of machine tool motions is controlled. Compared to diamond turning. The position of the cutting edge of the tool is less certain.
- Grinding wheels tend to be compliant and can get worn off which makes it more difficult to achieve the desired form accuracy compared with diamond turning.
- Besides these disadvantages there are some notable advantages of precision grinding over diamond turning.



- For small wheels and depth of cut, it can be used to work on brittle materials such as ceramics and glass in a ductile fashion (chip removal by ductile shearing of material)
- In some cases the surface finish obtained with precision grinding is so good that polishing is unnecessary.
- The grinding process has the advantage over polishing of having higher removal rates and the ability to remove vastly different amounts of material from small areas.
- Thus, the grinding operation is particularly suited to produce especially small complex shapes in materials that cannot be diamond turned.

GRINDING WHEEL

- Grinding wheels are made of two materials, abrasive grains and a bonding material.
- They are produced by mixing the appropriate grain size of the abrasive with the required bonding material and pressed into shape.
- The abrasive grains do the actual cutting, and the bonding material holds the grains

together and supports them while they cut.

- The cutting action of a grinding wheel is dependent on the bonding material, the abrasive type, grain size (grit size), wheel grade and the wheel structure.
- Selection of the right combination of these features is therefore essential for obtaining an optimum solution for different grinding tasks.

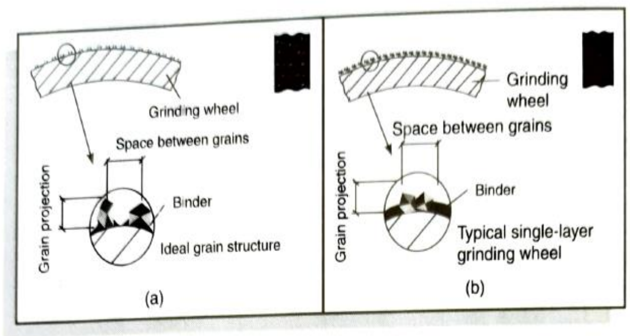


Fig. 4.4: Schematic diagrams showing (a) the ideal grain structure with a controlled grain spacing and projection height and (b) a typical single-layer grinding wheel with random grain spacing and projection height [21].

-

1 .Bonding Materials

- Bonds are usually formed using different types of raw materials and are basically classified as follows
- vitrified materials (ceramics consist of glass, feldspar or clay)
- resinoid materials (thermoset plastics phenol formaldehyde resin)
- rubber (both natural and synthetic)
- shellac
- Metal (sintered powdered metals and electroplated -bronze, nickel aluminum alloys, zinc.
- oxychloride (chemical action of magnesium chloride and manganese)
- silicate (sodium silicate NaSiO, or water glass)
- no bond (bondless)

2. Abrasive Types

- Abrasive grains used for grinding wheels are very hard, highly refractory materials and are randomly oriented.
- Although brittle, these materials can withstand very high temperatures. They have the ability to fracture into smaller pieces when the cutting force increases.
- This phenomenon gives these abrasives a self-sharpening effect. Four types of abrasives commonly used are as follows:
- Aluminium oxide or alumina (AI,O

- Silicon carbide (SiC)
- Cubic Boron Nitride (CBN)
- Diamond
- Tungsten carbide (WC)

3. Grit Size

- The size of an abrasive grain is identified by a number, which is normally a function of the mesh width of the sieve size either in microns or mesh openings per inch.

4. Grade

- The grade of a grinding wheel refers to its strength in holding the abrasive grains in the wheel.
- This is largely dependent on the amount of bonding material used.
- As the amount of bonding material is increased, the linking structure between the grains become larger which makes the wheel act harder.

5. Structure

- The structure of a grinding wheel represents the grain spacing and is a measure of the porosity of a bonded abrasive wheel.
- Porosity allows clearance space for the grinding chips to be removed for a proper cutting action during grinding operation.
- If this clearance space is too small, the chip will remain in the wheel, causing what is known as wheel loading.
- A loading cutting wheel heats up and is not efficient in the cutting action. When this happens, a frequent dressing is needed to remove loaded workpiece particles on the wheel.
- On the other hand, it is inefficient to have too large a space, as there will be too few cutting edges.

Bondless/Binderless Diamond Grinding Wheel

- The wheel is produced by depositing diamond on a metal, commonly a carbide substrate.
- Three types of wheels can be found based on the type of the deposition method applied.
- Unlike a bonded wheel, the diamond layer's only on the top of the substrate surface and can be of a very fine grain size, whereas the smallest grain in bonded wheels must be larger than that of the bond.

- The maximum grain size can go up to 10 um. However, it has a higher density than diamond grains.
- Three types of wheels can be found based on the type of the deposition method applied.
  1) Thermally treated wheel
  2) chemically treated wheel
  3) Chemically treated wheel with cauliflower like facelets

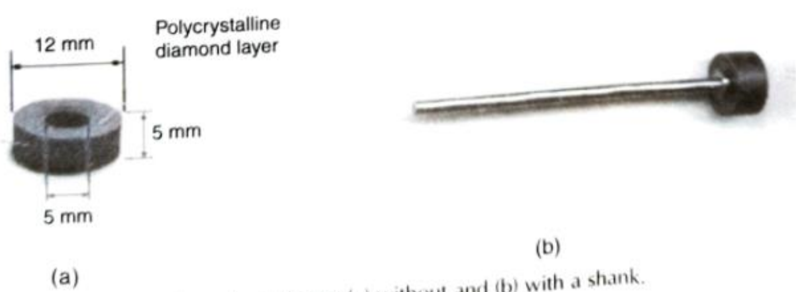
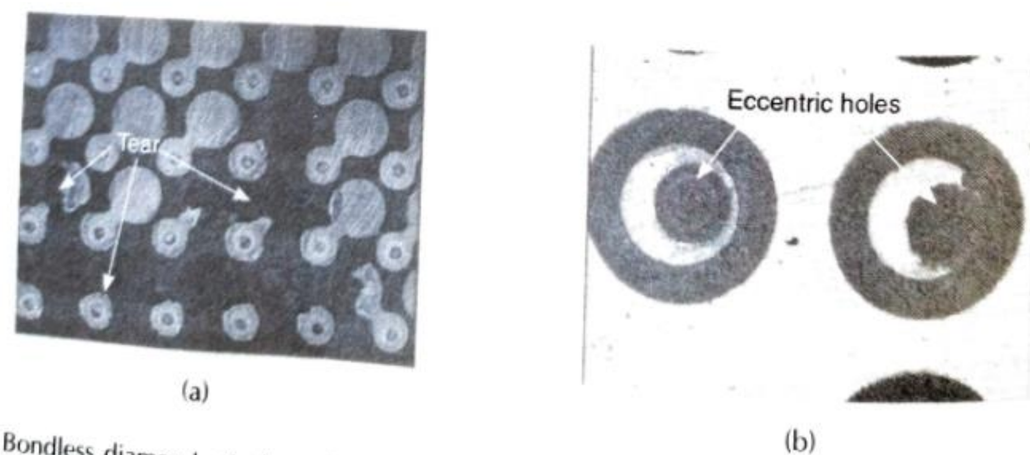


Fig. 4.9: A bondless diamond grinding wheel shown (a) without and (b) with a shank.



4.12: Bondless diamond grinding of chip packaging on the Pentium III IC chip revealing defects such as (a) tear of Cu pads and (b) eccentric viaducts [28].

- The invention of this bondless diamond grinding wheel has made the machining of the silicon die and the chip packing much easier and more economical.
- It has the potential of grinding glass and infrared optical materials, Si and Ge.

Advances in Precision Grinding 155

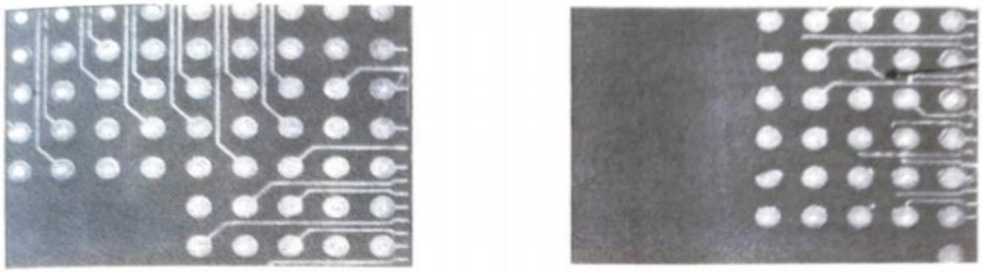
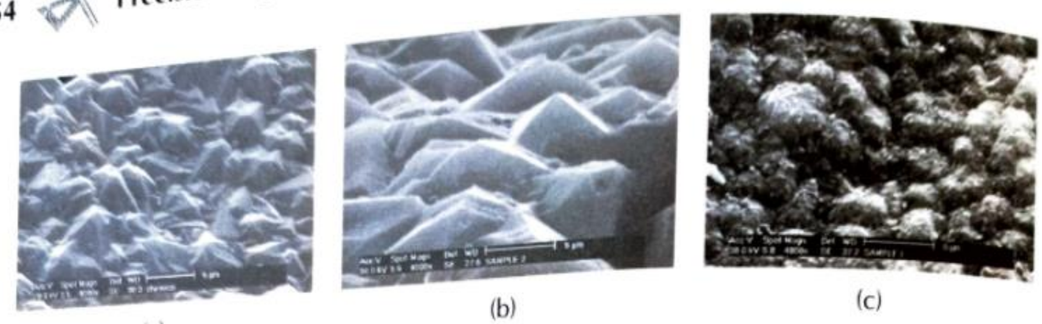


Fig. 4.13: Binderless diamond grinding of chip packaging showing a near perfect fifth layer with an open circuit at one end in the lower picture [29].

154 Precision Engineering



(a) (b) (c)

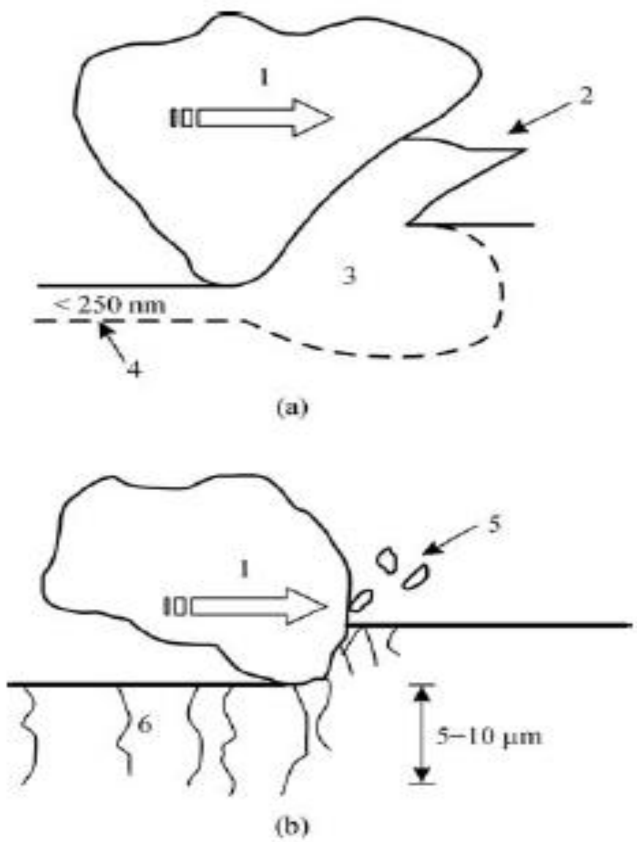
Fig. 4.10: SEM micrographs of the bondless diamond wheel surface: (a) a thermally treated wheel, (b) a chemically treated wheel and (c) a chemically treated wheel with cauliflower-like facets [27].

<u>Ductile mode grinding</u>

- Brittle material like glass, silicon, tungsten carbide (WC),germanium and silicon nitride have been widely employed in the industries such as precision engineering, optics, instruments, semi-conductor and micro-electromechanical systems (MEMS) because of its excellent mechanical optical, physical and chemical properties.
- Traditionally ,abrasive processes such as grinding, lapping and polishing have been widely used for the final surface finishing of these brittle materials.
- Furthermore, the abrasive processes will cause surface flatness deviation due to its uncontrollable material removal resulting in the machined profile inaccuracy.
- Therefore, after grinding and lapping processes, the chemical-mechanical polishing (CMP) is essential to remove the subsurface damage layer caused by the hard abrasive particles, which makes a very costly production.
- In ductile materials, generally the material removal occurs by plastic flow of material

in the form of severely sheared machining chips.

- But in brittle materials, initially median and lateral cracks are developed. The final material removal occurs through the propagation and intersection of cracks.
- Due to this crack generation, the machining in brittle materials results in poor surface finish and loss of surface integrity.
- This becomes a major drawback for components used in applications requiring a high degree of precision.
- Therefore to meet these challenges, a new mode of machining called ductile mode of machining is required to be developed to machine these brittle materials satisfactorily.
- Also called as partial ductile mode or ductile regime machining, these process involve the material removal through plastic deformation as compared to the crack formation and propagation in conventional machining of brittle materials.
- This method can be applied to many traditional machining processes like grinding, turning, drilling etc., thereby increasing the scope of applications.
- A conclusion that this mode of machining is fast and economical is made and when applied for the manufacture of aspherical glass lenses, the method proved to be very economical.
- As a result, the subsequent polishing process is no longer necessary
- the polishing time can largely reduced because the crack-free surfaces can be directly produced by DMC without sub surface damage
- Even though the subsurface damage layer thickness being much smaller, which would significantly reduce the manufacturing time and cost for brittle materials.
- This advantage cannot be under addressed because in machining even a minor improvement in productivity would lead to a major impact in mass production.



Schematic diagrams of two cutting modes for brittle materials

(a) DMC by removing a ductile metallized layer resulted from the large contact pressure in cutting region;

(b) BMC by material fracture leaving subsurface damages, of which the subsurface damage is as deep as 5–10 µm due to crack propagations in machining of silicon.

Mechanism and Factors involved in ductile mode machining

- There are a number of factors which result in the high hardness of the brittle materials which is t he main reason for the difficulty to machine.
- Generally brittle materials are characterized mostly by covalent bond which has a higher thermal conductivity and a low coefficient of thermal expansion.
- The ratio of covalent bonding to ionic bonding in brittle materials is very high resulting

in higher hardness and lower values of Young's Modulus.

- But in ductile material hardness is low and they have higher Young's Modulus. These factors can be attributed to low density, low mobility of dislocations, large inter atomic distances and low surface energy.
- The **material removal** energy can become the main consideration involved in the transition of brittle to ductile material removal at smaller depth of cuts.
- Plastic flow is energetically more favorable than fracture for smaller depth of cuts.
- Ductile chips are controlled by depth of cuts. There exists a critical **depth of cut** which marks the transition from ductile to brittle machining.
- In ductile mode machining, the critical depth of cut is around 50 nm to 1 micro m.
- When the depth of cut employed in the machining process is less than the critical depth of cut, then the material removal can occur through plastic flow rather than by fracture.

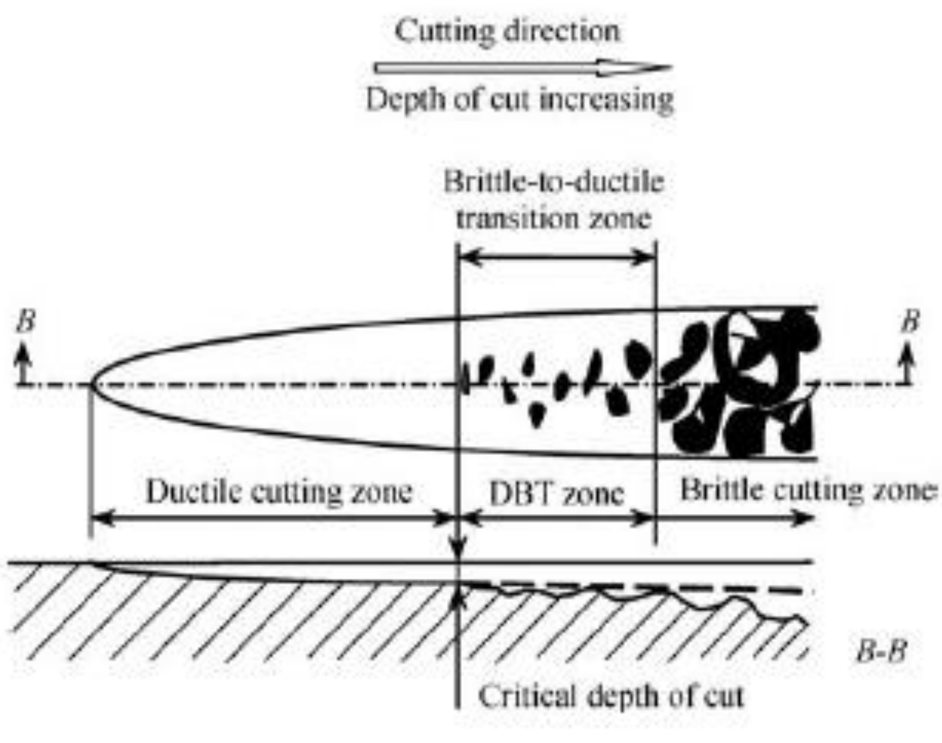


Fig. 3 Schematic diagram illustrated brittle-ductile transition in grooving [31]

•

- Another factor impacting the transition from brittle to ductile mechanism while machining is the **size of the indenter**.
- While the indenter size has no impact on the plastic flow while machining in ductile mode, this becomes an important factor for brittle machining.
- A large tip size produces a cone crack and a small size results in plastic deformation while applied with less pressure.
- Ductile mode cutting thus became an alternative way for finishing of brittle materials as it could produce crack-free mirror surface finish at a much higher efficiency and lower cost than polishing processes owing to its high material removal rate.
- **Ductility** of a material is defined as the material's ability to undergo permanent deformation through elongation (area reduction in the cross section) or bending without fracturing
- While **plasticity** is defined as the material's deformation, which undergoes non-reversible changes of shape in response to applied forces and/or loading.
- All materials exhibit the ductile nature no matter how brittle they are, save for the fact that the extent of ductility or plasticity varies for different materials
- In evaluating the ductility of a material, an indentation test has been most employed in tandem with other processes such as scratching and grinding.
- It has been reported that fully ductile mode surfaces with nonmetric finish are possible when using this kind of machine but at the expense of time and cost as the feed rate and depth of cut used are very fine.
- Bulk material removal is hardly possible using ultraprecision machines; therefore this process becomes less favorable for generating complex surfaces.
- As such, grinding process continues to be the most viable method for generating complex surfaces like aspheric, spheres and tonics.
- Studies have shown that fully ductile mode machining was not possible with diamond grinding due to difficulty to control grain depth of cut as the protrusion height of diamond grits are randomly distributed all over the wheel surface.
- Instead, **partial ductile mode machining** is feasible where minimum post-machining process is required if abundant ductile streaks are present.

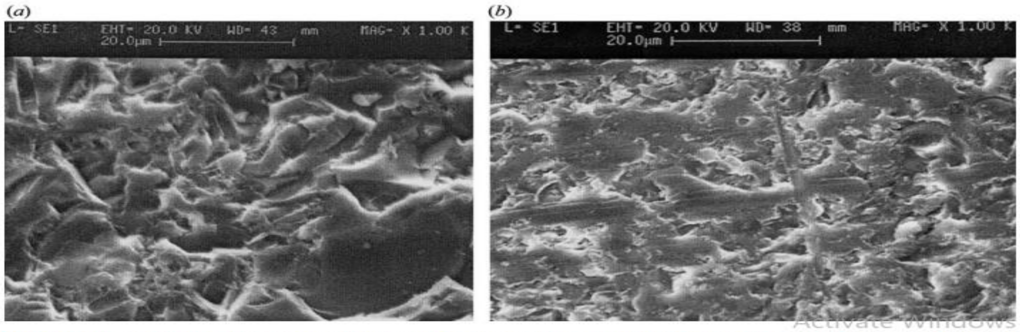


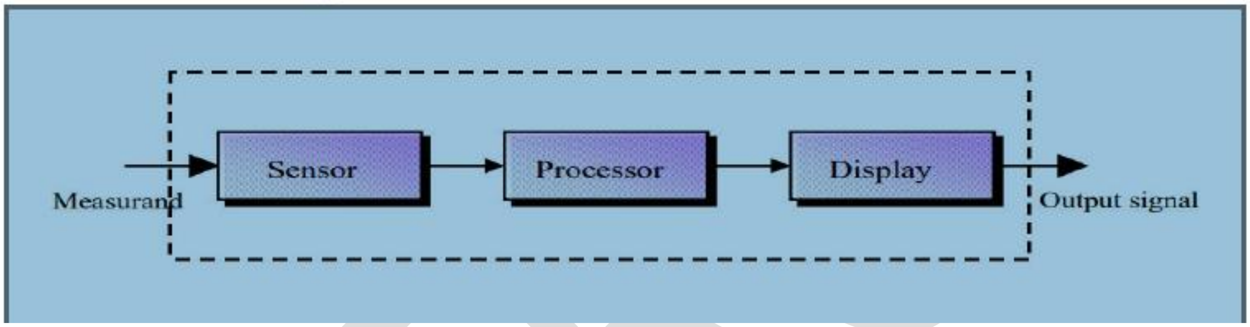
Fig. 3. SEM pictures of spherical glass surfaces machined (*a*) by conventional grinding showing a 100% fractured surface, and (*b*) by optimal lapping showing a partial ductile mode machined surface.

- Manufacture of spherical glass lenses by fracture mode or partial ductile mode grinding followed by partial ductile mode.
- Lapping and ductile mode polishing is fast and economical.
- Reduced polishing time and improved surface quality are due to the presence of ductile streaks.
- Using partial ductile mode grinding and ductile mode polishing has been very successful for manufacturing aspherical glass lenses.
- Again, an increase in ductile streaks helps to reduce polishing time and improve surface quality.
- Partial ductile grinding and lapping obtained by using conventional machines and commercial tools works well for the ophthalmic industry, and results in reduced manufacturing costs.

MODULE 5

MICROSENSORS

- Rapid advance in the field of micro fabrication Technologies has enabled many new MEMS products to emerge in the market place.
- Micro sensors are the most widely used MEMS device today.
- Micro sensors are used to measure many physical quantities.
- Device that converts a non-electrical physical or chemical quantity into an electrical signal



- **A smart sensor** unit would include automatic calibration, interference signal reduction, and compensation for parasitic effect, offset correction and self-test.
- All the intelligent function make this sensors unit as an intelligent microsystems.

Trends in sensor technology

Miniaturization

- Integration (sensor, signal processing and actuator)
- Sensor with signal processing circuits for linearizing sensor output, etc.
- Sensor with built-in actuator for automatic calibration, change of sensitivity etc.
- Sensor arrays
- one-function units (to improve reliability)
- Multiple-function units

- **Applications**

Automotive industry

- average electronics content of a car is today 20%
- to increase safety (air bag control, ABS), reduce fuel consumption and pollution

Medical applications

- measurement of physical/chemical parameters of blood (temperature, pressure, pH)
- integrated sensors in catheters

Consumer electronics

- **Environmental applications**
- Determination of concentration of substances (carbon monoxide, heavy metals, etc.)
- Food industry
- contaminants and impurities

Process industry

Robotics

- distance, acceleration, force, pressure, temperature

Acoustic Wave SensorS

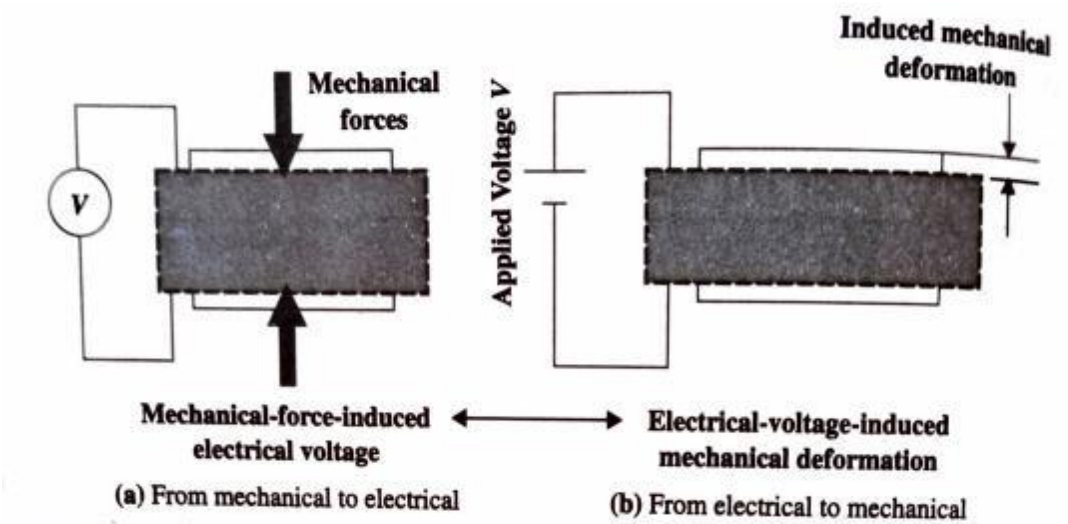
- The principal application of an acoustic wave sensor is to measure the chemical composition in a gas.
- In the simplest configuration, a device will consist of a piezoelectric material sandwiched between two metallic electrodes. The natural frequency of the material and the thickness are used as design parameters to obtain a desired operating frequency.
- The sensor generate acoustic waves by converting mechanical energy to electrical.
- Acoustic wave device also used to actuate fluid flow in microfluidic systems.

Actuation energy of this type of sensor is provided by two principle mechanisms.

  - Piezo-electrical
  - Magnetostrictive

- One of the most commonly used non semiconducting materials in MEMS and microsystems is piezoelectric crystals.
- Piezoelectric crystals are the solids of ceramic compounds that can produce a voltage when a mechanical force is applied between their faces.
- The reverse situation, that is the application of voltage to the crystal, can change its shape. This conversion of mechanical energy to electronic signals
- This unique material behavior is called as the piezoelectric effect.

- This effect exists in a number of natural crystals such as quartz, tourmaline, and sodium potassium tartrate, and quartz has been used in electromechanical transducers for many years.
- For a crystal l to exhibit the piezoelectric effect, its structure should have no center of symmetry. A stress applied to such a crystal will alter the separation between positive and negative charge sites in each elementary cell, leading to a net polarization at the crystal surface.
- The most common use of the piezoelectric effect is for high voltage generation through the application of high compressive stress.
- It can also be used to send signals for depth detection in sonar systems.



(From Kasap [1997].)

The effectiveness of the conversion of mechanical to electrical energy and ersa can be assessed by the electromechanical conversion factor K, define ollows [Kasop 1997]:

$$K^2 = \frac{\text{output of mechanical energy}}{\text{input of electrical energy}} \qquad (7$$

or

$$K^2 = \frac{\text{output of electrical energy}}{\text{input of mechanical energy}} \qquad (7.$$

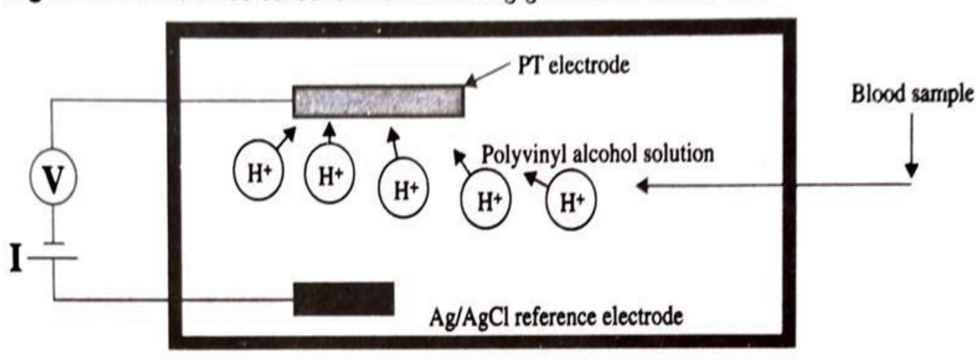
BIOMEDICAL SENSORS AND BIOSENSORS

- Micro sensors constitute the most fundamental element in any bio MEMS product.
- There are generally two types of sensors used in biomedicine:
    - **Biomedical sensors**
    - **Biosensors**
- Biomedical sensors are used to detect biological substances
- Biosensors may be broadly defined as any measuring devices that contain a biological element.
- These sensors usually involve biological molecules such as antibodies or enzymes, which interact with analyses that are to be detected.

<u>Biomedical Sensors</u>

- Biomedical sensors can be classified as biomedical instruments that are used to measure biological substances as well as for medical diagnosis purposes.
- These sensors can analyze biological samples in quick and accurate ways.
- These miniaturized biomedical sensors have many advantages over the traditional instruments.
- They require typically a minute amount of samples and can perform analyses much faster with virtually no dead volume. There are many different types of biomedical sensors in the marketplace.
- Electrochemical sensors work on the principle that certain biological substances, such as glucose in human blood, can release certain elements by chemical reaction.
- These elements can alter the electricity flow pattern in the sensor, which can be readily detected.

Figure 2.1 I A biomedical sensor for measuring glucose concentration.



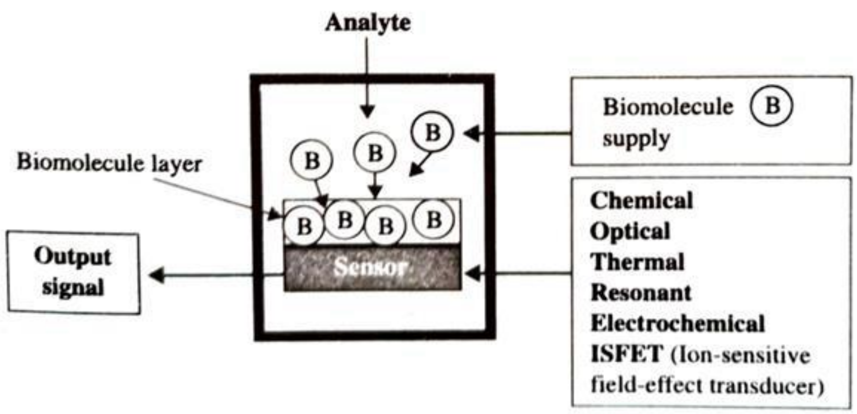
- A small sample of blood is introduced to a sensor with a polyvinyl alcohol solution.
- Two electrodes are present in the sensor: a platinum film electrode and a thin Ag/AgCIfilm (the reference electrode).The following chemical reaction
- Glucose + 02-----> gluconolactone + H20

- The H2O, produced by this chemical reaction is electrolyzed by applying a potential to the platinum electrode, with production of positive hydrogen ions, which will flow toward this electrode.
- The amount of glucose concentration in the blood sample can thus be measured by measuring the current flow between the electrodes.

Biosensors

- Biosensors work on the principle of the interaction of the analytes that need to be detected with biologically derived biomolecules, such as enzymes of certain forms, antibodies, and other forms of protein.
- These biomolecules, when attached to the sensing elements, can alter the output signals of the sensors when they interact with the analyte.
- Proper selection of biomolecules for sensing elements (chemical, optical, etc., as indicated in the right box in the figure) can be used for the detection of specific analyte.

Figure 2.2 I Schematic of biosensors.



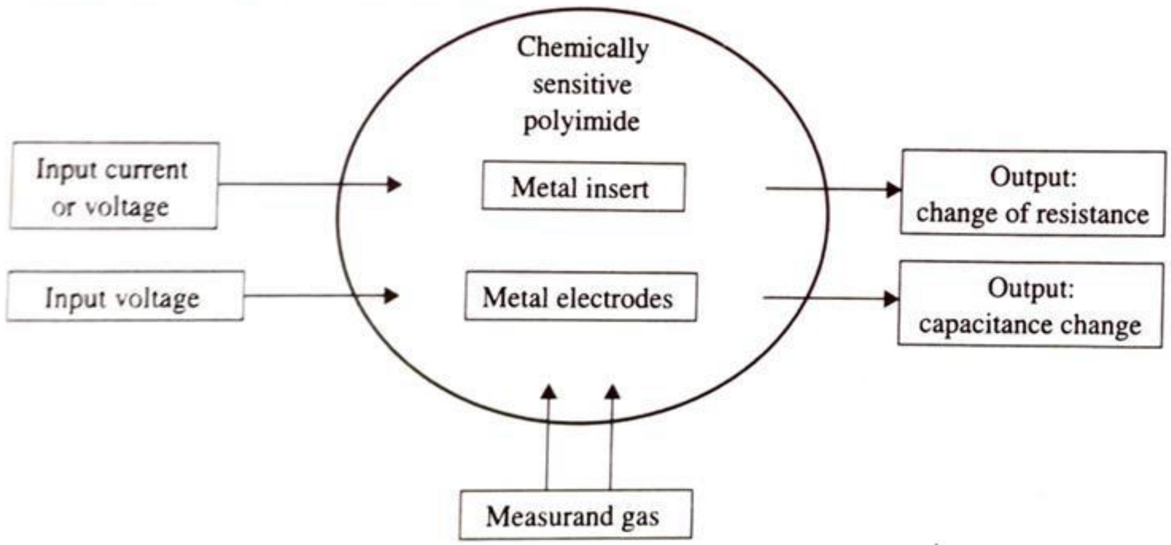
CHEMICAL SENSORS

- Chemical sensors are used to sense particular chemical compounds, such as various gas species.
- The working principle of this type of sensor actually is very simple. As we may observe from our day-to-day lives, many materials are sensitive to chemical attacks.
- For example, most metals are vulnerable to oxidation when exposed to air for a long time.
- Significant oxide layer built up over the metal surface can change material properties such as the electrical resistance of the metal.
- This natural phenomenon illustrates the principle on which many micro chemical sensors are designed and developed.
- Materials' sensitivity to specific chemicals is indeed used as the basic principle for many chemical sensors. Following are four typical cases worth mentioning.

1) Chemiresistorsensors. In Figure 2.4, organic polymers are used with embedded metal inserts. These polymers can cause changes in the electric conductivity of metal when it is exposed to certain gases.

2) Chemicapacitor sensors. Also in Figure 2.4, some polymers can be used as the dielectric material in a capacitor. The exposure of these polymers to certain gases can alter the dielectric constant of the material, which in turn changes the capacitance between the metal electrodes.

Figure 2.4 | Working principle of chemical sensors.



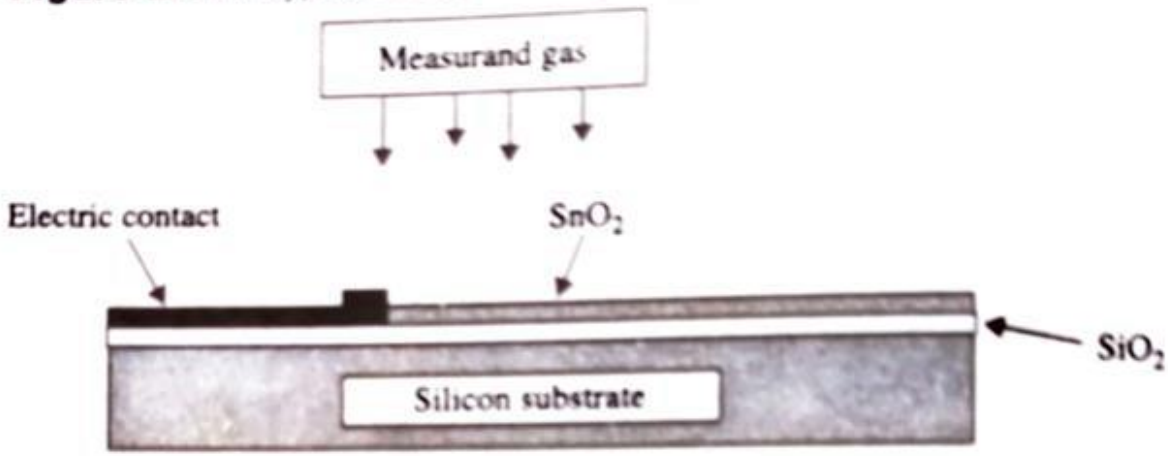
3) C**hemi-mechanical sensors**.

- There are certain materials, e.g. polymers, that change shape when they are exposed to chemicals (including moisture).may detects such chemicals by measuring the change of the dimensions of the material.

4) metal oxide sensors:

- This type of sensor works on a principle similar to that of chemiresistor sensors. Several semiconducting metals, such as SnO2.change their electric resistance after absorbing certain gases.
- The process is faster when heat is applied to enhance the reactivity of the measured gases and the transduction semiconducting metals.

Figure 2.5 | A typical metal oxide gas sensor

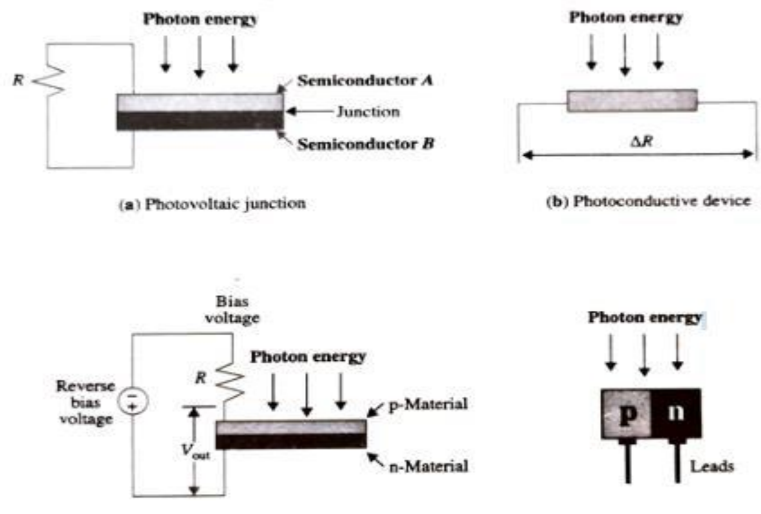


(After Kovacs [1998])

OPTICAL SENSORS

- A Device that can convert optical signals into electronic output have been developed and utilized in many consumer products such as television.
- Micro-optical sensors have been developed to sense the intensity of light. Solid-state materials that provide strong photon-electron interactions are used as the sensing materials.
- The **photovoltaic junction** in Figure 2.6a can produce an electric potential when the more transparent substrate of semiconductor A is subjected to incident photon energy. The produced voltage can be measured from the change of electrical resistance in the circuit by an electrical bridge circuit.

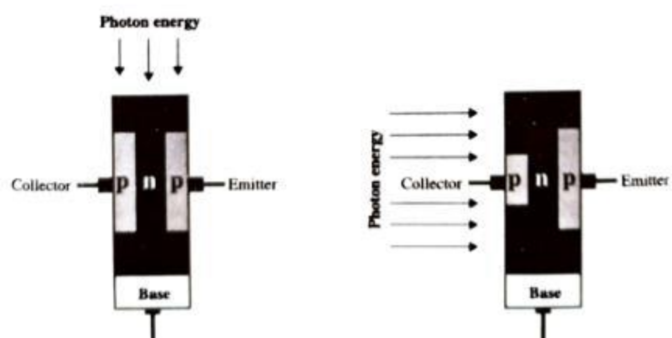
Figure 2.6 | Optical sensing devices



(c) Photodiodes

- Figure 2.6 b illustrates a special material that changes its electrical resistance when it is exposed to light.
- The photodiodes in Figure 2.6 c are made of p-and n-doped semiconductor layers.
- The phototransistors in Figure 2.6 d are made up of p-, n-, and p-doped layers. As illustrated in these figures, incident photon energy can be converted into electric current output from these devices.
- All the devices illustrated in Figure 2.6 can be miniaturized in size and have extremely short response time in generating electrical signals. They are excellent candidates for micro-optical sensors.

(c) Photodiodes

- 

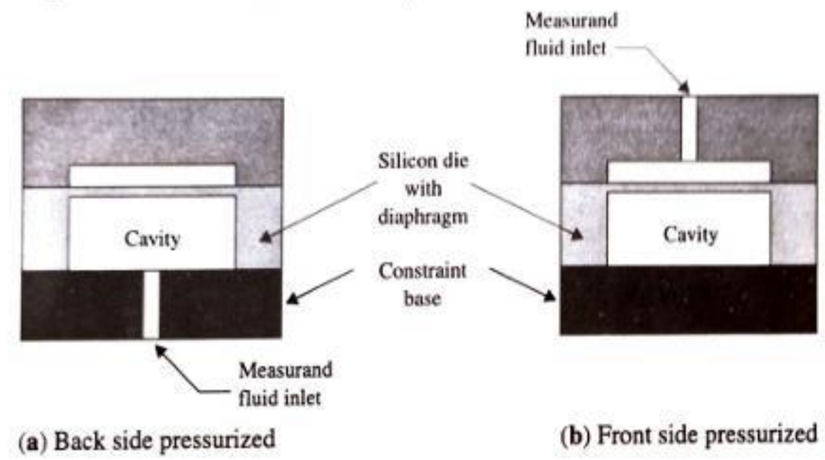
(d) Phototransistors

PRESSURE SENSOR

- Micro pressure sensors are widely used in automotive and aerospace industries. **Most these sensors function on the principle of mechanical de-formation and stresses of thin diaphragms induced by the measure and pressure**.
- Mechanically induced diaphragm deformation and stresses are then converted into electrical signal output through several means of transduction.
- There are generally two types of pressure sensor:
    - **Absolute sensors**
    - **Gauge pressure sensors.**

- The absolute pressure sensor has an evacuated cavity on one side of the diaphragm. The measured pressure is the "absolute" value with vacuum as the reference pressure.
- In the gage pressure type, no evacuation is necessary.
- There are two different ways to apply pressure to the diaphragm. With back side pressurization, as illustrated in Figure 2.7a, there is no interference with signal transducer, such as a piezo resistor, that is normally implanted at the top surface of the diaphragm.
- The other way of pressurization, i.e., front-side pressurization, Figure 2.7b, is used only under very special circumstances because of the interference of the pressurization medium with the signal transducer.
- Signal transducers are rarely placed on the back surface of the diaphragm because of space limitation as well as awkward access for interconnects.

Figure 2.7 | Cross sections of micro pressure sensors.



As shown in Figure 2.7, the sensing element is usually made of thin silicon die with varying in size from a few micrometers to a few millimeters square.

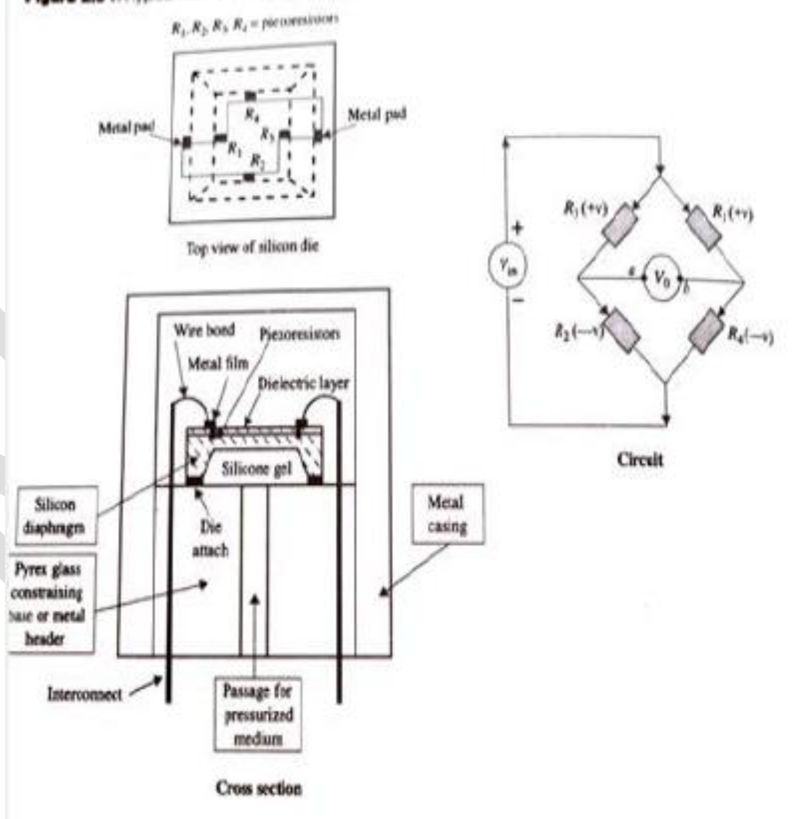
•A cavity is created from one side of the die by means of a microfabrication technique.

•The top surface of the cavity forms the thin diaphragm that deforms under the applied pressure from the measure and fluid.

•The thickness of the silicon diaphragm usually vary from a few micrometers to tens of micrometers.

•The deformation of the diaphragm by the applied pressure is transduced into electrical signals by various transduction techniques.

Figure 2.8 | A typical micro pressure sensor assembly



- Figure 2.8 schematically illustrates a packaged pressure sensor. The top view of the silicon die shows four piezo resistors (R. Rz, R3, and R) implanted beneath the surface of the silicon die.
- These piezo resistors convert the stresses induced in the silicon diaphragm by the applied pressure into a change of electrical resistance, which is then converted into voltage output by a Wheatstone bridge circuit as shown in the figure.
- T**he piezo resistors are essentially miniaturized semiconductor strain gages, which can produce the change of electrical resistance induced by mechanical stresses**. In the case illustrated in Figure 2.8, the resistors R and Rg are elongated the stresses induced by the applied pressure.
- Such elongation causes an increase of electrical resistance in these resistors, whereas the resistors R2 and R4 experience the opposite resistance change.
- These changes of resistance as induced bythe applied measure and pressure are measured from the Wheatstone bridge in the dynamic de-flection operation mode as
- Where V, and Vin are respectively measured voltage and supplied voltage to the Wheatstone bridge.

$$V_o = V_{\text{in}}\left(\frac{R_1}{R_1 + R_4} - \frac{R_3}{R_2 + R_3}\right)$$

- Fig 2.9 illustrates a micro pressure sensing unit utilizing capacitance change for pressure measurement.
- Two electrodes made of thin metal films are attached the bottom of the top cover and the top of the diaphragm. Any deformation of the diaphragm due to the applied pressure will narrow the gap between the two electrodes leading to a change of capacitance across the electrodes.
- This method has the advantage of being relatively independent of the operating temperature.

Figure 2.9 | Micro pressure sensors using capacitance signal transduction

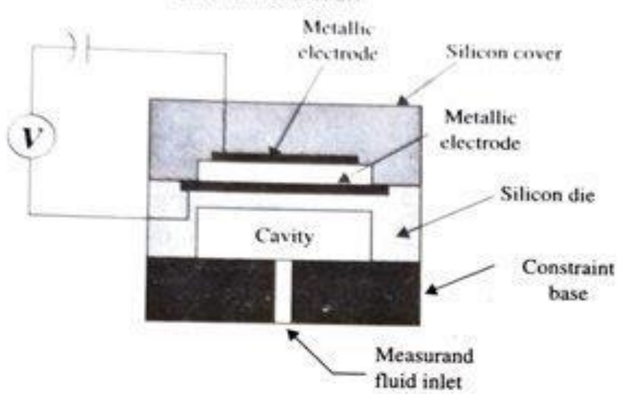
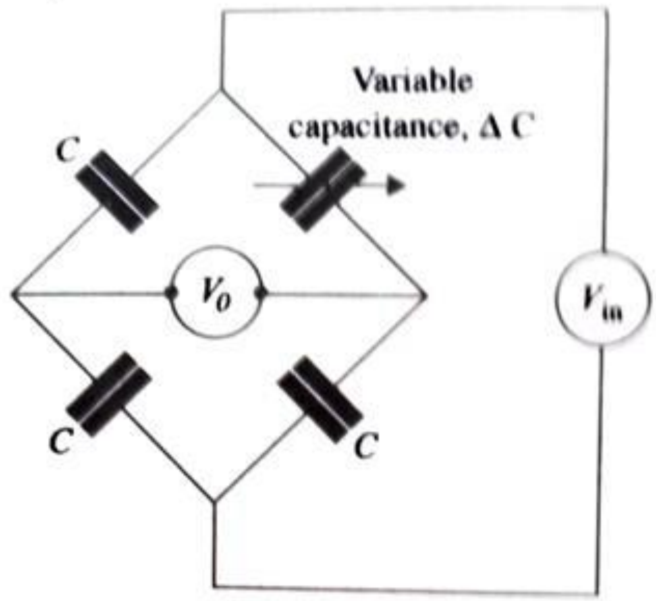


Figure 2.10 | A typical bridge for capacitance measurements

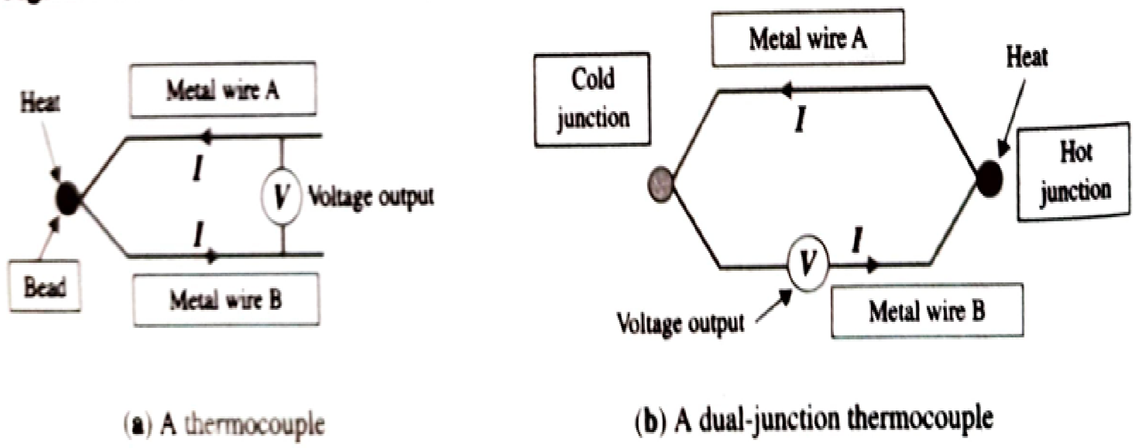


THERMAL SENSOR

- Thermocouples are the most common transducer used to sense heat.
- They operate on the principle of electromotive force (emf) produced at the open ends of two dissimilar metallic wires when the junction of the wires (called the bead) is heated.
- The temperature rise at the junction due to heating can be correlated to the magnitude of the produced emf, or voltage.
- These wires and the junction can be made very small in size. By introducing an additional junction in the thermocouple circuit, as shown in Figure 2.13b, and exposing that junction to a different temperature than the other, one would induce a temperature gradient in the circuit itself.
- This arrangement of thermocouples with both hot and cold junctions can produce the See beck effect, discovered by T. J.Seebeckin 1821.
- The voltage generated by the thermocouple can been evaluated by $V= \beta\Delta T$ in whichβ is the Seebeck coefficient and ΔT is the temperature difference between the hot and cold junctions.
- In practice, the cold junction temperature is maintained constant, e.g., at 0'C, by dipping that junction in ice water the coefficientβ depends on the thermocouple wire materials and the range of temperature measurements.
- One serious drawback of thermocouples for micro thermal transducers is that output of thermocouples decreases as the size of the wires and the beads is reduced.

Thermocouples alone are thus not ideal for microthermal sensors.

Figure 2.13 I Schematics of thermocouples.



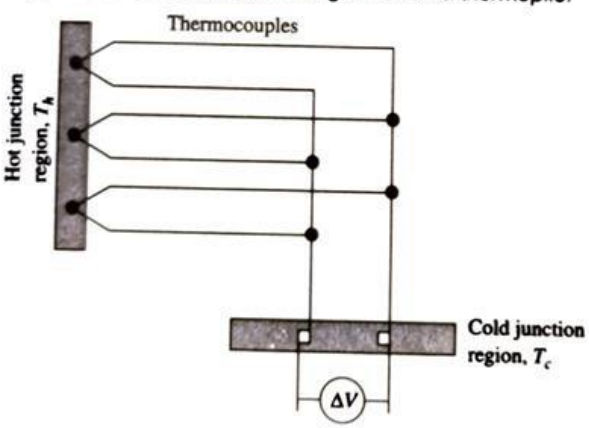
(a) A thermocouple

(b) A dual-junction thermocouple

Micro thermopile

- A micro thermopile is a more realistic solution for miniaturized heat sensing.
- Thermopiles operate with both hot and cold junctions, but they are arranged with thermocouples in parallel and voltage output in series.
- This arrangement is illustrated in Figure 2.14. Materials for thermopile wires are the same as those used in thermocouples
-

Figure 2.14 I Schematic arrangement for a thermopile.



MICROACTUATION

Actuator is defined as 'a mechanical device for moving or controlling something." The actuator is a very important part or a microsystem that involves motion.

Four principal means are commonly used Io actuating motions of micro devices:

(1) Thermal forces

(2) Shape memory alloys

(3) Piezoelectric crystals

(4) Electrostatic forces

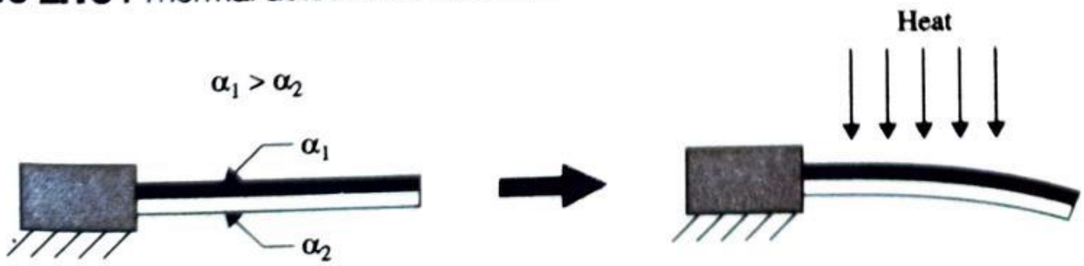
Electromagnetic actuation is widely used in devices and machines at macro scales It, however, is rarely used in micro devices because of the unfavorable miniaturization scaling laws.

- An actuator is designed to deliver a desired motion when it is driven by a power source. Actuators can be as simple as an electrical relay switch or as complex as an electric motor.
- The driving power for actuators varies, depending on the specific ap-plications.
- An on/off switch in an electric circuit can be activated by the deflection of a bimetallic strip as a result of resistance heating of the strip by electric current.
  On the other hand, most electrical actuators, such as motors and solenoid devices, are driven by electromagnetic induction, governed by Faraday's law.

Actuation Using Thermal Force

- Bimetallic strips are actuators based on thermal forces. These strips are made by bonding two materials with distinct thermal expansion coefficients.
- The strip will bend when is heated or cooled from the initial reference temperature because of in compatible thermal expansions of the materials that are bonded together.
- It will re-turn to its initial reference shape once the applied thermal force is removed.
- The same principle has been used to produce several micro actuators, such as micro clamps or valves.
- In these cases, one of the strips is used as a resistance heater. The other strip could be made from a common microstructural material such as silicon or polysilicon.
- The behavior of thermally actuated bimetallic strips is illustrated in Figure 2.16. The two constituent materials have coefficients of thermal expansion, $\alpha 1$ and $\alpha 2$, respectively, with$\alpha 1 > \alpha 2$.
- The beam made of the bimetallic strips will deform from its original straight shape to a bent shape shown in the right of the figure when it is heated by external sources.

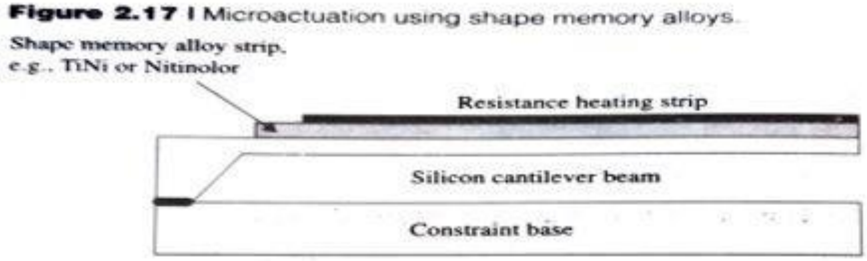
Figure 2.16 I Thermal actuation of dissimilar materials.



Actuation Using Shape-Memory Alloys

- Micro actuation can be produced more accurately and effectively by using shape memory alloys (SMA) such as Nitinol or, or TiNi alloys.
- These alloys tend to return to their original shape at a pre-set temperature.
- To illustrate the working principle of a micro actuator using SMA, let us refer to Figure 2.17. An SMA strip originally in a bent shape at a designed preset temperature T is attached to a silicon cantilever beam.
- The beam is set straight at room temperature. However, heating the beam with the attached SMA strip to the temperature T would prompt the strip's "memory" to return to its original bent shape.
- The deformation of the SMA strip causes the attached silicon beam to deform with the strip, and micro actuation of the beam is thus achieved.
- This type of actuation has been used extensively in micro rotary actuators.

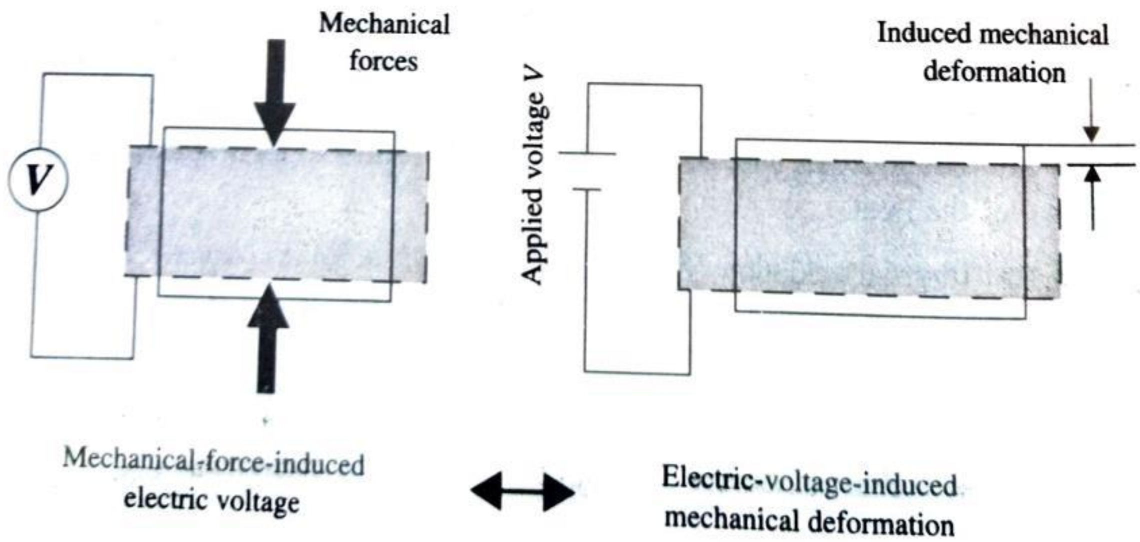
Figure 2.17 I Microactuation using shape memory alloys.



Actuation Using Piezoelectric Crystals

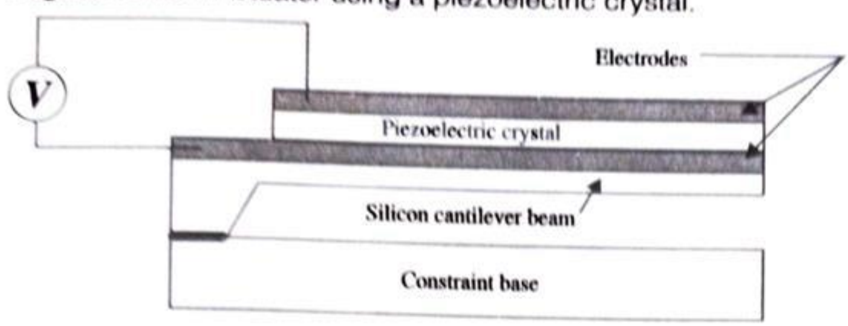
- Certain crystals, such as quartz, that exist in nature deform with the application of an electric voltage.
- The reverse is also valid; i.e., an electric voltage can be generated across the crystal when an applied force deforms the crystal. This phenomenon is illustrated in Figure 2.18.

Figure 2.18 | The piezoelectric effect.



- We may attach such a crystal to a flexible silicon beam in a micro actuator, as shown in Figure 2.19.
- An applied voltage across the piezoelectric crystal prompts a deformation of the crystal, which can in turn bend the attached silicon cantilever beam.
- Piezoelectric actuation is used in a micro positioning mechanism and micro clamp.

Figure 2.19 | Actuator using a piezoelectric crystal.



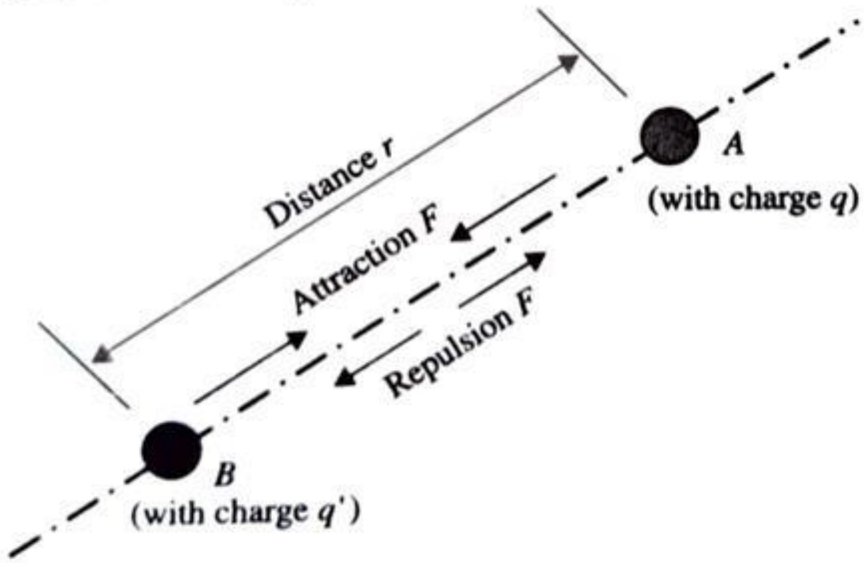
Actuation Using Electrostatic Forces

- Electrostatic forces are used as the driving forces for many actuators.
- Accurate assessment of electrostatic forces is an essential part of the design of many microm0 tors and actuators.
- **Coulomb's Law:**
- Electrostatic force F is defined as the electrical force of repulsion or attraction induced by

an electric field E. As we have learned from physics, an electric field E exists in a field carrying positive and negative electric charges.

- Charles Augustin Coulomb (1736-1806) discovered this phenomenon and postulated the mathematical formula for determining the magnitude of the force F between two charged particles.

Figure 2.20 | Two particles in an electric field.



With reference to Figure 2.20, where two charged particles A and B are in an electric field, the induced electrostatic force, according to Coulomb, can be expressed as:

$$F = \frac{1}{4\pi\epsilon}\frac{qq'}{r^2} \quad [2.5]$$

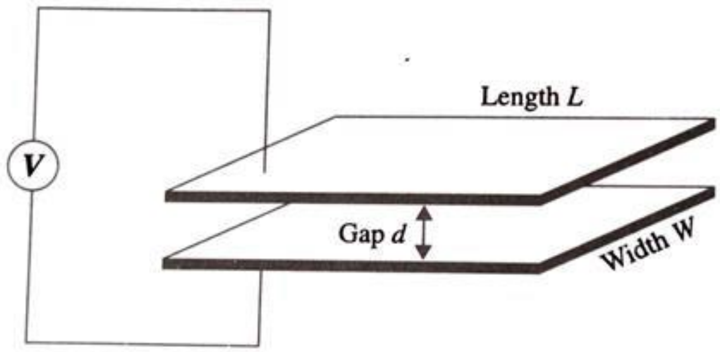
---

in which ϵ = permittivity of the material separating the two particles. We will have $\epsilon_0 = 8.85 \times 10^{-12}$ $C^2/N\text{-}m^2$ in free space (this is equivalent to 8.85 pF/m in a capacitor). The symbol r in Equation [2.5] is the distance between the two charged particles in the field.

The force F is repulsive if both charges, q and q', carry positive or negative charges, or attractive if the two charges have opposite signs.

Electrostatic Forces in Parallel Plates

Figure 2.21 | Electric potential in two parallel plates.



One may imagine that the difference in electric charge between the top and bottom plates in Figure 2.21 can be maintained as long as a voltage is applied to the system. However, the charges that are stored in either plate can be discharged instantly by short circuiting the plates with a conductor. One may thus realize that an electric potential does exist in the situation illustrated in Figure 2.21. The energy associated with this electric potential can be expressed as:

$$U = -\frac{1}{2}CV^2 = -\frac{\epsilon_r \epsilon_0 WLV^2}{2d} \quad [2.7]$$

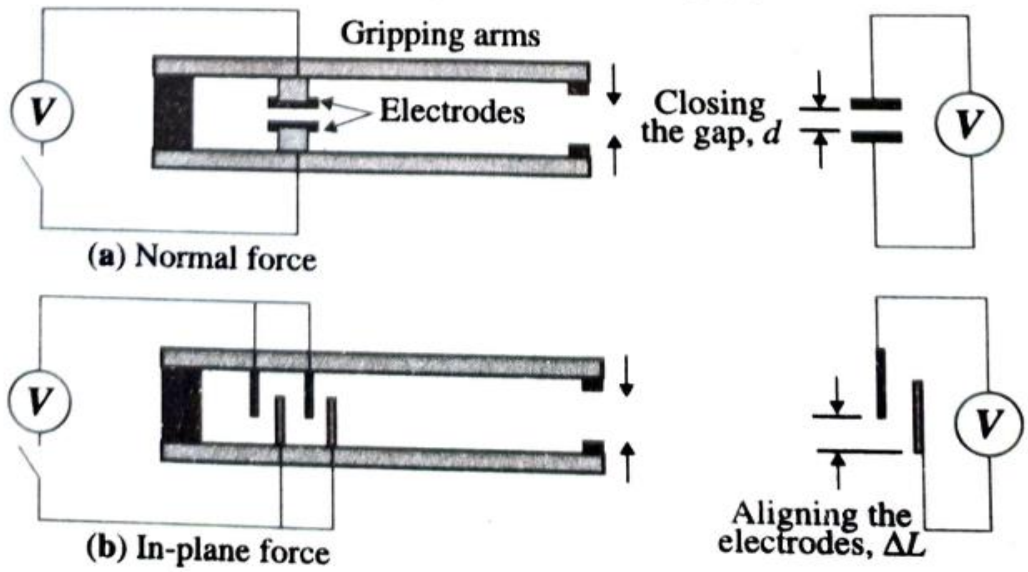
A negative sig [illegible] s a loss of the potential energy with increasing applied voltage.

- These electrostatic forces are the prime driving forces of micro-motors.
- One drawback of electro-static actuation is that the force that is generated by this method usually is low in magnitude.
- Its application is thus primarily limited to actuators for optical switches

MICROGRIPPERS

- The electrostatic forces generated in parallel charged plates can be used as the driving forces for gripping objects.
- Figure 2.24. As the figure shows, the required gripping forces in a gripper can be provided either by normal forces (fig 2.24a) or by the in-plane forces from pairs of misaligned plates.
- The arrangement that uses normal gripping forces from parallel plates, Figure 2.24a. Appears to be simple in practice.
- A major disadvantage of this arrangement, however, is the excessive space that the electrodes occupy in a micro gripper. Consequently, it is rarely used.

Figure 2.24 | Gripping forces in a microgripper.

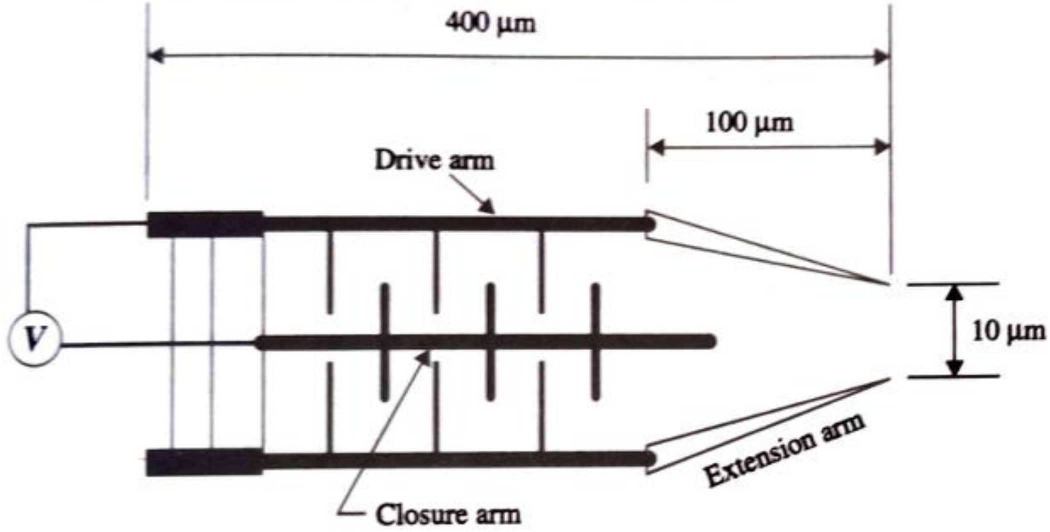


- The other arrangement, with multiple pairs of misaligned plates, is commonly used in micro devices.
- This arrangement is frequently referred to as the comb drive.

Comb drive

- The gripping action at the tip of the grip per is initiated by applying a voltage across the plates attached to the drive arms and the closure arm.
- The electrostatic force generated by these pairs of misaligned plates tends to align them, causing the drive arms to bend, which in turn closes the extension arms for gripping.
- These micro grippers can be adapted to micromanipulators or robots in micro manufacturing processes or microsurgery.

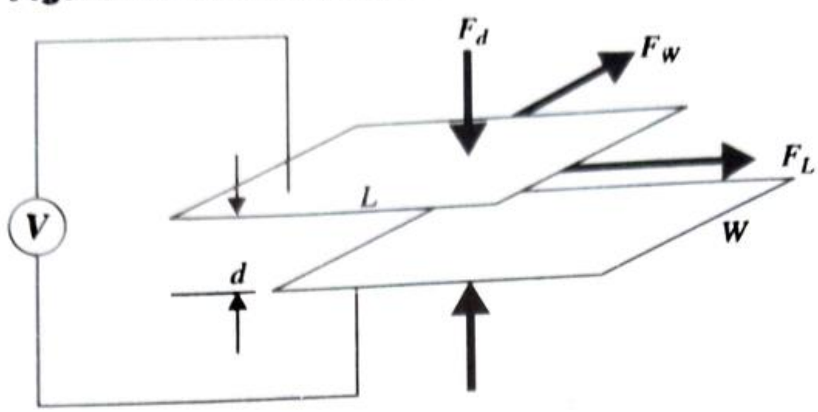
Figure 2.25 I Schematic diagram of a microgripper.



Micro motors

- There are two types of micro motors that are used in micro machines: and devices: linear motors and rotary motors.
- The actuation forces for micro motors are primarily electrostatic forces. The sliding force generated in pairs of electrically energized misaligned plates, such as illustrated in Figure 2.23. prompts the required relative motion in a linear motor

Figure 2.23 I Electrostatic forces on parallel plates.



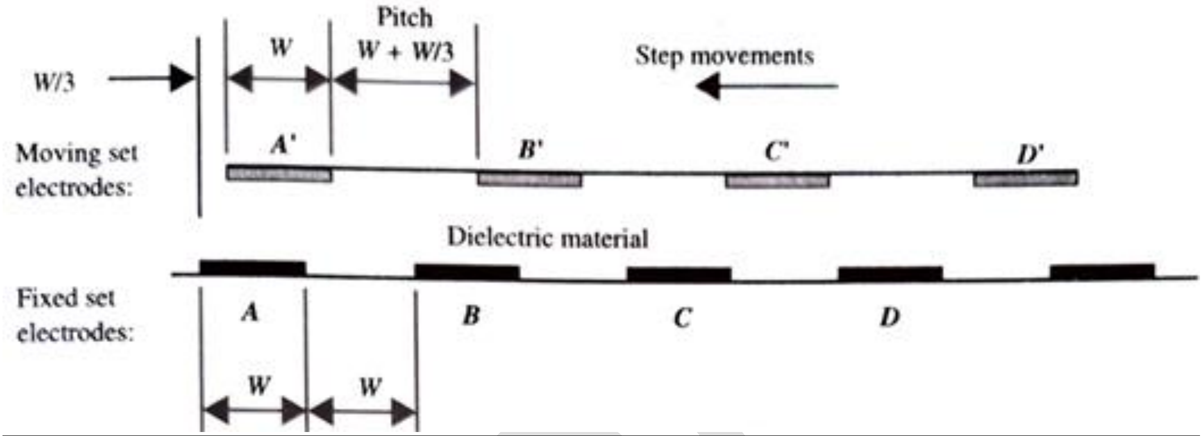
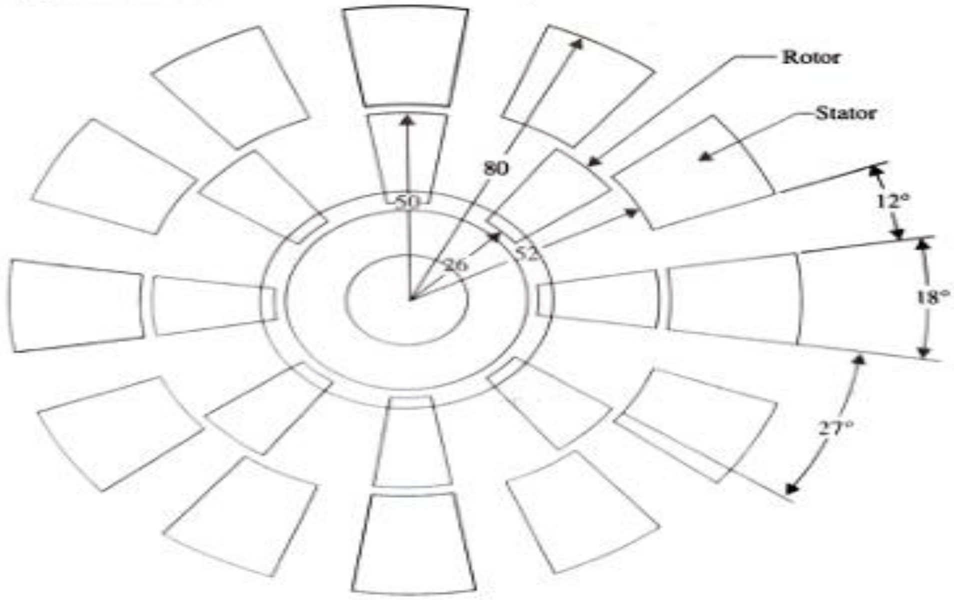


Figure 2.27 | Working principle of electrostatic micromotors.

- Figure 2.27 illustrates the working principle of the linear motion between two sets of parallel base plates.
- Each of the two sets of base plates contains a number of electrodes made of electric conducting plates.
- All these electrodes have a length W. The bottom base plate has an electrode pitch of W, whereas the top base plate has a slightly different pitch, say W+ W/3.
- The two sets of base plates are initially misaligned by W/13, as shown in the figure.
- We may set the bottom plates as stationary so the top plates can slide over the bottom plates in the horizontal plane.
- Thus, on energizing the pair of electrodes A and A' can cause the motion of the top plates moving to the left until A and A are fully aligned.
- At that moment, the electrodes B and B' are misaligned by the same amount, W/3. One can energize the misaligned pair B-B' and prompt the top plates to move by another W/3 distance toward the left.
- We may envisage that by then the C-C pair is misaligned by W/3 and the subsequent energizing of that pair would produce a similar motion of the top plates to the left by another distance of W/3.
- The motion will be completed by yet another sequence of energizing the last pair, D-D We may thus conclude that with carefully arranged electrodes in the top and bottom base plates and proper pitches, one can create the necessary electrostatic forces that are required to provide the relative motion between the two sets of base plates.
- It is really seen that the smaller the preset misalignment of the electrode plates, the smoothest the motion becomes.
- Rotary micro motors can be made to work by a similar principle.

Figure 2.28 I Schematic of a micro rotary motor.



- Rotary motors driven by electrostatic forces can be constructed in a similar way.
- Figure 2.28 shows a top view of an electrostatically driven micro motor. As can be seen from the figure, electrodes are installed in the outer surface of the rotor poles and the inner surface of the stator poles.
- As in the case of linear motors, pitches of electrodes in rotor poles and stator poles are mismatched in such a way that they will generate an electrostatic driving force due to misalignment of the energized pairs of electrode.
- The reader will notice that the ratio of poles in the stator to those in the rotor is 3:2.
- The air gap between rotor poles and stator poles can be as small as 2 µm The outside diameter of the stator poles 18 in the neighborhood of 100 µm, whereas the length of the rotor poles is about 20 to 25 µm.
- One serious problem that is encountered by engineers in the design and manufacture of micro rotary motors is the wear and lubrication of the bearings.
- Typically these motors rotate at over 10,000 revolutions per minute (rpm). With such high rotational speed, the bearing quickly wears off, which results in wobbling of the rotors.

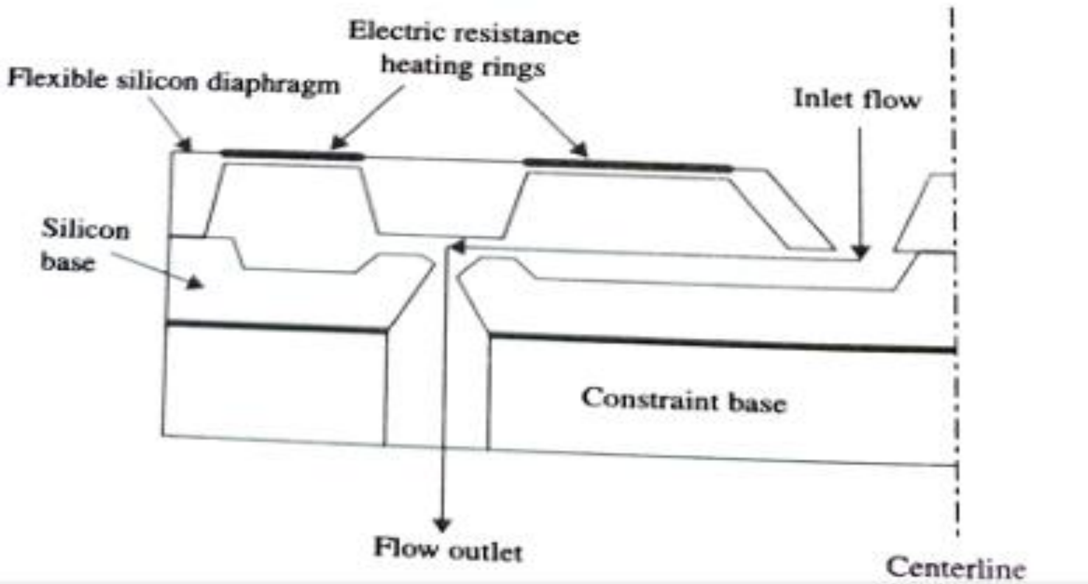
Micro valves

- Micro valves are primarily used in industrial systems that require precision control of gas flow for manufacturing processes, or in biomedical applications such as in controlling the blood flow in an artery.
- A growing market for micro valves is in the pharmaceutical industry, where these valves

are used as a principal component in microfluidic systems for precision analysis and separation of constituents. Micro valves operate on the principles of micro actuation.

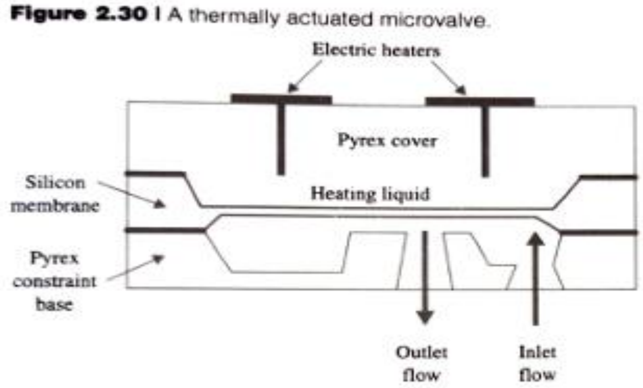
- As illustrated in Figure 2.29, the heating of the two electrical resistor rings attached to the top diaphragm can cause a downward movement to close the passage of flow.

Figure 2.29 | Schematic diagram of a microvalve.



- Removal of heat from the diaphragm opens the valve again to allow the fluid to flow.
- In Jerman's design, the diaphragm is 2.5 mm in diameter and is 10 um thick.
- The heating rings are made of aluminum 5 um thick.
- The valve has a capacity of 300 cm/min at a fluid pressure up to 100 psi, and 1.5 W of power is required to close the valve at 25 psi pressure.
- A rather simple micro valve design uses a thermal actuation principle The cross-section of this type of valve is schematically shown in Figure 2.30.

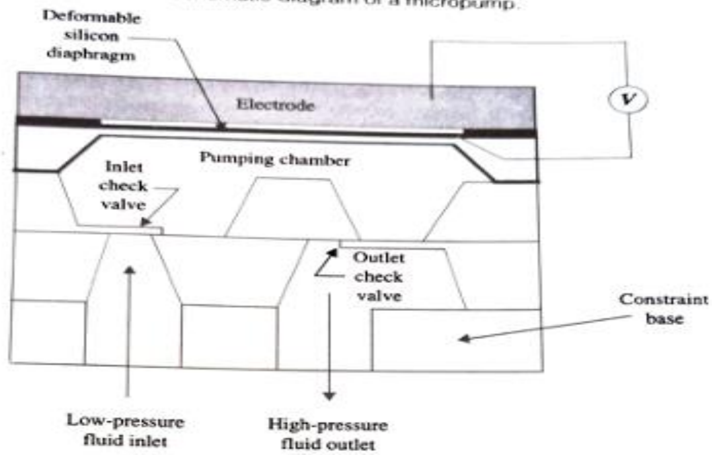
Figure 2.30 | A thermally actuated microvalve.



- This design is used to control the flow rate from a normally open valve (as shown) to a fully closed state.
- The downward bending of the silicon diaphragm regulates the amount of valve opening.
- Bending of the diaphragm is activated by heat supplied to a special liquid in the sealed compartment above the diaphragm.
- The heat source in this case is the electric resistance foils attached at the top of the device.

Micro pumps

Figure 2.31 | Schematic diagram of a micropump.



- A simple micro pump can be constructed by using the electrostatic actuation of a diaphragm as illustrated in Figure 2.31.
- The deformable silicon diaphragm forms one electrode of a capacitor. It can be actuated and deformed toward the top electrode by applying a voltage across the electrodes.
- The upward motion of the diaphragm increases the volume of the pumping chamber and hence reduces the pressure in the chamber.
- This reduction of pressure causes the inlet check valve to open to allow in- flow of fluid.
- The subsequent cutoff of the applied voltage to the electrode prompts the diaphragm to return to its initial position, which causes a reduction of the volume in the pumping chamber.
- This reduction of volume increases the pressure of the en- trapped fluid in the chamber.
- The outlet check valve opens when the entrapped fluid pressure reaches a designed value, and fluid is released.
- A pumping action can thus be accomplished. The actuation frequency is I to 100 Hz. At 25 Hz, a pumping rate of 70 µL/min is achieved.
- Another type of micro pump, called a piezo pump is built on the principle of producing

wave motion in the flexible wall of minute tubes in which the fluid flows.

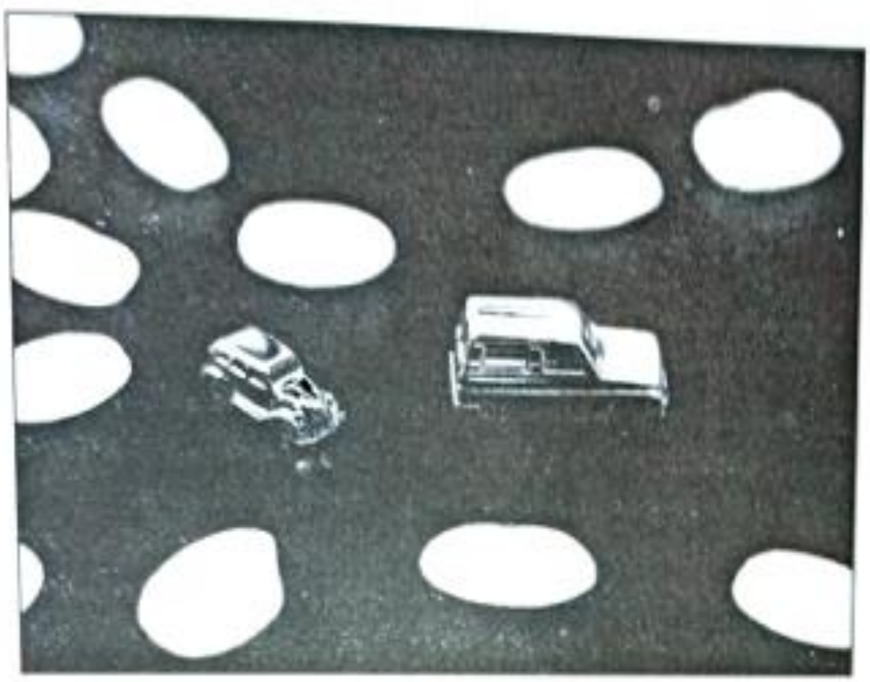
- Piezoelectric materials coated outside the tube wall generate the wave motion. The wave motion of the tube wall exerts forces on the contained fluid for the required notion.

MODULE 6

- MEMS and microsystem products have become increasingly dominant in every aspect of commercial marketplace as the technologies for microfabrication and miniaturization continue to be developed.
- At the present time, two major commercial markets for these products are computer storage systems and automobiles.
- The automotive industry has been the major user of MEMS technology m the last two decades because of the size of its market.
- A 1991 report indicated that industry had a production of 8 million vehicles per year, with 6 million of this is from United States

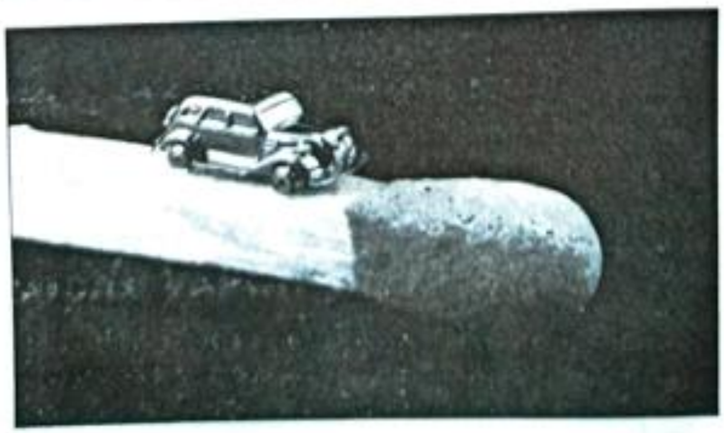
Figure 1.19 | Miniature electric cars: **(a)** Compared with rice grains. **(b)** Compared with an American 5-cent coin. **(c)** Compared with the tip of a match stick.

(a)



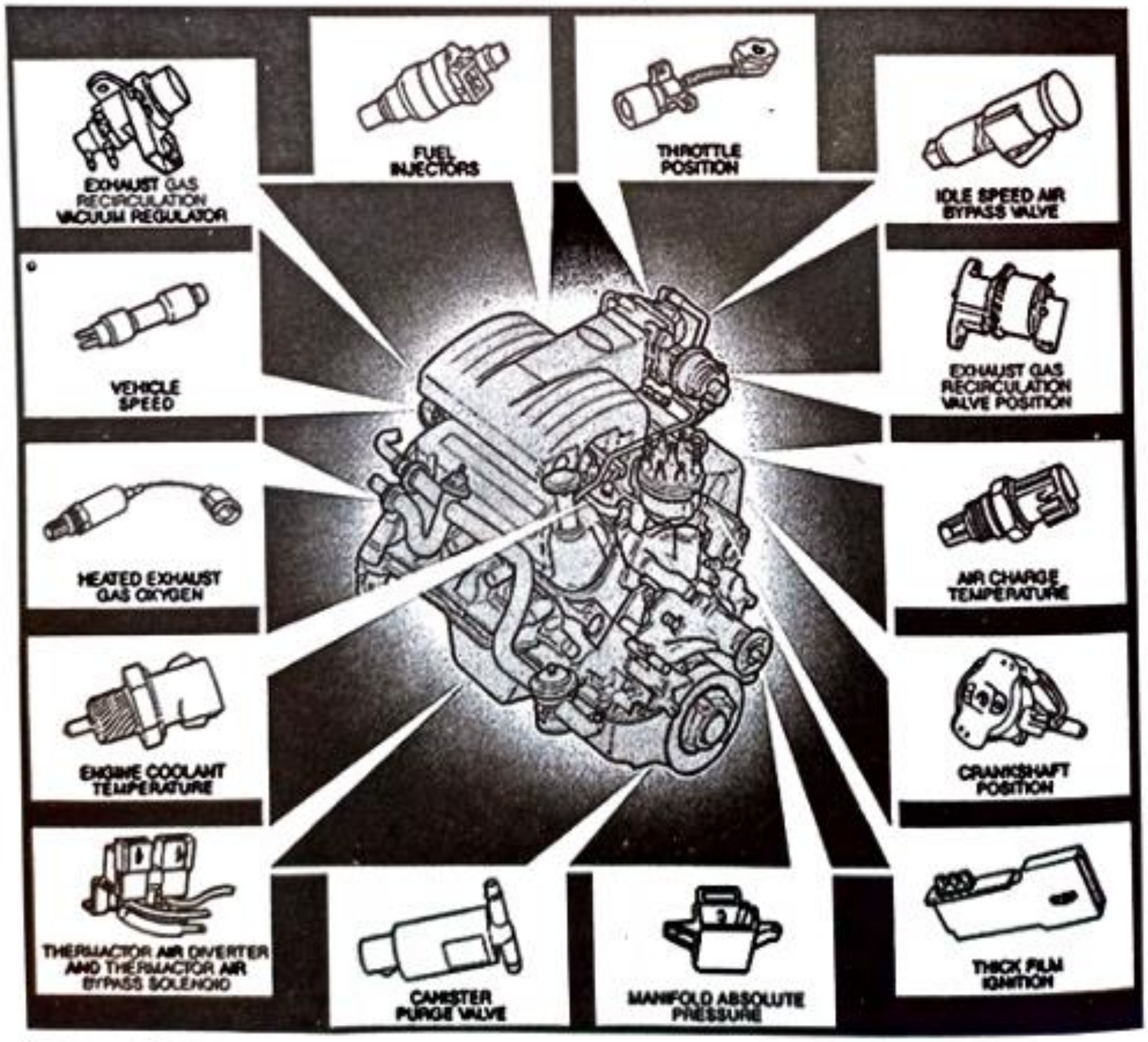
(b)

(c)



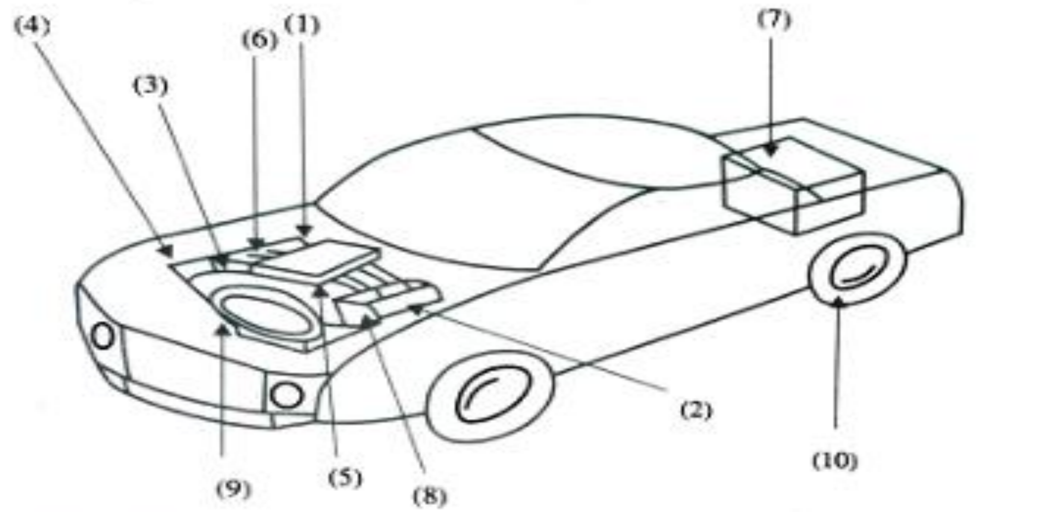
- The primary motivation for adopting MEMS based microsystems in automobiles is to make automobiles safer and more comfortable for the riders
- to meet the high fuel efficiencies
- low emissions standards required by governments.
- In all, the widespread use of these products can indeed make the automobile "smarter" for consumers' needs.
- The term smart cars was first introduced in the cover story of a special issue of a trade magazine |Smart Cars 1988].
- Many of the seemingly fictitious predictions of the intelligent functions of a smart car are in place in today's vehicles
- Smart vehicles are based on the extensive use of sensors and actuators.
- Various kind of sensors are used to detect the environment or road conditions, and the actuators are used to execute whatever actions are required to deal with these conditions.
- Micro sensors and actuators allow automobile makers to use smaller devices, and thus more of them, to cope with the situation in much more effective ways.

Figure 1.20 | Sensors in an automobile engine and powertrain.



- (Paulsen and Giachino [1989], with permission.)

Figure 1.21 | Pressure sensors in automotive applications.



(1) Manifold or temperature manifold absolute pressure sensor
(2) Exhaust gas differential pressure sensor
(3) Fuel rail pressure sensor
(4) Barometric absolute pressure sensor
(5) Combustion sensor
(6) Gasoline direct injection pressure sensor
(7) Fuel tank evaporative fuel pressure sensor
(8) Engine oil sensor
(9) Transmission sensor
(10) Tire pressure sensor

(Chiou [1999], with permission.)

Safety

- Air bag deployment system to protect the driver and passengers from injury in event of serious vehicle collision. The system uses micro accelerometers or micro inertia sensors
- antilock braking systems (position sensors).
- Suspension systems (displacement, position and pressure sensors, and micro valves).
- Object avoidance (pressure and displacement sensors).
- Navigation (micro gyroscope).

Engine and Power-Train

- Manifold control with pressure sensors.
- Airflow control Exhaust gas analysis and control (see Figure 1.21)
- Crankshaft positioning Fuel pump pressure and fuel injection control
- Transmission force and pressure control
- Engine knock detection for higher power output Comfort and Convenience Seat control (displacement sensors and m

MODULE I

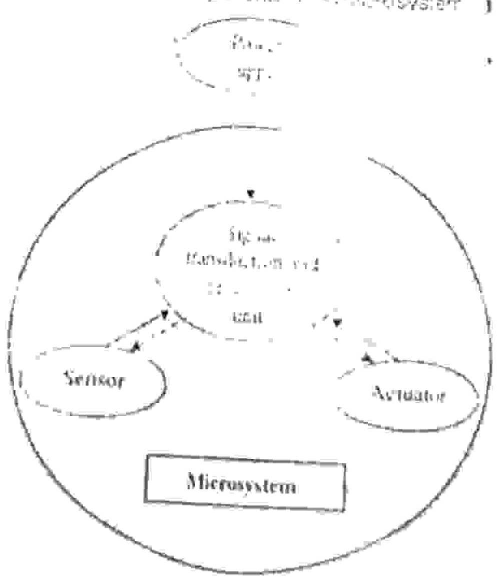
MEMS AND MICROSYSTEMS

- The term MEMS is an abbreviation of microelectromechanical system.
- MEMS is a process technology used to create tiny integrated devices or system that combine mechanical and electrical components, and they are fabricated using batch processing techniques.
- Its range in size from a few micrometers to millimeters.

- A microsystem is an engineering system that contains MEMS components that are designed to perform specific engineering functions.

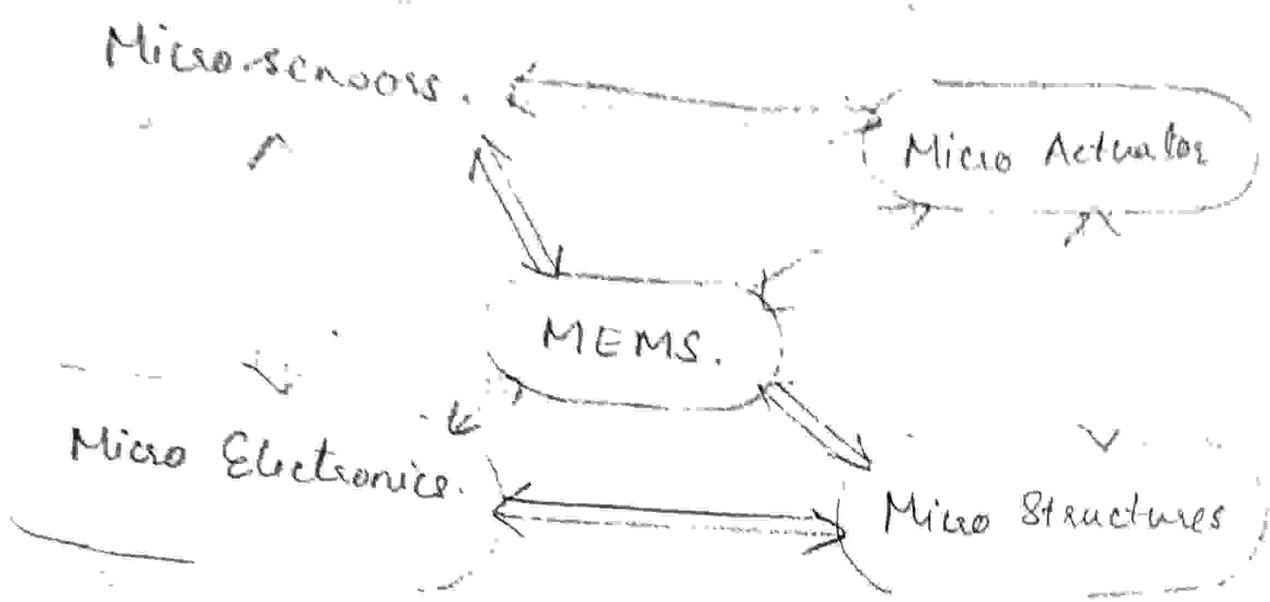
Components of a Microsystem

Figure 1.5 | Components of a microsystem



- The signals received by a sensor in a microsystem are converted into forms compatible with the actual through the signal transduction and processing unit.

Schematic illustration of MEMS Components



Micro electronics.

- It is the brain of the system that receives signals or data and processes it and make appropriate decisions.
- The data comes from the micro sensors.

Micro Sensors.

- Constantly gather data from environment
- It passes data to the micro electronics section for processing.
- It can monitor mechanical, thermal, biological chemical readings etc.

Micro Actuator -

- It acts as trigger to active the external devices.
- Micro electronics will tell micro actuator to activate the device.

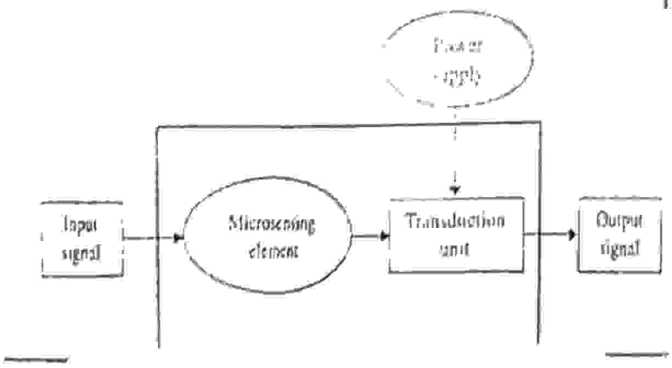
Micro Structure.

- Extremely small structures built onto the surface of chip.
- The materials used are usually silicon.

Smart phones, Tablets, Camera, Gaming devices and many other electronics have MEMS technology inside of them.

MEMS as a Micro Sensor.

Figure 1.1 MEMS as a microsensor

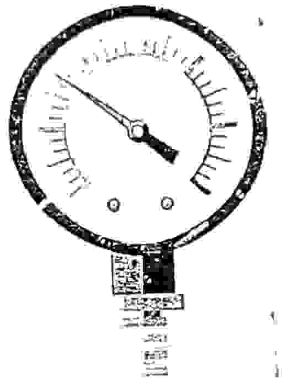


- Microsensors are built to sense the exist, and the intensity of certain physical, chem or biological quantities such as temperature, pressure, force, sound, light, nuclear radiation magnetic flux and chemical compositions etc.
- Microsensors have the advantages of being sensitive and accurate with minimal amount of required sample substance.
- Common sensors includes biosensors, chemical sensors, optical sensors, thermal and pressure sensors etc.
- Working principle: eg: pressure sensor.
  - An i/p signal such as pressure from a source is sensed by a microsensing element, which may include simply a silicon diaphragm which is only a few micrometers thick.
  - The deflection of the diaphragm induced by the applied pressure is converted into a change of electrical resistance by micropiezoresistors that are implanted in the diaphra.
  - The piezoresistors constitute a part of the transduction unit.
- The change of electrical resistance in the resistors induced by the change of the crystal structure geometry can be further converted into corresponding voltage changes by a micro wheatstone bridge

The voltage

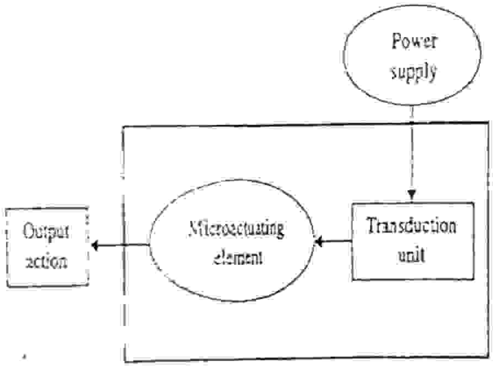
The o/p of the microsensor is thus is the voltage change corresponding to the i/p pressure.

fig: Pressure Sensor.



MEMS as a microactuator.

Figure 1.3 | MEMS as a microactuator.



- The Actuator is a very important part of a microsystem that involves motion.
- An actuator is designed to deliver a desired motion when it is driven by a power source.

- Actuators can be as simple as an elec relay switch or as complex as an electric motor.

- The driving power for actuator varies, dependi on the specific applications.

- Most of the electrical actuator, such as motors and solenoid devices, are driven by electromagnet induction governed by Faraday's law.

- There are mainly 4 pricipal means commonly used for actuating motions of microdevices
  → Thermal force
  → Shape memory alloys
  → piezoelectric crystals
  → Electrostatic forces.

Explanation for the above block diagram (you should mention this in the very first)

Power supply : Electrical current or voltage.

Transduction unit : To convert the appropriate form of power supply into the desired form of actions of the actuating element.

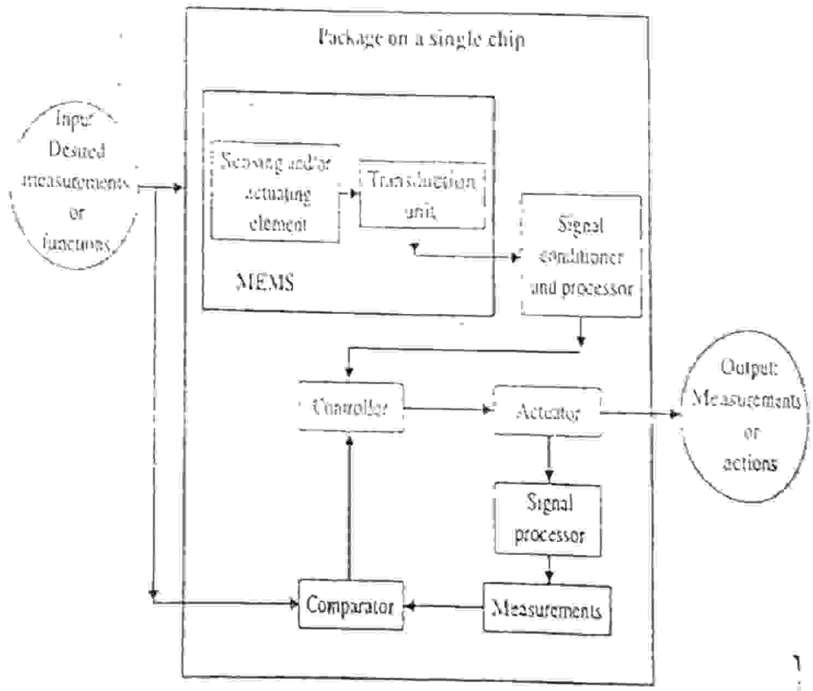
Actuating element : A material or component that moves with power supply.

Output action: usually in a prescribed motion.

Intelligent micro systems.

Most microsystems are designed and constructed to perform single functions, but there is a clear trend in the industry to incorporate signal processing and include closed-loop feedback control systems in a microsystem to make the integrated system "intelligent".

Figure 1.7 | Intelligent microsystems



- Typical MEMS and microsystem products a

1) Microgears , 2) Micromotors , 3). Microturbines

4) Micro-optical components . etc.

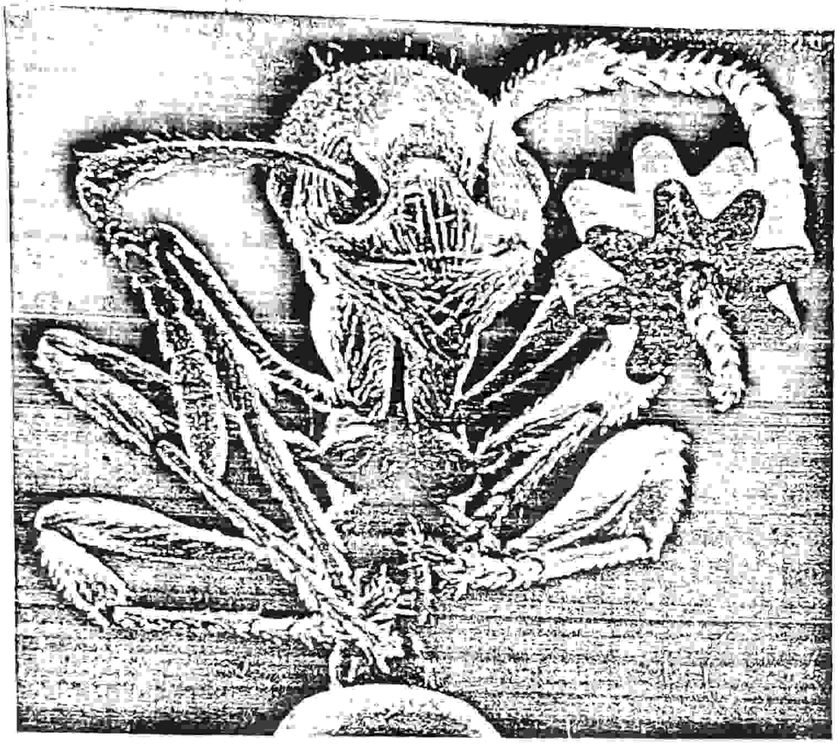


fig: Microgear placed at the tip of an ant's leg

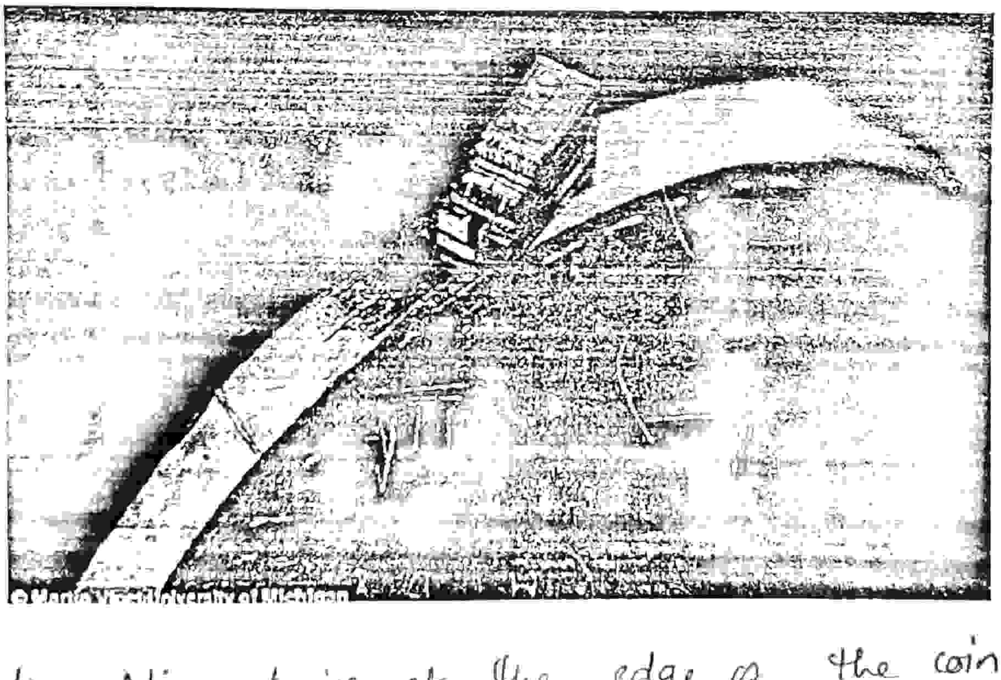


fig: Micro device at the edge of the coin.

Microsystem and Miniaturization

- Miniature means a copy on a much reduced scale. Miniaturization is an art that substantially reduces the size of the original object yet retaining the characteristics of the original (even more) in the reduced copy.
- We are now having ultimate miniaturization of machines and devices such as dust-size computers, needle tip size robots etc.
- As engineering systems and devices have become more and more complex and sophisticated, the need for miniaturization has become more prominent than ever in recent decades.

Some of the benefits of having smaller components are given below.

- Smaller system tend to move quickly than larger systems because of lower inertia of the mass.
- The minute size of small devices encounter fewer problems in thermal distortion and vibration because resonant vibration of a system is inversely proportional to mass.
- The minute size makes them particularly suitable for applications in medicine and surgery and in microelectronic assembly in which miniaturized tools are necessary.

- Miniaturization is also desirable in satellites / spacecraft engineering to satisfy the prime conc. about high precision and payload size.
- The high accuracy of miniaturised system in motion and diamensional stability make them particularly suitable for telecommunication system.

- Miniaturization also drastically reduces the consumption of energy and material.
- Compairing its performance, it is cost effective
- Less materials used for manufacturing
- Easy disposal.
- Low power consumption

History of miniaturization

The foremost example of miniaturization began with the development of Integrated circuits in the mid 1950's

The advances in IC and microprocessor technolo. have led to a spectacular level of miniaturization of complex digital electronic computers.

Most sensors and actuating components use silicon as the primary material.

High aspect ratio micro structure have been successfully manufactured by the LIGA process

- The broader use of materials, along with the possibility of producing MEMS with high aspect ratio by the LIGA process have prompted the production of miniaturized machines. → Machine tools such as microlathes and millimeter size drills have been produced. →

- The electrical motor that drives the cars uses magnetic induction, with a rotor 0.6mm in diameter. → Miniaturization is the only way to have new and competitive engineering systems performing multifunctions with manageable sizes.

→ Another example is Autonomous robotic vehicle (MARV). → Application of MARV include micro surgery, tiny surveillance etc. The vehicle contains on-board computer, sensors and control.

Disadvantages:

- Increased complexity in circuit design
- Increased Engineering / R and D costs
- Not serviceable after manufacture.

→ Another spectacular micromachine example is the microcars, the size of this microcars are comparable with the size of the rice grains.
- These cars are fabricated by microprecision machining with semiconductor processes.

Application

- Automobile Industries
- Communication fields
- Medical fields
- Satellites and Space craft engg.

Miniaturization is the trend to manufacture for their existance by manufacturing ever smaller mechanical, optical and electronic products and devices. The future of miniaturization of computer technology will be in 3 diamentional circuits. These cubes will replace the two dimensional chips in computer technology.

Material for MEMS

- Many microsystems use microelectronics materials such as silicon and gallium arsenide (GaAs) for the sensing or actuating elements. These materials are chosen mainly because they are dimensionally and mechanically stable and their microfabrication and packaging techniques are well established in microelectronics.
- Other materials used such as Quartz and pyrex, polymers and plastics, and ceramics, are used for MEMS and microsystems and not for micro electronics

Substrate and wafers.

* Common substrate materials are in MEMS are Si, Ge, GaAs.

- Substrate in microelectronics means a flat microscopic object on which fabrication process take place.
- In microsystems, a substrate acts as single transducer besides supporting other transducers that convert mechanical actions into electrical output or vice versa.
  eg:- pressure sensors, Micro actuators

Wafers.

- In semiconductors, the substrate is a single crystal cut in slices from a large piece called wafer.
- Wafer can be silicon or other single crystalline material such as quartz or GaAs (Gallium Arsenide)
- There are 2 types of substrate materials used in microsystems
  1. Active substrate materials
  2. Passive " " (Rarely used)

materials ... day. Miniature ... Mechatronics.

Active Substrate materials (1)

- Active Substrate materials are primarily used for Sensors and actuators in microsystems.
- Tipical materials: Si, GaAs, Ge and Quartz.
- These Substrate materials have basically a cubic crystal lattice with a tetrahedral atomic bond.
- These materials have the properties:
  - relatively insensitive to environmental conditions
  - having diamensional stability.
  - high precision.
- Each atom carries 4 e's in the outer orbit, each atom shares these 4 e's with its four neighbors.
- They can be doped with foreign materials to alter their electric conductivity.

Silicon as a Substrate material.

→ Single crystal Si is the most widely used Substrate materials for MEMS and microsystems, due to the following reason.

* Mechanically stable
* Ideal structural material because of high young's modulus, and light weight.
* High melting point at 1400°c.
* Low thermal expansion co-efficient
* Shows virtually no mechanical hysteresis
* fabrication processes are well established and documented.

Single-crystal Silicon and wafers

- The Czochralski (Cz) method is the most po[illegible] method to produce pure silicon crystal.

Figure 7.1 | The Czochralski method for growing single crystals. (Ruska [1987])

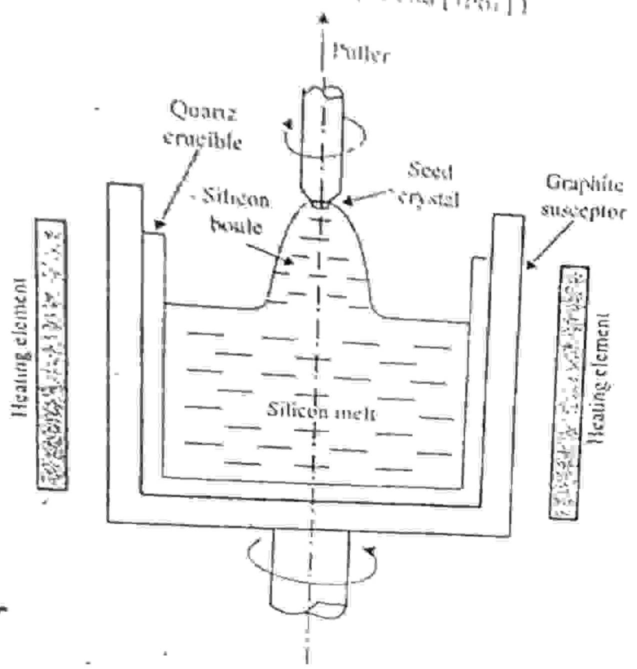
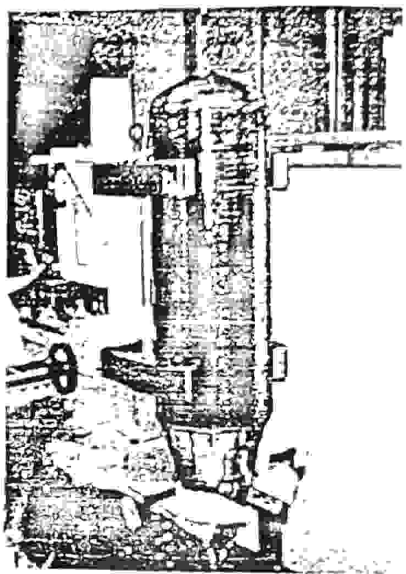


Figure 7.2 | A 300-mm single-crystal silicon boule sitting on a material-handling device



- The raw silicon in the form of quartzite are melted in a quartz crucible with carbon which is placed in a furnace.

$$SiC + SiO_2 \rightarrow Si + CO + SiO.$$

- A 'seed' crystal which is attached at the tip of a puller, is brough into contact with the molten silicon to form a larger crystal.
- The puller is slowly pulled up along with a continuous deposition of silicon melt onto the seed crystal.
- As the puller is pulled up, the deposited silicon me[lt] condenses and a large bolonga-shaped (tube shaped) boule of single crystal silicon [illegible]

(8)

- The Si boule is then ground (mould) to a perfect circle on its outside surface, and then sliced to form thin disks of the desired thickness by fine diamond saws.
- These then disks are then chemically-lap polished to form the finished wafers.

Current industry Standard wafer sizes and thickness

100 mm (4 in) diameter x 500 μm thick.
150 mm (6 in) diameter x 750 μm "
200 mm (8 in) " x 1 mm thick.

- Silicon Compounds.

In microsystems, there are mainly 3 silicon compounds used are: Silicon dioxide
Silicon Carbide
Silicon Nitride.

- Silicon in polycrystalline form can be deposited onto silicon substrate by chemical vapor deposition and it is the principal material in surface micromachining.
- Both p and n-type silicon exhibit excellent piezoresistive effect (A change in electric resistance of solid when subjected to stress field

II Gallium Arsenide.

- GaAs is a compound semiconductor, It is made of equal numbers of gallium and arsenic atoms.
- GaAs is an excellent material for monolithic integration of electronic and photonic devices on a single substrate

Commercial

- GaAs has about 7 times higher electron mob than silicon. (i.e.) much easier for electric current.
- Superior thermal insulator with excellent dimens. stability at high temperature.

Disadvantages.

- More difficult to process than silicon.
- Low yield strength. ($1/3^{rd}$ of that of Si)
- More expensive than silicon due to its low use.

Comparison of GaAs and Si

Properties	GaAs	Si
① Optoelectronics →	Very good	Not good.
② piezoelectric effect →	Yes	No.
③ Thermal Conductivity →	Relatively low	Relatively high.
④ Cost →	High	low.
⑤ operational temperature →	High	low.
⑥ physical stability →	fair	very good.

III Quartz.

- Quartz is a compound of SiO_2.
- Its unit cell is in the shape of tetrahedron.
- It is an ideal material for sensors because of its near absolute thermal diamensional stabilit
- It is used in many piezoelectric devices.

materials (metallic, ...
... Miniature parts have

Commercial applications: wristwatches, electronic filter, Resonators etc.

- It is inexpensive and it works well in electrophoretic fluid transportation, due to its excellent elec insulation properties. [(motion of dispersed particles relative to a fluid under the influence of electric field).]

- Transparent to UV light which is good for the purpose of species detection.

- Hard to machine,
  - could use diamond cutting or ultrasonic cutting
  - Can be etched chemically by HF/NH_4F into the desired shape. (Hydrofluoric acid and Ammonium fluoride)

- More diamensionally stable than silicon.
- More flexibility in geometry than silicon.

IV. Piezoelectric crystals.

- One of the most commonly used nonsemiconducting materials in MEMS and microsystems is piezoelectric crystals.
- Piezoelectric effect:
  - Produce a voltage when subjected to an applied force.
  - and vice versa.
  - The application of voltage to the crystal can change its shape.

Applications
- In actuators
- Dynamic signal transducers for pressure sensors
- Accelerometers
- pumping mechanisms.
- for microfluidic flows
- Inkjet printer heads.

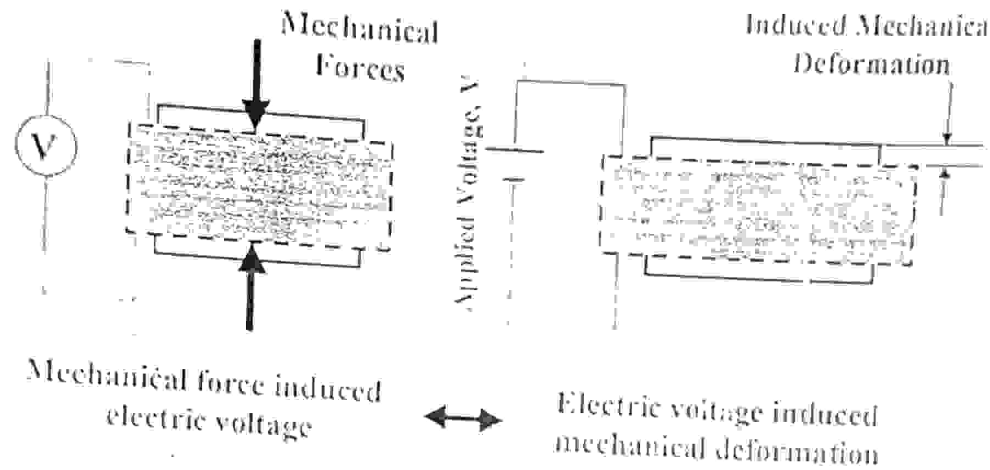


fig: Conversion of mechanical and electrical energies by piezoelectric crystals.

- This piezoelectric effect exists in a no: of natural and synthesized crystal.
  * natural crystals : Quartz, tourmaline, Sodium potassium tartrate
  * Synthesized crystals : Rochelle salt, Barium titanate lead zirconate titanate (PZT).
- For a crystal to exhibit the piezoelectric effect, its structure should have no center of symmetry.

- The applied stress will alter the seperation between the +ve and -ve charge sites in each elementary cell, leading to a net polarization at the crystal surface.
- Because of such polarization, an electric field with voltage potential is created.

→ The effectiveness of the conversion of mechanical to electrical energy and viceversa can be assessed by the electromechanical conversion factor K:

$$K^2 = \frac{\text{o/p of mechanical energy.}}{\text{i/p of mechanical energy.}}$$

or

$$K^2 = \frac{\text{o/p of electrical energy.}}{\text{i/p of electrical energy.}}$$

- The electric field produced by stress

$V = f\sigma$. where $V \rightarrow$ electric field in V/m
$f \rightarrow$ constant co-efficient
$\sigma \rightarrow$ Applied stress (Pa).

- The mechanical strain produced by the electric field

$\varepsilon = dV$ $\varepsilon \rightarrow$ induced strain
$V \rightarrow$ Applied electric field.
$d \rightarrow$ piezoelectric co-efficient.

- Relation between f and d

$\frac{1}{fd} = E$ where $E \rightarrow$ Young's modulus.

V Polymers.

- Includes diverse materials as plastics, Adhesive, plexiglas, and Lucite.
- Become increasingly popular materials for MEMS and Microsystems

eg:- → plastic Cards (approximately 150 mm wide) containing 1000 microchannels for microfluidic electrophoretic system by the biomedical industry.

→ Epoxy resins and adhesives such as Silicon rubber are used in MEMS and microsystem packaging.

- This typical material is made up of long Chains of organic molecules.

Characteristics.

- Low mechanical strength.
- low melting point
- poor electric conductivity.

2 groups of Common polymers are

1) Thermoplastics :- They are easily formed to the desired shape.

2) Thermo set plastics :- Have better mechanical strength and temperature resistan up to 350°c.

- Polymers as industrial materials

Applications: used in insulators, Sheathing, Capacitor films in electric devices and die pads in integrated circuits. (die means in the context of IC, the wafer is cut into many pieces each containing one copy of the circuit called die)

- Advantages
  - Light weight - Ease in processing
  - Low cost of raw materials . High Corrosion resistance
  - High electrical resistance - High flexibility in structu
  - High dimensional stability - Great variety availabili

- Polymers for MEMS and microsystem.

Applications

1. Photoresist polymers: ① used as masks for creating desired patterns
   ② used to produce the prime mold in LIGA process.
2. Conductive polymers:
   - used as organic substrates.
3. Ferroelectric polymers: used as a source of actuation in micropumping.
4. used for electromagnetic interference and radio-frequency interference, and shielding in Microsystems.
5. Used for encapsulation of microsensors and packaging of other microsystems.

Materials for microsystem packaging

- Materials used in microsystem packaging include those used in IC packaging - wires made of noble metals at the silicon die level. At the die level, we use aluminium or gold metal films as the ohmic contacts to the piezoresistors that are diffused in silicon diaphragms. Similar materials are used for the lead wires to interconnects outside the casing. Glass such pyrex or ceramics such as alumina are often used as constraint base. Copper and aluminum are good materials for soldering purpose.

MICROSYSTEM PACKAGING.

- MEMS and microsystem involve micrometers size components and these components are vulnerable to malfunctions or structural damage if they are not properly packaged.
- It includes 3 major tasks namely Assembly, Packaging and Testing (called AP&T). AP&T cost for MEMs and microsystems varies from product to product. But on an average this covers 80% of the total production cost.
- Due to many constraints microsystem packaging is much more challenging to engineers than microelectronic packaging.
- The purpose of microelectronic packaging is to provide mechanical support, electrical connection, protection of the delicate integrated circuits from all possible attacks by mechanical and environmental sources and removal of heat generated by the integrated circuits.
- There are generally 4 levels in the electronic system packaging hierarchy,

first level : is "chip and module" level in which the IC on silicon chips (L0) and are packaged into a module (L1)

and level : (L...

Third ...

packa...

cond Level : (L2) is the card level. The modules are packaged as the function cards that perform various specific functions.

Third Level : (L3) involves the assembly of cards to the board.

Final or fourth level : (L4) involves the assembly of various boards to make the system.

General considerations in packaging Design.

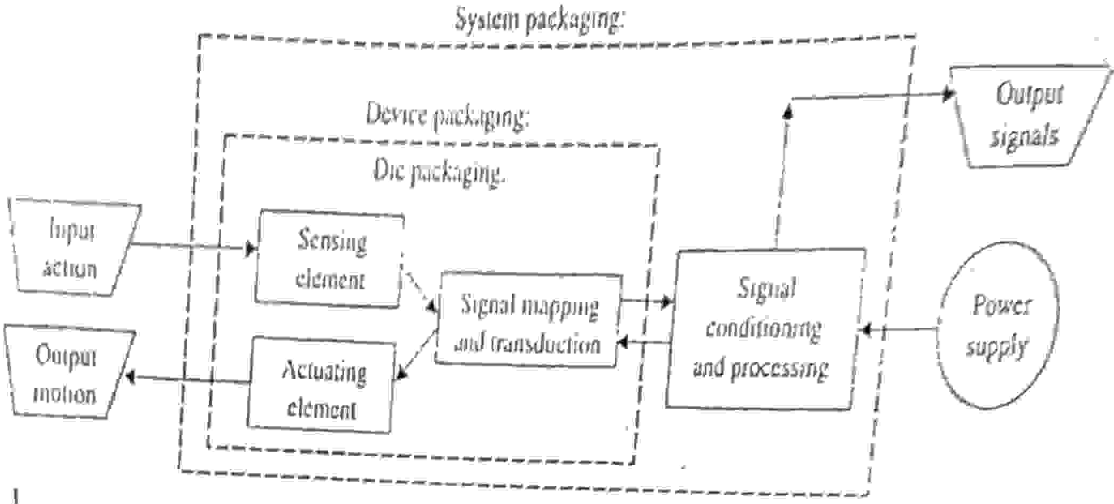
- → The required costs in manufacturing, assembly and packaging of the components.
- → The expected environmental effects such as temperature humidity and chemical toxicity that the product is designed for.
- → Adequate overcapacity in the packaging design for mishandling and accidents.
- → proper choice of materials for the reliability of the package.
- → Achieving minimum electrical feed-throughs and bond in order to minimize the probability of wire breakage and malfunctioning.

Microsystem packaging levels.

- 3 levels
  - Level 1 : Die level.
  - Level 2 : Device "
  - Level 3 : System ".

submicrometer

Figure 11.3 | The three levels of microsystem packaging.



Die level packaging:

Objectives:

→ To protect the die or other core elements from plastic deformation and cracking.

→ To protect the active circuitry for signal transduction of the system.

→ To provide necessary electrical and mechanical isolation of these elements.

→ To ensure that the system functions at both normal operating and overload conditions.

Device level packaging:

- Includes the proper signal conditioning and processing which in most cases involves electric bridges and signal conditioning circuitry for sensors and actuators. Proper regulation of input electric power is always necessary.

· Major challenge to design engineers at this level of packaging are as following.

... etching ...

1. The interfaces of delicate dice and core elements with other parts of the packaged product at radially different sizes.

2. The interfaces of these delicate elements with the environmental, particularly in regard to factors such as temperature, pressure and toxicity of the working and the contacting media.

System level packaging.

- It involves the packaging of primary signal circuitry with the die or core element unit.
- System level packaging requires proper mechanical and thermal isolation as well as electromagnetic shielding of the circuitry.
- Metal housings usually give excellent protection from mechanical and electromagnetic influences.
- The interface issue at this level of packaging is primarily the fitting of components of radically different sizes.
- Assembly tolerence is the more serious problem at this level of packaging than at the device level.

Interfaces in Microsystem packaging.

Biomedical Interface:

The packaged systems need to be biologically compatible with human systems and they are expected to function for a specific lifetime.

Requirements for biomedical interface:

1. Be inert to chemical attack during the useful lifetime of the unit.

2. Cause no damage or harm to the surrounding biological cells in instrumented catheters such as pacemakers.

3. Cause no undesirable chemical reactions such as corrosion between the packaged device and the contacting cells.

Optical Interface:

Requirements:

1- proper passage for the light beams to received and reflected.

2. proper coating of the surface on which light beams are received and reflected.

3. Enduring quality of the coated surface during the lifetime of the device.

4. Free from contamination of foreign substance and moisture in the enclosure.

Mechanical Interface:

- It is a design issue with moving parts in MEMS these parts need to be interfaced with their driving mechanisms.

- Thermal contact conditions at the interfaces can result in negative effects on performance or overstress of the diaphragm structure.

- Mechanical sealing at the interfaces is another major problem to be overcome in this type of MEMS graphy is one of

Electromechanical Interface. (14)

- Electrical isolation, grounding and shielding are typical problems associated with MEMS and microsystems. Selection of materials for electrical terminals and the shielding of electrical conductors for microdevices is another major consideration in the packaging.

- Die preparation, surface bonding, Soldering, Anodic bonding, wire bounding, thermocompression wire bonding etc are some of the useful technologies which are useful in microsystem packaging.

- 3D packaging is a relatively mature technology in the microelectronic industry. It involves the stacking of ICs and multichip modules in compact configurations. Some of the advantages are: 1) High volumetric efficiency, 2) High capacity layer to layer signal transport 3) Ability to accomodate multiple modalities. 4) Adequate heat removal from the package layers.

Evolution of microfabrication

Microfabrication technologies originate from the microelectronics industry, and the devices are usually made on silicon wafers even though glass, plastics and many other substrate are in use. Micromachining, semiconductor processing, microelectronic fabrication, semiconductor fabrication, MEMS fabrication and integrated circuit technology are terms used instead of microfabrication, but microfabrication is the broad general term.

Traditional machining techniques such as *electro-discharge machining*, *spark erosion machining*, and *laser drilling* have been scaled from the millimeter size range to micrometer range, but they do not share the main idea of microelectronics-originated microfabrication: replication and parallel fabrication of hundreds or millions of identical structures. This parallelism is present in various imprint, casting and moulding techniques which have successfully been applied in the microregime. For example, injection moulding of DVDs involves fabrication of submicrometer-sized spots on the disc.

Microfabrication is actually a collection of technologies which are utilized in making microdevices. Some of them have very old origins, not connected to manufacturing, like lithography or etching. Polishing was borrowed from optics manufacturing, and many of the vacuum techniques come from 19th century physics research. Electroplatingis also a 19th-century technique , adapted to produce micrometre scale structures, as are various stamping and embossing techniques.

To fabricate a microdevice, many processes must be performed, one after the other, many times repeatedly. These processes typically include depositing a film, patterning the film with the desired micro features, and removing (or etching) portions of the film. Thin film metrology is used typically during each of these individual process steps, to ensure the film structure has the desired characteristics in terms of thickness (t), refractive index (n) and extinction coefficient (k), for suitable device behavior. For example, in memory chipfabrication there are some 30 lithographysteps, 10 oxidation steps, 20 etching steps, 10 doping steps, and many others are performed. The complexity of microfabrication processes can be described by their *mask count*. This is the number of different pattern layers that constitute the final device. Modern microprocessors are made with 30 masks while a few masks suffice for a microfluidicdevice or a laser diode. Microfabrication resembles multiple exposure photography, with many patterns aligned to each other to create the final structure.

Microfabricated devices are not generally freestanding devices but are usually formed over or in a thicker support substrate. For electronic applications, semiconducting substrates such as silicon wafers can be used. For optical devices or flat panel displays, transparent substrates such as glass or quartz are common. The substrate enables easy handling of the micro device through the many fabrication steps. Often many individual devices are made together on one substrate and then singulated into separated devices toward the end of fabrication.

Microfabricated devices are typically constructed using one or more thin films (see Thin film deposition). The purpose of these thin films depends on the type of device. Electronic devices may have thin films which are conductors (metals), insulators (dielectrics) or semiconductors. Optical devices may have films which are reflective, transparent, light guiding or scattering. Films may also have a chemical or mechanical purpose as well as for MEMS applications. Examples of deposition techniques include:

- Thermal oxidation
- Local oxidation of Silicon (LOCOS)

- Chemical Vapor Deposition (CVD)
  - APCVD
  - LPCVD
  - PECVD
- Physical Vapor Deposition (PVD)
  - Sputtering
  - Evaporative deposition
  - Electron beam PVD
- Epitaxy
- **PatterningEdit**

  It is often desirable to pattern a film into distinct features or to form openings (or vias) in some of the layers. These features are on the micrometer or nanometer scale and the patterning technology is what defines microfabrication. The patterning technique typically uses a 'mask' to define portions of the film which will be removed. Examples of patterning techniques include:

- Photolithography
- Shadow Masking

- **Etching**

  Main article: Etching (microfabrication)

  Etching is the removal of some portion of the thin film or substrate. The substrate is exposed to an etching (such as an acid or plasma) which chemically or physically attacks the film until it is removed. Etching techniques include:

- Dry etching (Plasma etching) such as Reactive-ion etching (RIE) or Deep reactive-ion etching(DRIE)
- Wet etching or Chemical Etching

The MEMS technology has evolved a lot in the past years and a lot of revolutionary devices have been developed at a very low cost. It will take originality and creativity to make it possible, and even so it may never be. It is a promising direction, and, as with all basic research, one pursues it for that reason while at the same time realizing that the unexpected is expected.

1.4 | MICROSYSTEMS AND MICROELECTRONICS

It is a well-recognized fact that microelectronics is one of the most influential technologies of the twentieth century. The boom of the microelectromechanical systems industry in recent years would not have been possible without the maturity of microelectronics technology. Indeed, many engineers and scientists in today's MEMS industry are veterans of the microelectronics industry, as the two technologies do share many common fabrication technologies. However, overemphasis on the similarity of the two technologies is not only inaccurate, but it can also seriously hinder further advances of microsystems development. We will notice that there are significant differences in the design and packaging of microsystems from that of integrated circuits and microelectronics. It is essential that engineers recognize these differences and develop the necessary methodologies and technologies accordingly. Table 1.1 summarizes the similarities and differences between the two technologies.

Table 1.1 | Comparison of Microelectronics and Microsystems

Microelectronics	Microsystems (silicon-based)
Uses single crystal silicon die, silicon compounds, and plastic	Uses single-crystal silicon die and a few other materials, such as GaAs, quartz, polymers, and metals
Transmits electricity for specific electrical functions	Performs a great variety of specific biological, chemical, electromechanical, and optical functions
Stationary structures	May involve moving components
Primarily 2-D structures	Complex 3-D structures
Complex patterns with high density over substrates	Simpler patterns over substrates
Fewer components in assembly	Many components to be assembled
IC die is completely protected from contacting media	Sensor die is interfaced with contacting media
Mature IC design methodology	Lack of engineering design methodology and standards
Large number of electrical feedthroughs and leads	Fewer electrical feedthroughs and leads
Industrial standards available	No industrial standards to follow
Mass production	Batch production or on customer-needs basis
Fabrication techniques are proved and well documented	Many microelectronics fabrication techniques can be used for production
Manufacturing techniques are proved and well documented	Distinct manufacturing techniques
Packaging technology is relatively well established	Packaging technology is at the infant stage

We may observe from the table that there are indeed sufficient differences between the two technologies. Some of the more significant differences between these two technologies are:

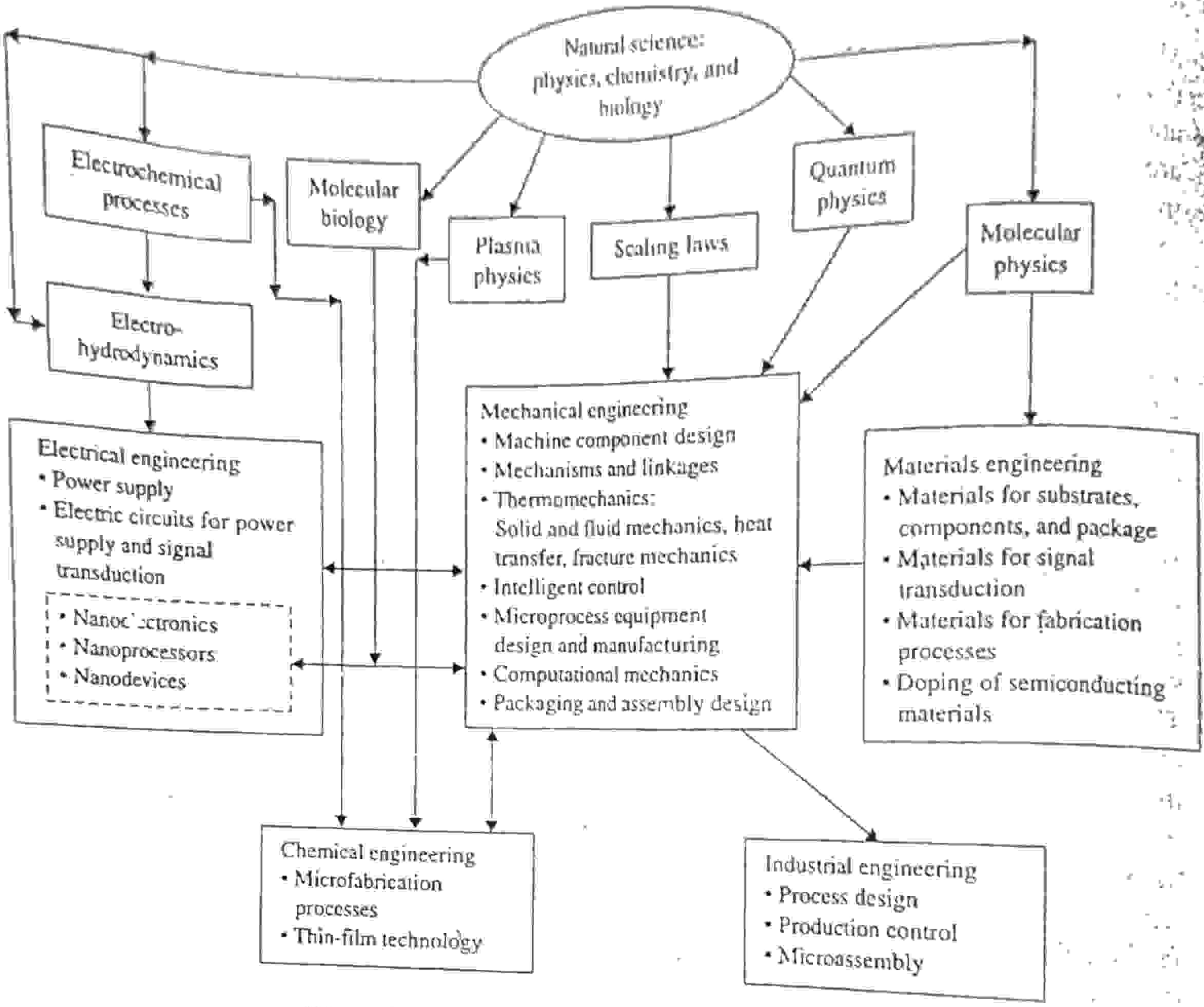
1. Microsystems involve more different materials than microelectronics. Other than the common material of silicon, there are other materials such as quartz and GaAs used as substrates in microsystems. Polymers and metallic materials are common in microsystems produced by LIGA processes. Packaging materials for microsystems include glasses, plastic, and metals, which are excluded in microelectronics.
2. Microsystems are designed to perform a greater variety of functions than microelectronics. The latter are limited to specific electrical functions only.
3. Many microsystems involves moving parts such as microvalves, pumps, and gears. Many require fluid flow through the systems such as biosensors and analytic systems. Micro-optical systems need to provide input/output (I/O) ports for light beams. Microelectronics, on the other hand, does not have any moving component or access for lights or fluids.
4. Integrated circuits are primarily a two-dimensional structure that is confined to the silicon die surface, whereas most microsystems involve complicated geometry in three dimensions. Mechanical engineering design is thus an essential part in the product development of microsystems.
5. The integrated circuits in microelectronics are isolated from the surroundings once they are packaged. The sensing elements and many core elements in microsystems, however, are required to be in contact with working media, which creates many technical problems in design and packaging.
6. Manufacturing and packaging of microelectronics are mature technologies with well-documented industry standards. The production of microsystems is far from that level of maturity. There are generally three distinct manufacturing techniques, as will be described in Chapter 9. Because of the great variety of structural and functional aspects in microsystems, the packaging of these products is indeed in its infant stage at the present time.

The slow advance in the development of microsystems technology is mainly attributed to the complex nature of these systems. As we will learn from Section 1.5, there are many science and engineering disciplines involved in the design, manufacture, and packaging of microsystems.

1.5 | THE MULTIDISCIPLINARY NATURE OF MICROSYSTEM DESIGN AND MANUFACTURE

Despite the fact that micromanufacturing evolved from IC fabrication technologies, there are several other science and engineering disciplines involved in today's microsystems design and manufacturing. Figure 1.14 illustrates the applications of principles of natural science and several engineering disciplines in this process.

Figure 1.14 | Principal science and engineering disciplines involved in microsystem design and manufacture.



With reference to Figure 1.14, natural science is deeply involved in the following areas:

1. Electrochemistry is widely used in electrolysis to ionize substances in some micromanufacturing processes. Electrochemical processes are also used in the design of chemical sensors. More detail will be given in Chapters 2 and 3.
2. Electrohydrodynamics principles are used as the driving mechanisms in fluid flows in microchannels and conduits, such as those for capillary fluid flow, as will be described in Chapters 5 and 10.
3. Molecular biology is intimately involved in the design and manufacture of biosensors and biomedical equipment, as will be shown in Chapter 2. Much of the basic molecular biology principles are used in nanotechnology to make products such as nanoprocessors and nanodevices.
4. Plasma physics involves the production and supply of ionized gases with high energy. It is required for etching and deposition in many microfabrication

processes. The generation of plasma will be covered in Chapter 3, whereas the application of plasma in microfabrication will be described in Chapter 8.

5. Scaling laws provide engineers with a sense for the scaling down of physical quantities involved in the design of microdevices. We will realize from Chapter 6 that not all physical quantities can be scaled down favorably.
6. Quantum physics is used as the basis for modeling certain physical behaviors of materials and substances in microscales, as will be described in regard to microfluid flow and heat transportation in solids in Chapter 5.
7. Molecular physics provides many useful models in the description of materials at microscales, as well as the alteration of material properties and characteristics used in microsystems, as will be described in Chapters 3 and 7. Molecular dynamics theories are the principal modeling tool for describing mechanical behavior of materials in nanoscale.

Five engineering disciplines are involved in microsystem design, manufacture, and packaging as described below:

1. Mechanical engineering principles are used primarily in the design of microsystem structures and the packaging of the components. These would involve many aspects of design analyses as indicated in the central box in Figure 1.14. Intelligent control of microsystems has not been well developed, but it is an essential part of *micromechatronics systems*, which are defined as intelligent microelectromechanical systems.
2. Electrical engineering involves electrical power supplies and the functional control and signal processing circuit design. For integrated microsystems, e.g., "laboratory-on-a-chip," the IC and microelectronic circuitry that integrates microelectronics and microsystems makes electrical engineering a major factor in the design and manufacturing processes.
3. Chemical engineering is an essential component in microfabrication and micromanufacturing, as will be described in Chapters 8 and 9. Almost all such processes involve chemical reactions. Some of microdevice packaging techniques also rely on special chemical reactions, as will be described in Chapter 11.
4. Materials engineering offers design engineers a selection of available materials that are amenable to microfabrication and manufacturing, as well as packaging. Theories of molecular physics are often used in the design of materials' characteristics, such as doping of semiconducting materials for changing electrical resistivity of the material. Materials engineering plays a key role in the development of chemical, biological, and optical sensors, as will be described in Chapter 2.
5. Industrial engineering relates to the production and assembly of microsystems. Optimum design of the fabrication process and control is essential in microsystem production.

MODULE II

MICRO MANUFACTURING TECHNIQUES:

Almost all microfabrication techniques or processes involve physical and chemical treatment of materia. The demand of industries for micromanufacturing of various types of materials (metallic, ceramics and plastics) is increasing day by day. Miniature parts have applications in various industries like electronics, medicine, communication, avionics and others.

Various techniques are:

1. PHOTOLITHOGRAPHY.

Photolithography is one of the most important steps in microfabrication.

The photolithography process involves the use of an optical image and a photosensitive film to produce a pattern on a substrate. It is the only technique that is available at present to create patterns on substrate with submicrometer resolution.

- used in:
  - → used to set patterns for masks for cavity etching in bulk micromanufacturing
  - → used for thin film deposition and etching of sacrificial layers in surface micromachining
  - → used for the primary circuitry of electrical signal transduction in sensors and actuators.
  - → widely used in IC manufacturing.

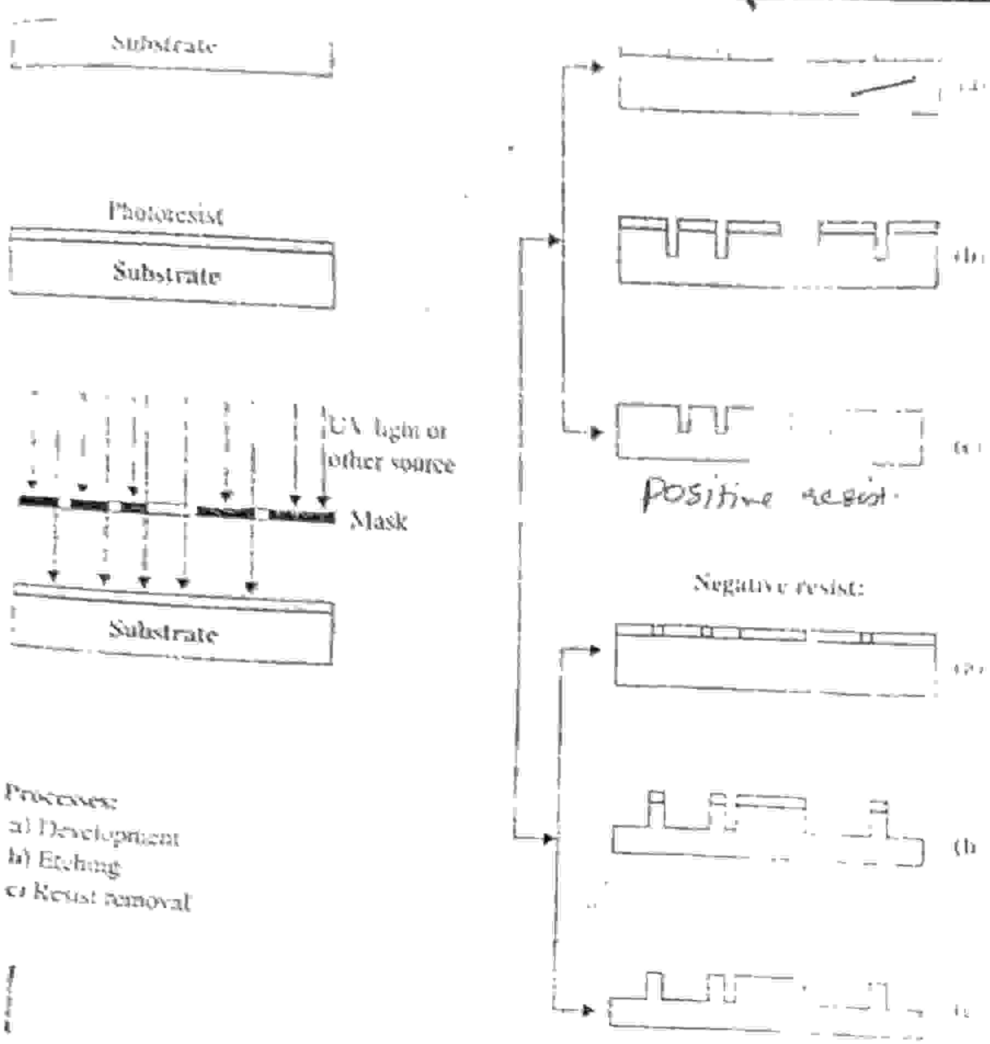


Fig: General Procedure for Photolithography.

Photolith requirement

* High Resolution
* High P.R. Sensiti.
* precision Alignment
* precise process parameter contro
* low DEFECT density.

Applications: ① used to produce computer chips
② IC patterning process ③ Printed electronic board
④ Name plate, printer plate etc.
(Photoresists is an organic polymer which becomes soluble/insoluble when exposed to UV light).

Substrate: Substrate can be a silicon wafer such as SiO_2 or siliconnitride. A photoresist is first coated onto the flat surface of the substrate. It is then exposed to a set of lights through a transparent mask with the desired patterns. mask made of Quartz. Patterns on the mask are photographically reduced from macro- or mesosizes to the desired microscales. photoresists materials change their solubility when they are exposed to light.

Positive photoresists: photoresists that become more soluble under light, → Better resolution

Negative " : It become more soluble under shadow → Cheaper.

∴ The retained photoresists materials create the imprinted patterns after the development. (step (a)).
The portion of the substrate under the shadow of the photoresists is protected from the subsequent etching (step
A permanent pattern is thus created in the substrate after the removal of the photoresists (step c).

- photolithography for MEMS and microsystems needs to be performed in a class-10 clean room. The class no: of a clean room is a designation of the air quality in (A class 10 clean room means that the no: of dust particles, .5μm or larger in a cubic foot of air in the room is less than 10)

Light source: The most popular light source for photolithography is the mercury vapor lamp. This light source provides a wavelength spectrum from 310 to 440nm. For high resolution X-rays are used. X-rays have the wavelength of the range of 4 to 50Å ($1Å = 0.1nm$ or $10^{-4}μm$)

Ion Implantation: – Applns: Applⁿ in metal finishing, Ion beam mixing, semiconductor device fabrication.
Challenges: crystallographic damage, Amorphization, Sputtering

→ Ion implantation involves 'forcing' free atoms such as boron or phosphorus (with charged particles, ie ions) into a substrate and thereby achieving imbalance between the no: of protons and electrons in the resulting atomic structure. → These ions (whether Boron or Phosphorus ions) must carry sufficient kinetic energy to be implanted (ie, to penetrate into Si substrate.

→ ∴ The ion implantation procedure always involves the acceleration of the ions in order to gain sufficient kinetic energies for the implantation

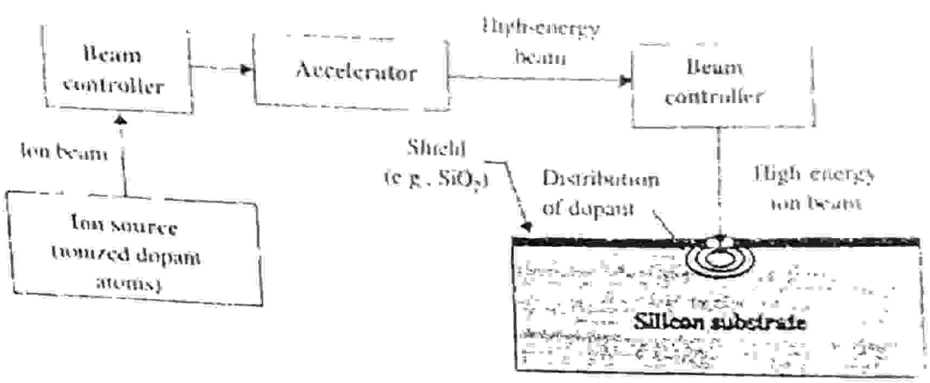
- Ion implantation is low-temperature process by which ions of one element are accelerated into a target, thereby changing the physical, chemical or electrical properties of the target.

Working
- The fig. below shows how ions can be produced in an ion source in which an ion beam is formed.

- The ion beam is led into a beam controller in which the size and direction of the beam can be adjusted.
- The ions in the beam are then energized in the acceleration tube or accelerator.

- Then using beam controller the ion beams are focused on to the substrate, which is protected by a shield (usually SiO_2)
- The ions will transfer all their energy to the substrate upon collision and finally come to a stop at a certain depth inside the substrate.

Figure 8.4 | Ion implantation on a substrate



Thermal ... used in semiconductors and mechanical industries
→ used mainly in semiconductors and mechanical industries
→ Application in surface treatment process
→ Biomedical Application: ① Metal parts as heart valves are ion implanted by carbon to make them biocompatible
② Radio isotops are implanted in prosthesis (artificial body parts) for radio therapy.

2. Chemical Vapour Deposition (CVD)

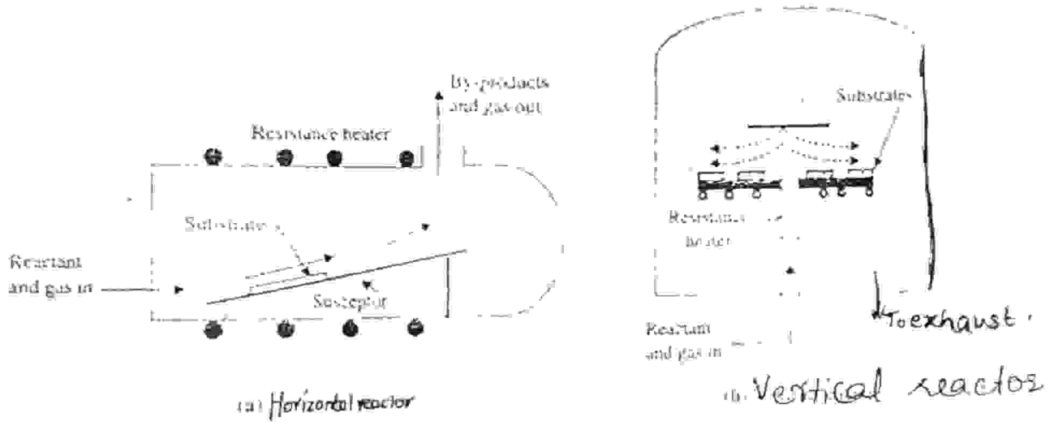
- CVD is a chemical process used to produce high purity, high performance solid materials, typically under vacuum.
- used in: Semiconductor industry.
: useful in the process of atomic layer deposition

Df: CVD is a process whereby a solid material is deposited from a vapor by a chemical reaction occuring on or in the vicinity of a normally heated substrate surface.
- Solid material is obtained as a coating, a powder or as single crystals.
- By varying the experimental conditions such as materia substrate temp, composition of reaction gas mixture, total pressure gas flows etc, materials with different properties can be grown
- CVD is an example for solid vapor reaction.

Working principle: It involves the flow of a gas with a diffused reactants over a hot substrate surface. The gas that carries the reactant is called the carrier gas.

- While the gas flows over the hot solid surface, the energy supplied by the surface temperature provokes ch. reactions of the reactants that form films during and after the reactions.
- The by-products of the chemical reactions are then vented.
- Thin films of desired composition can thus be created over the surface of the substrate.

Figure 8.9 | Two typical CVD reactors.



Chemical reactions in CVD.

1. **Deposition of Silicon dioxide over Silicon substrate.**

$$SiH_4 + O_2 \longrightarrow SiO_2 + 2H_2.$$

The chemical reaction takes place in a temp range of $400°$ to $500°C$ with an activation energy around $E_a = 0.4\,eV$

2. Deposition of Silicon Nitride over Silicon substrate.

$$3SiH_4 + 4NH_3 \longrightarrow Si_3N_4 + 12H_2.$$

$$3SiCl_4 + 4NH_3 \rightarrow Si_3N_4 + 12HCl.$$

$$3SiH_2Cl_2 + 4NH_3 \rightarrow Si_3N_4 + 6HCl + 6H_2.$$

Ammonia is the common gas for depositing silicon nitride on Silicon Substrates. The temp range: 700° to 900°.
Activation energy: $E_a = 1.8\,eV$.

3. Deposition of polycrystalline silicon over silicon substrate

$$SiH_4 \rightarrow Si + 2H_2.$$

It is a pyrolysis process, which is a decomposition process using heat. Temp. range: 600 to 650°C
Activation energy 1.7 eV.

Types of CVD

2 types based on the operating pressure.

1. Atmospheric pressure CVD
2. Low pressure CVD
   - → plasma Enhanced CVD
   - → photochemical Vapour Deposition.
   - → Thermal CVD.

Atmospheric pressure CVD.

- Aluminium oxide films are deposited by this method from $AlCl_3$, argon and Oxygen gas mixture at temperature ranging from 800 - 1000 °C.
- The film have low chlorine content which continue to decrease with increasing temperature.

Limitations:
- → Film thickness uniformity cannot be maintained.
- → Large no: of pin hole defects can occur.
- → The deposits get contaminated very easily since it takes place at atmospheric pressure.

Low pressure CVD.

- Deposition of silicon carbide is performed using low pressure CVD.
- The silicon carbide film deposited at 3 different temp has 3 different properties.

  eg: 1023 K → Amorphous.
  1073 K → Microcrystalline
  1173 K → preferentially oriented.

- The process results in the deposition of compounds with excellent purity and uniformity.
- The technique requires higher temperature and deposition rate is low.

plasma Enhanced CVD.

- It utilize the radio-frequency (RF) plasma to transfer electrical energy into the reactant gases, which allows the substrates to remain at lower temperature than ~~that~~ in APCVD or low pressure CVD.
- Precise temp control of the substrate surfaces is necessary to ensure the quality of the deposit films.
- Chemical reactions are involved in the process which occur after creation of a plasma of the reacting gases.
- plasma helps in increasing the film quality at low temperature and pressure.
- Properties: → Good Adhesion.
  → Low pinhole density
  → uniformity.

Figure 8.12 | A PECVD reactor.

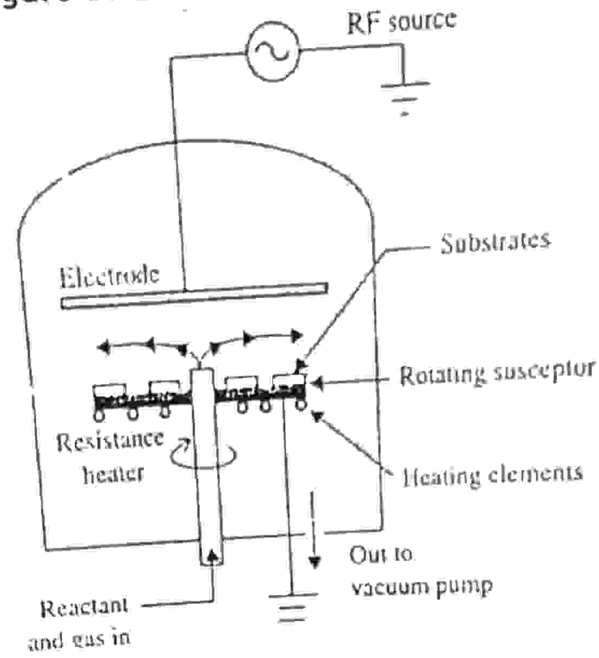
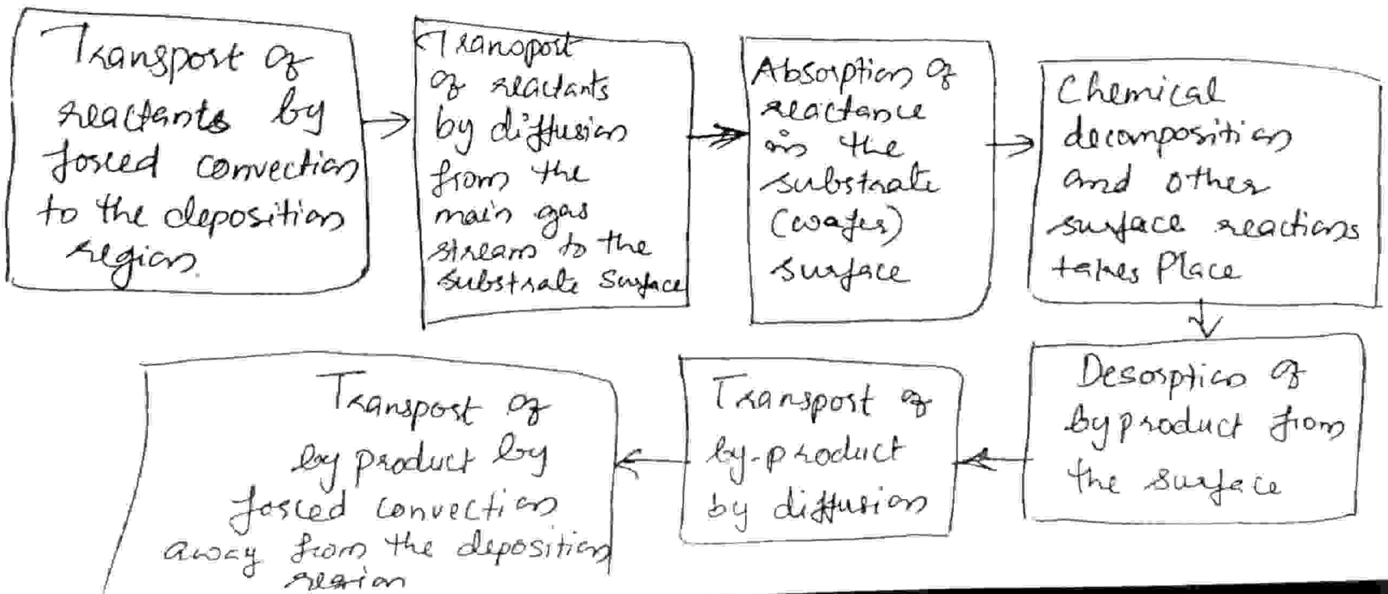


Table 8.8 | Summary and comparison of three principal CVD processes

CVD process	Pressure/ temperature	Normal deposition rates, 10^{-10} m/min	Advantages	Disadvantages	Applications
APCVD	100–10 kPa/ 350–400°C	700 for SiO_2	Simple, high rate, low temperature	[illegible] coverage, particle contamination	[illegible]
LPCVD	1–8 torr/ 550–900°C	50–180 for SiO_2, 30–80 for Si_3N_4, 100–200 for [illegible]	Excellent purity and uniformity, large wafer capacity	High temperature and high [illegible] deposition rates	[illegible] oxides [illegible]
PECVD	0.2–5 torr/ 300–400°C	300–350 for Si_3N_4	Lower substrate temperature, fast, good adhesion	Vulnerable to [illegible] contamination	[illegible]

Various steps involved in CVD.



Thermal CVD.

Here temp. as high as 2000°C is needed to deposit the compounds.

2 basic types of reactors for thermal CVD.

1. Hot water reactor
2. Cold water reactor.

- A hot water reactor is an isothermal surface into which the substrates are placed. But disadvantage is that deposition occurs on the walls of the chamber as well as on the substrate. Here higher throughput can achieved.
- In cold water reactor, only the substrate is heated. Deposition takes place on the area of the highest temperature since CVD reactions are generally endothermic. Here Contamination of particle is reduced considerably because the deposition is only on the substrate.

Advantages of CVD

- Versatile - Any element or compound can be deposited
- High purity can be obtained.
- High density
- Economical in production.

Application.

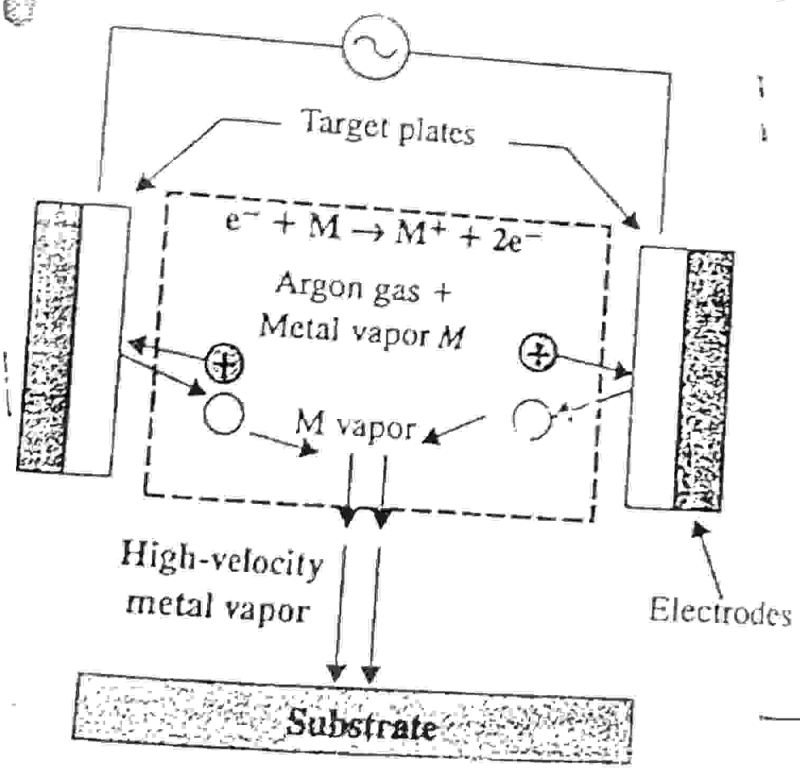
- Appln's in coatings. (ex: wear resistance, corrosion resistance, high temp protection etc)
- Appln in IC's, sensors and optoelectronics devices
- Appln in powder production.

PHYSICAL VAPOR DEPOSITION

- PVD and CVD are the techniques that are used to create a very thin layer of material into a substrate commonly referred to as thin films.
- PVD uses only the physical forces to deposite the layer while CVD uses the chemical process or chemical reaction.
- Most common physical methods which produce the atoms that deposit on the substrate are
  - * SPUTTERING
  - * EVAPORATION

SPUTTERING.

- Sputtering is a process that is often used to deposit thin metallic films in the order of 100Å thickness ($1Å = 10^{-10}m$) on the substrate surfaces. Sputtering is a term used to describe the mechanism in which atoms are ejected from the surface of a material when that surface is stuck by sufficient energetic particles.
- Sputtering process is carried out with plasma under very low pressure. This process involves low temperature compared to CVD and only very little chemical reaction will takesplace. Thus the process is regarded as physical deposition.



Applications:

1. Thin film deposition
   - Microelectronics
   - Decorative Coating
   - Protective Coating
2. Etching of targets
   - CMOS, NMOS, PMOS fabrication.
3. Surface treatment
   - Hardening.

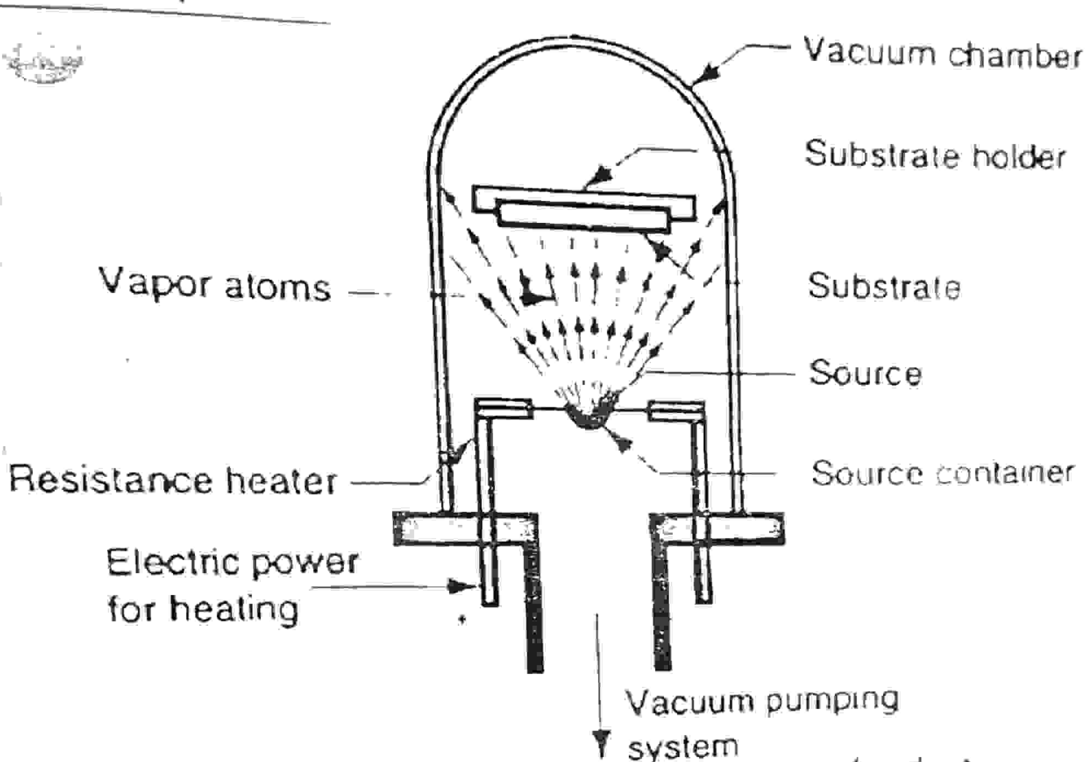
Working:

The +ve ions of the metal in an inert argon gas carrier bombard the surface of the target at such a high velocity that the momentum transfer on impingement causes the metal ions to evaporate.

The metal vapor is then led to the substrate surface and is deposited after condensation.

- Sputtering depends on: ① mass of bombarding ions ② Energy of bombarding ions ③ direction of incidence of ions ④ pressure.

Vacuum Evaporation.



- The material to be evaporated is heated in an evacuated chamber so that it attains a gaseous state.
- The vapor of this material traverse the space from the source to the substrate.
- Typical deposition rates in industry is around 0.5 μm/min.
- Al and Au is quite usable in thermal evaporation system with heated crucible, and can be melt in crucible and generate enough quantity of vapors.

→ Adv: ① Little damage to the wafer
② Deposited films are usually very pure.

PVD Advantages and Disadvantages

Advantages

→ PVD coatings are harder and corrosion resistant than electroplating coatings.

→ PVD coatings have high temperature and good impact strength, excellent abrasion resistance and are so durable.

→ More environment friendly process

Disadvantages.

PVD needs high capital cost.

› The rate of coating deposition is usually quite slow.

› Cooling systems are required.

› Mostly high temperature and vacuum control needs skill and experience.

Application.

› Aerospace

› Automotive.

› Dies and moulds for all manner of material processing.

› Cutting tools.

› optics and watches.

ETCHING PROESS.

- Etching is one of the most important processes in microfabrication.
- It involves the removal of materials in desired areas by physical or chemical means.

def: Etching is traditionally the process of using strong acid or mordant to cut into the unprotected parts of a metal surface to create a design in incised in the metal. [incised = mask or decorate with a cut or series of cut]

uses:

→ used for the selective removal of material from the surface of a PCB by means of the chemical action of an etching agent.

→ Etching usually removes the copper areas which are not desired on the finished PCB.

→ Etching is used to shape the geometry of microcomponents in MEMS and microsystems.

→ used to established permanent patterns developed at the substrate surface by photolithography.

2 Common types

1. Chemical Etching (wet etching).
2. physical Etching (Dry etching or Plasma etching)

1. Chemical Etching: (Wet Etching). (8)

→ It involves using solutions with diluted chemicals to dissolve substrates.

→ eg: Diluted hydrofluoric (HF) solution is used to dissolve SiO_2, Si_3N_4 and polycrystalline silicon.

Potassium peroxide (KOH) is used to etch the silicon substrates.

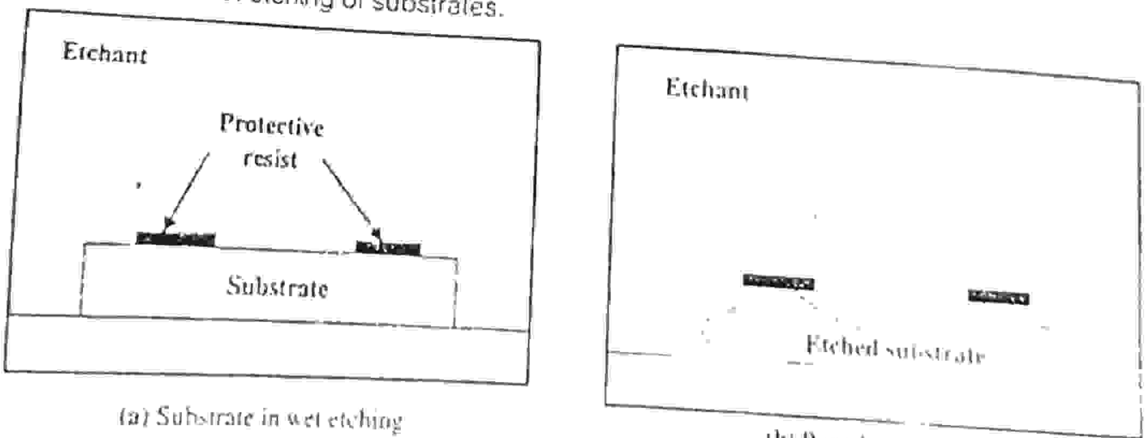
→ Rate of etching vary depending on the

1. Substrate materials to be etched
2. Concentration of the chemical reactants in the sol.
3. Temperature of the solution.

→ 2 types of etching available for shaping the geometry of MEMS components

1. Isotropic etching: It is a process in which the etching of substrate takes place uniformly in all direction at the same rate.
2. Anisotropic etching: It is a process in which the etching of substrate material takesplace at faster rates in preferred directions.

Figure 9.1 | Wet etching of substrates.



(a) Substrate in wet etching

(b) Partially etched substrate

Working: The chemical solution used in etching attack the parts of the substrate that are not protected by the mask. The mask used in micromachining may be either the photoresists for SiO_2 substrate in HF solution.

Wet etching is easy to apply, and it involves inexpensive equipment and facility for the process. It is also a faster etching process than the dry etching.

Adv:

→ fast etch rate

→ Cheaper cost.

→ good etch uniformity across wafer.

→ High etch selectivity.

→ process occur at atmospheric environment.

Disadv:

→ Isotropic etching.

→ No control for precision etching.

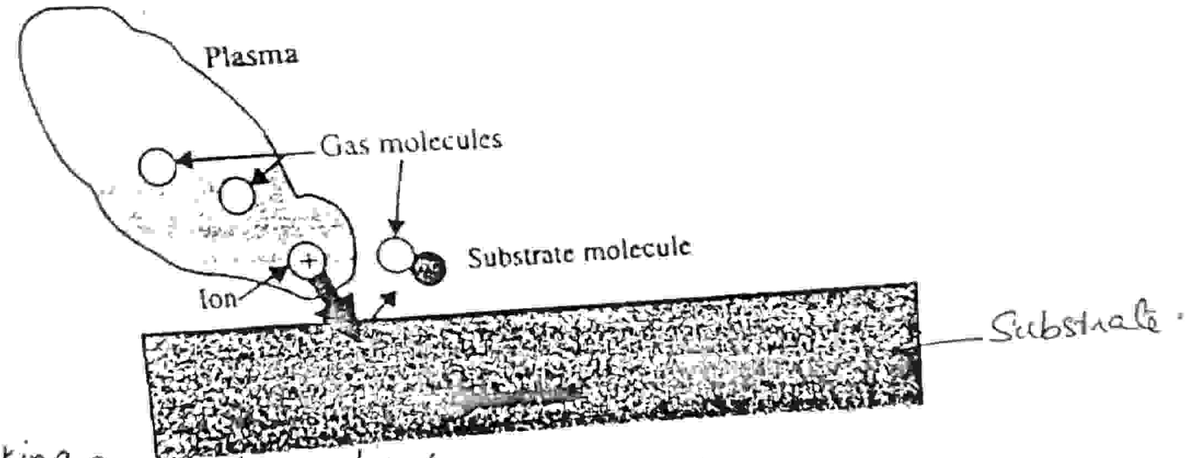
→ Poor quality of etched surface due to bubbles and flow patterns of the solutions.

→ No effective wet etching is available for some substrate such as silicon nitrides.

Working of plasma etching: The high energy plasma containing gas molecules, free electrons and gas ions bombards the surface of the target substrate and knock off the substrate material from its surface. It takes place at high vacuum.

2. Plasma Etching or Dry Etching (9)

- Plasma etching is a form of plasma processing used to fabricate integrated circuits.
- It involves a high-speed stream of glow discharge (plasma) of an appropriate gas mixture being shot (in pulses) at a sample.
- Plasma used for etching is a stream of positive-charge carrying ions of a substance with a large no. of electrons.
- It can be generated by continuous application of high-voltage electric charge, or by RF sources.
- Plasmas are normally generated in low-pressure environment or vacuum.
- Here the material removal is by ion-bombardment



Working: The high energy plasma containing gas molecules, free electrons and gas ions bombards the surface of the target substrate and knocks off the substrate material from its surface. It takes place at high vacuum

Adv.

→ It gives faster production rate.

→ very hard and brittle metals can be machined.

→ Small cavities can be machined with good dimension accuracy. → Automated easily → Accuracy is high → Dissimilar material can easily welded

Disadv:

- Its initial cost is very high.
- It is uneconomical for bigger cavities to be machined.
- Inert gas consumption is high.

MICROMACHINING. OR (Micromanufacturing)

- The techniques used to produce MEMS products such as microsensors, accelerometer and actuators etc are called micromachining.

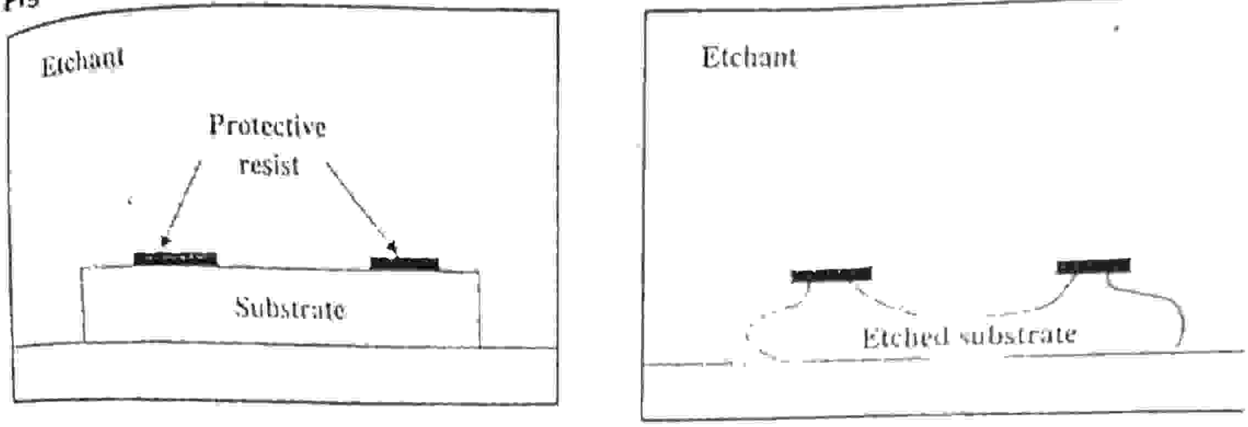
- There are 3 distinct micromachining techniques used by current industry. They are

(1) Bulk micromanufacturing
(2) Surface "
(3) LIGA process

They are the process used to create microstructure in MEMS devices

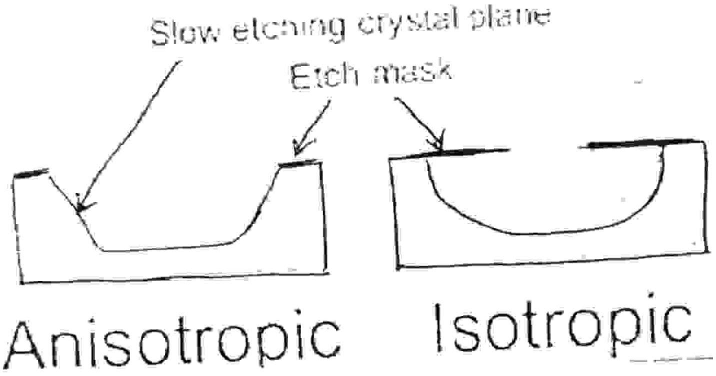
- There are other process-related micromachining techniques that have been developed in recent years. Laser drilling and machining appears to be gaining popularity.

Figure 9.1 | Wet etching of substrates.



(a) Substrate in wet etching (b) Partially etched substrate

Isotropic and Anisotropic etching :



- Isotropic etching is hardly desirable in micromanufacture because lack of control of the finished geometry of the workpiece.
- Most substrate materials are not isotropic in their crystalline structure, for eg: Silicon has a diamond cubic crystal structure. Therefore some parts in the crystal are stronger and more resistant to etching than others.
- Silicon has 3 orientation planes namely <100>, <110> and <111>. Two most common orientations used in the IC industry are the <100> and <111> orientation

(1) BULK MICROMANUFACTURING. (10)

- Bulk micromanufacturing is widely used in the production of microsensors and accelerometers.

- Bulk micromanufacturing or micromachining involves the removal of materials from the bulk substrates, usually silicon wafers to form the desired 3 dimensional geometry of the microstructure.

- It involves shaping of microsystem components of the size between 0.1μm and 1mm made of tough material such as silicon is beyond any existing mechanical means.

- physical or chemical techniques either by dry or wet etching are the only practical solutions. Substrates that can be treated this way involve silicon, SiC, GaAs and quartz.

- Key technology used in bulk micromanufacturing are:

  (1) Etching → (either orientation-independent isotropic or " dependent anisotropic)

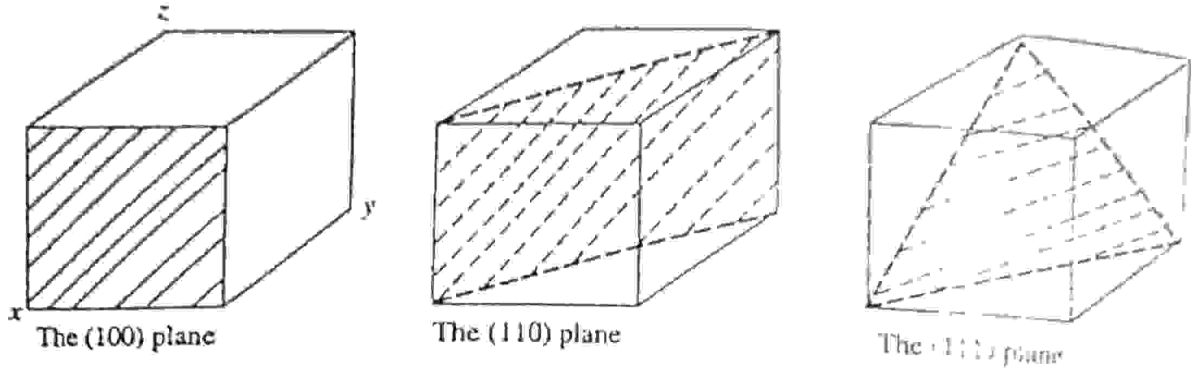
1. Overview of Etching.

(refer the previous topic)

def;

- But for micromachining, the <110> orientation is the favored orientation. This is because, in this orientation the wafer breaks or cleaves more cleanly than in the other orientations.

Figure 9.2 | The three principal planes in silicon crystal.



- usually silicon wafers are used as substrates for bulk micromachining, as they can be anisotropically wet etched forming highly regular structure.

Wet Etchants.

- The common isotropic etchant for silicon is called HNA (hydrofluoric, nitric, acetic) is an extremely aggressive acidic mixture which will vigorously attack silicon.
- HNA is an isotropic wet etchant, which etches silicon at a rate of approximately 1-3 microns per minute
- These etchants can be used effectively at room temperature.

- Selectivity ratio = $\frac{\text{Etching rate of Silicon}}{\text{Etching rate of another material with the same etchant}}$

- Higher the selectivity ratio of the material, the better the masking material it is.

- High selectivity ratio of silicon dioxide and silicon nitride (SiO_2 and Si_3N_4) makes these materials suitable for "mask" for etching silicon substrates.

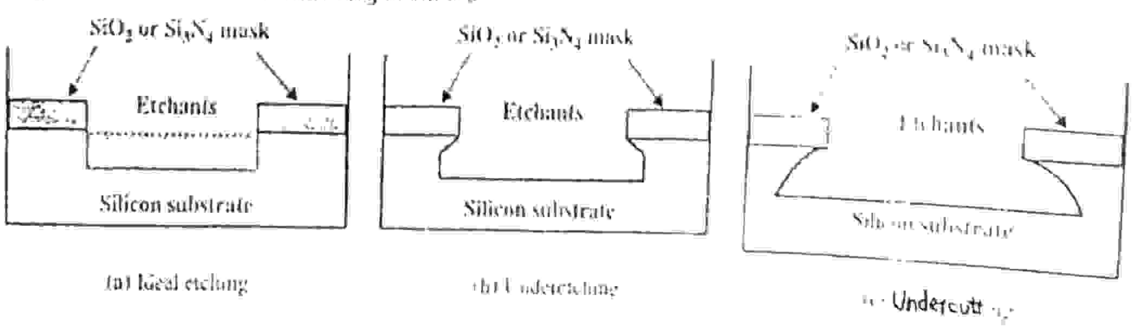
- The timing of etching and the agitated flow patterns of the etchants over the substrate surfaces need to be carefully controlled and also special caution in selecting masking mat. in order to avoid serious issues like under etching and under cutting. → Fig

Etch Stop : (A region at which net etching tends to slow down or diminish is called etch stop)

An effective way to control the shape of the etched silicon substrate and to achieve clean and accurate edge definition is to apply 'etch stop'.

These are (1) Dopant-controlled etch stop
(2) Electrochemical etch stop.

Figure 9.4 | Definition of etched geometries



Dopant controlled etch Stop. (12)

- The pure Silicon is doped with Boron for p type silicon or phospherous or Arsenic for n type Silicon. So that it shows a different etching rate than pure Silicon.
- In the case when the isotropic HNA etchants are used, the p or n areas are dissolved significantly faster than the undoped regions.
- But excessive doping of boron in silicon for faster etching can introduce lattice distortions in the silicon crystal and thus produce undesirable internal (residual) stresses.

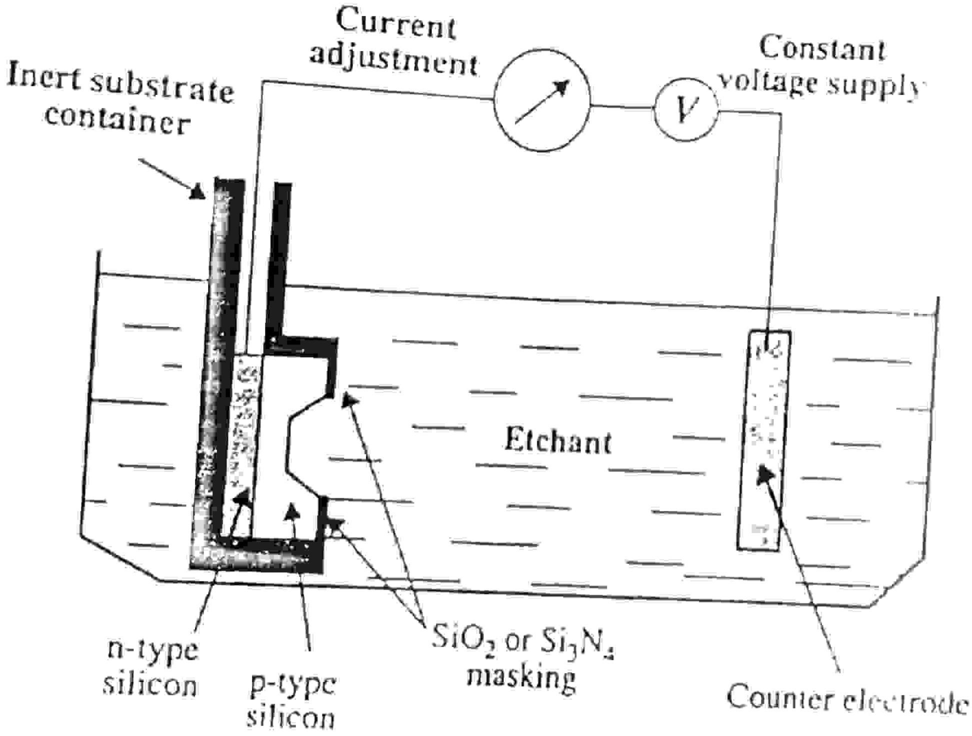
Electrochemical Etch Stop.

- Mainly used or popular for controlling anisotropic etching.
- Working:
- A lightly doped p-n junction is first produced in the Silicon wafer by a diffusion process.
- Doped Silicon Substrate is then mounted on an

inert substrate container made of a material such as Sapphire.

- The n-type silicon layer is used as one of electrodes in an electrolyte system with a constant voltage source.
- The unmasked part of the p-type substrate face is in contact with the etchant.
- Etching thus takesplace as usual until it reaches the interface of the p-n junction, at which point etching stops because of the rate difference in p and n doped silicon.
- One can effectively control the depth of etching simply by establishing the p-n silicon boundaries at the desired locations in a doped silicon substrate

Figure 9.5 | Illustrative arrangement for electrochemical etch stop.



Dry Etching:

Dry etching involves the removal of substrate materials by gaseous etchants without wet chemicals or rinsing.

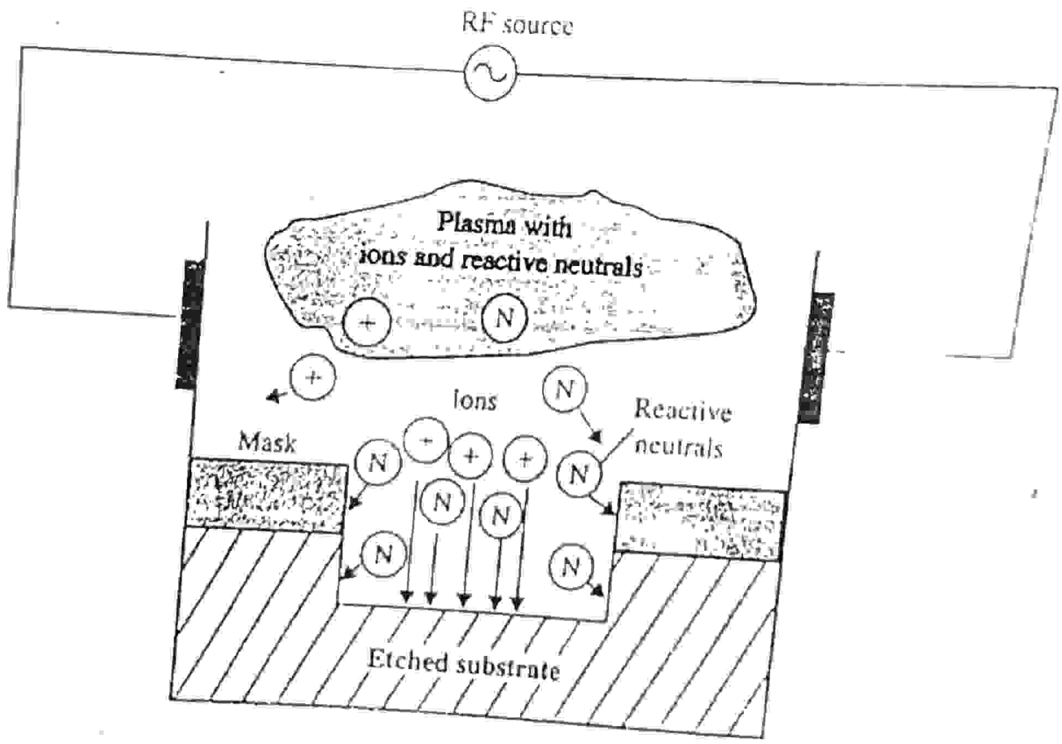
There are 3 dry etching techniques.

1. plasma Etching
2. Ion milling
3. Deep reactive ion etching.

ⓞ plasma Etching:

- plasma is a neutral ionized gas carrying a large numbers of free electrons and positively charged ions.
- Common source of energy for generating plasma is radio frequency (RF) source.
- Process involves adding a chemically reactive gas such as CCl_2F_2 (Dichlorodifluoromethane) to the plasma.
- Reactive gas produce reactive neutrals when it is ionized in the plasma.
- The reactive neutrals bombard the target on both sidewalls as well as the normal surface, whereas the charged ions bombard only the normal surface of the substrate

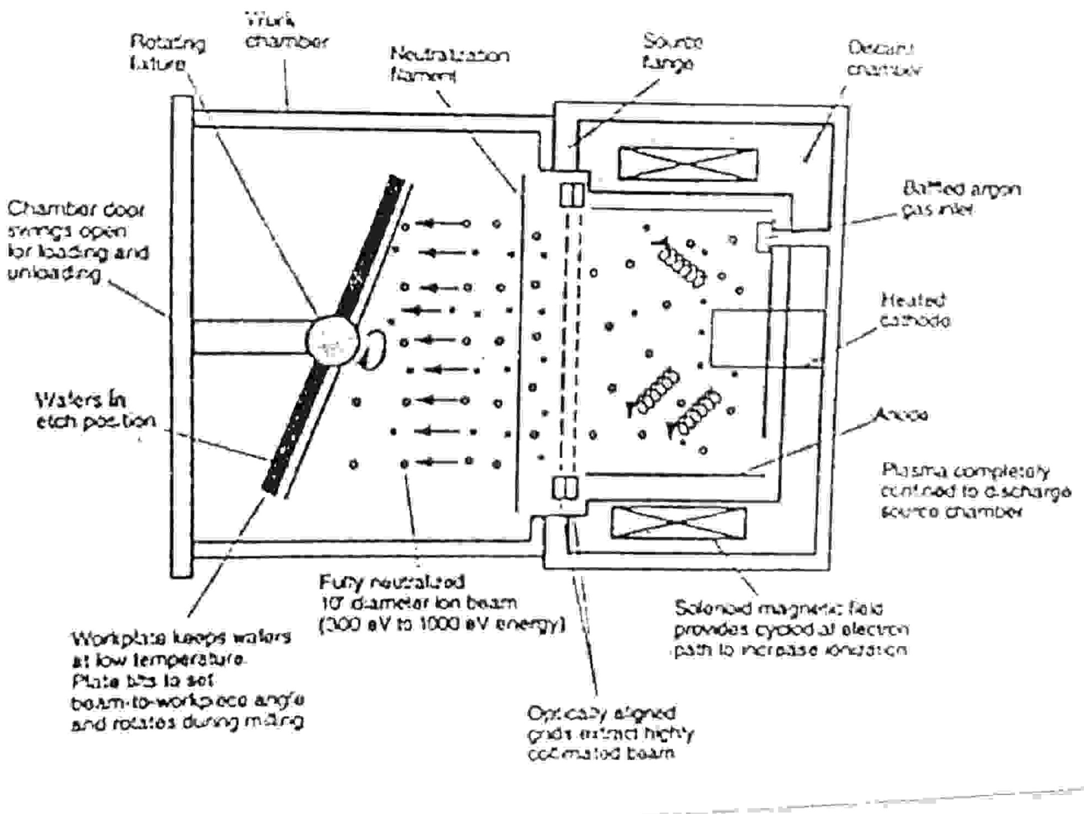
- Etching of the substrate materials is accomplished by high energy ions in the plasma bombarding the substrate surface with simultaneous chemical reaction between the reactive neutral ions and the substrate materials.
- This high energy reaction causes local evaporation and thus results in the removal of the substrate material.
- So that the etching front moves more rapidly in the depth direction than in the direction of the sidewalls. This is due to the larger no: of high energy particles involving both the neutral ions and the charged ions bombarding the normal surface, while the sidewalls are bombarded by neutral ions only.



- Dry etching of Silicon Substrate, such as by plasma, typically is faster and cleaner than wet etching.
- problem with dry etching relates to the contamination of the Substrate surface by residues.

Ion Milling:

- Also called dry ion etching method.
- In Simple terms it can be viewed as an atomic sand blaster.
- In place of actual grains of sand, Submicron ion particles are accelerated and bombard the Surface of the target work while it is mounted on a rotating table inside a vacuum chamber.



function:

→ Argon ions contained within plasma formed by an electrical discharge are accelerated by a pair of optically aligned grids. → The highly collimated beam is focused on a tilted work plate that rotates during the milling operation.

→ A neutralization filament prevents the buildup of positive charge on the work plate.

→ As in the fig, the work plate is cooled and rotates so as to ensure even uniformity of the ion beam bombardment.

→ The work plate usually sits at an 8° to 10° angle to the ion beam.

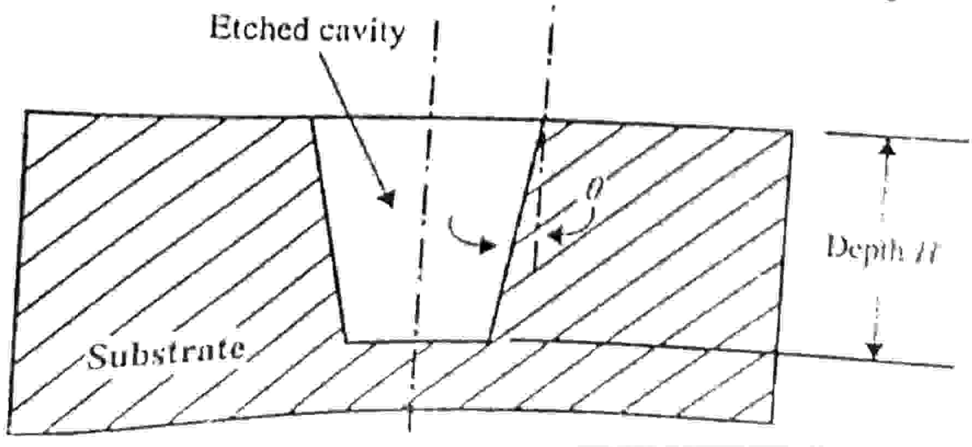
Definition: (Notes). Introduction. or 2 Marks: ⇒ Ion milling is a physical etching technique whereby the ions of an inert gas (typically Ar) are accelerated from a wide beam ion source into the surface of a substrate (or coated substrate) in vacuum in order to remove material to some desired depth or underlayer. It is easily visualized as "atomic sandblasting" or more accurately "ionic sandblasting".

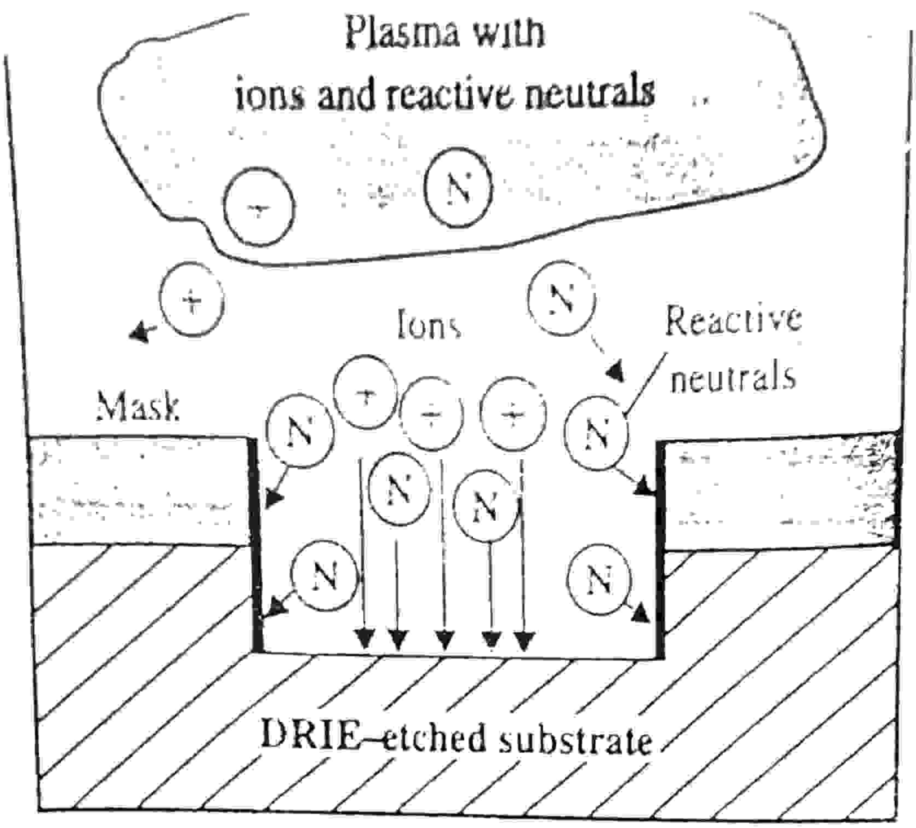
Deep Reactive Ion Etching (DRIE).

One of the disadvantage of plasma etching is, the etched walls in the trenches remains at a wide angle (θ) to its depth. This problem can be overcomed by using DRIE. $\therefore \theta \approx 0$.

Working:

- It produces thin protective films of a few μm on the sidewalls during the etching process.
- It involves the use of high-density plasma source which allows alternating processes of plasma (ion) etching of the substrate material and the deposit of etching protective material on the sidewalls.
- Suitable etching protective materials (shown in Black) are those materials of high selective ratio such as SiO_2. Polymers are also frequently used for this purpose.
- There are a no: of reactant gases that could be used in DRIE. One among them is fluropolymers (nCF_2) in plasma of Argon gas ions.
- This reactant can produce a polymer protective layer on the side walls while etching takes place.





(b) The DRIE process

COMPARISON OF DRY ADD WET ETCHING

DRY	WET
Dry etching is the process of etching done at plasma phase	Wet etching is the process of etching done at liquid phase
Uses gaseous phase chemicals	Uses liquid phase chemicals
Much safer than wet etching	Not safe since disposing of hazardous chemicals can cause water contamination
More precise	Less precise
Uses few chemicals	Uses many chemicals
Expensive because specialized equipment is required	Not very expensive because it needs only a chemical bath

Surface Micromachining:

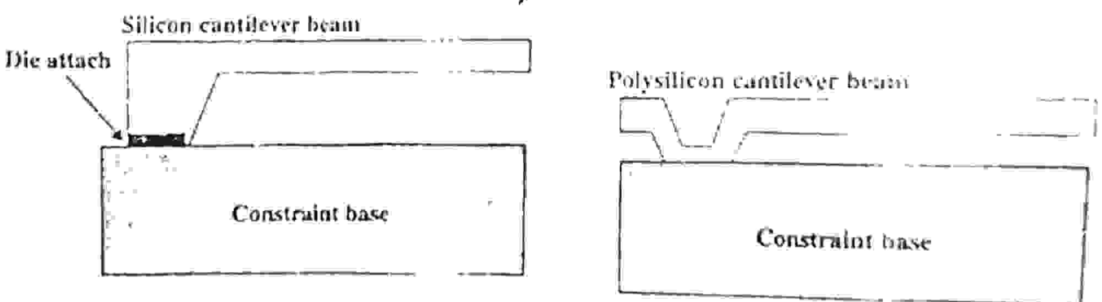
In bulk micromachining :→ It removes the substrate material by physical or chemical means.

→ But in surface machining : It builds microstructure by adding materials layer by layer on top of the substrate.

→ Deposition techniques, in particular the low pressure Chemical vapor deposition (LPCVD) technique are used for layer material.

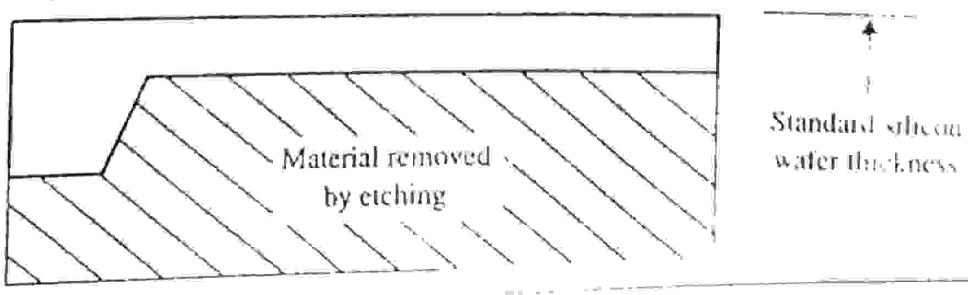
- Sacrificial layers made of SiO_2 are used in constructing the MEMS components but are later removed to create necessary void space in the depths. For this wet etching is the common method.

Figure 9.8 | Microcantilever beams produced by two micromachining techniques



(a) By bulk micromachining (b) By surface micromachining

Figure 9.9 | Waste of material in bulk micromanufacturing



Process in General

Surface micromachined devices are typically made up of 3 types of components

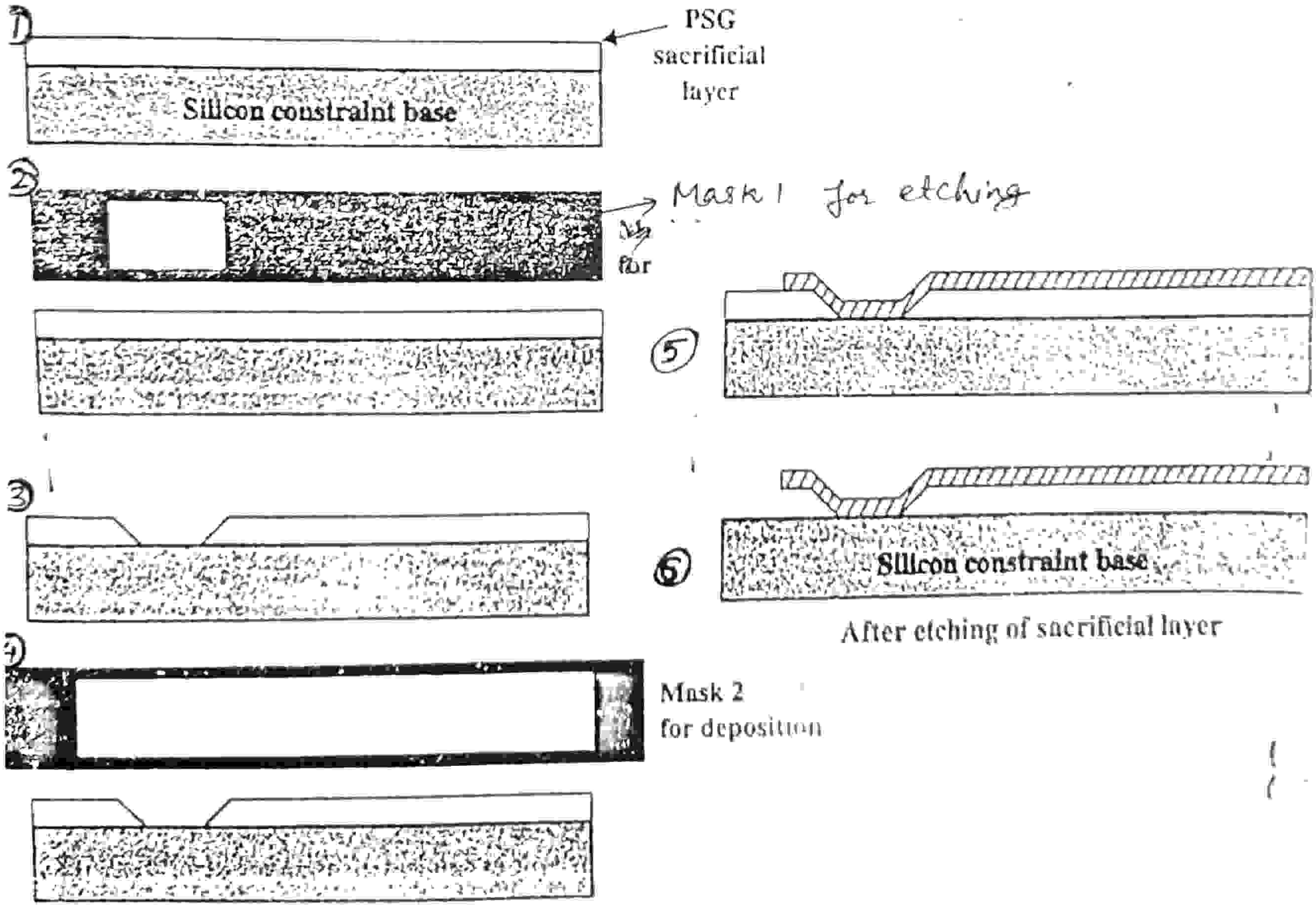
① A sacrificial component (called spacer layer)

② A microstructural "

③ An insulator component.

→ Sacrificial components are usually made of phosphosilicate glass (PSG) or SiO_2 deposited on substrates by LPCVD techniques.

ure 9.10 | Surface micromachining process.



Step 1: A Silicon substrate base with a PSG deposited on its surface.

Step 2 & 3: A mask is made to cover the surface of the PSG layer for the subsequent etching to allow for the attachment of the future Cantilever beam.

Step 4: Another mask is made for the deposition of polysilicon microstructural material.

Step 5: The PSG that ~~remains in step 5~~ is subsequently etched away to produce the desired Cantilever beam, as shown in step 6.
- The most suitable etchant is 1:1 HF.

Step 6: After etching, the structure is rinsed in deionized water thoroughly followed by drying under infrared lamps and the final product is manufactured.

Mechanical problems associated with Surface Micromachining

3 Main problems
1. Adhesion of layers.
2. Interfacial stresses
3. Stiction.

① Adhesion of layers.

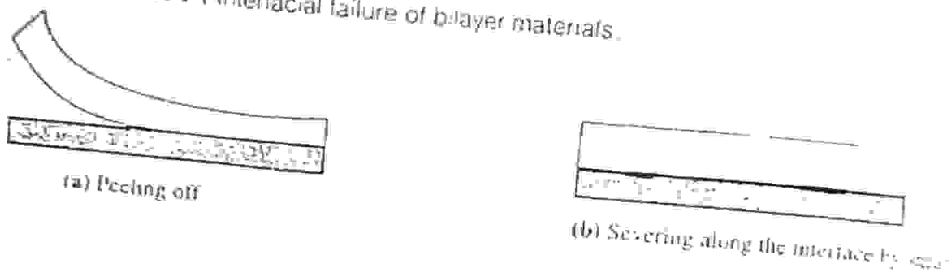
→ Whenever two layers of materials, whether similar or dissimilar are bonded together, a possibility of delamination exists. {Delamination = Separation into Constituent Layers}

→ A bilayer structure can delaminate at the interface
either by peeling of one layer from the outer or
by shear that causes the severing of the interfaces
locally along the interface.

→ Main Cause : Excessive thermal and mechanical stress.

→ Other causes : Surface conditions, like ① cleanliness,
② Roughness and ③ absorption energy.

Figure 9.11 | Interfacial failure of bilayer materials.



II. Interfacial Stresses :

3 types
① Thermal stresses.
② Residual "
③ Intrinsic stress.

① Thermal Stresses : → Caused from the mismatch of
the coefficients of thermal expansion of the component
materials.

→ Severe thermal stress can cause the delamination
of the SiO_2 layer from the silicon substrate
when the bilayer structure is subjected to high

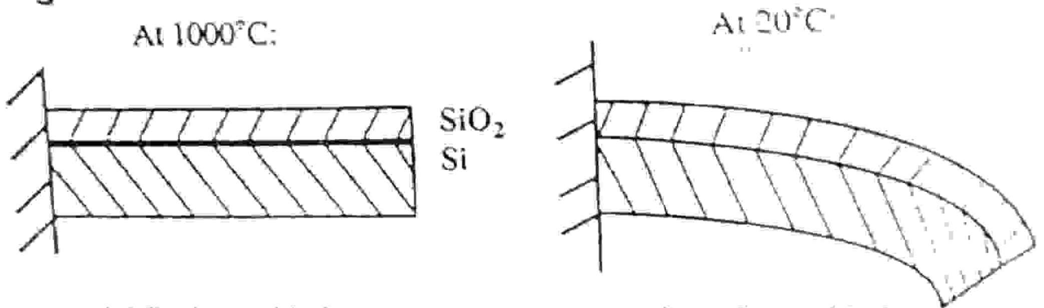
(2): Residual stresses.

Use: If there is a significant difference in the CTE (co-efficients of thermal expansion). ~~for~~

(i) → for eg:- a SiO_2 layer grown on the top surface of a silicon substrate beam at 1000°C by a thermal oxidation process, as shown in fig (a)

→ The resultant shape of the bilayer beam at room temperature will be different as in fig (b)

Figure 9.12 | Residual stress and strain in a bilayer beam



(a) During oxidation (b) After oxidation

→ Excessive tensile residual stress in SiO_2 layer can cause multiple cracks in the layer.

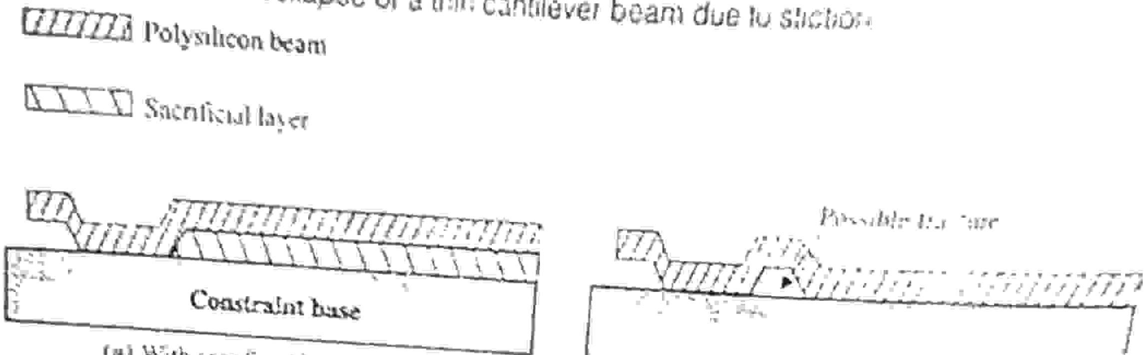
(3) Intrinsic stress

→ It is due to local change ~~or in~~ ~~thin films~~ atomic structures during microfabrication process.

→ Another reason is excessive doping.

III Stiction.

Figure 9.13 | The collapse of a thin cantilever beam due to stiction



(a) With sacrificial layer in place

(b) After the removal of sacrificial layer

→ Two Seperated pieces sticking together is called Stiction.

→ It occurs mostly at the time of the removal of Sacrificial layer from the layer of material.

→ Considerable mechanical forces are required to Seperate the two stuck layers again and these excessive forces can break the delicate microstructure

→ Suction is the main cause for large amount of Scraps in Surface micromachining.

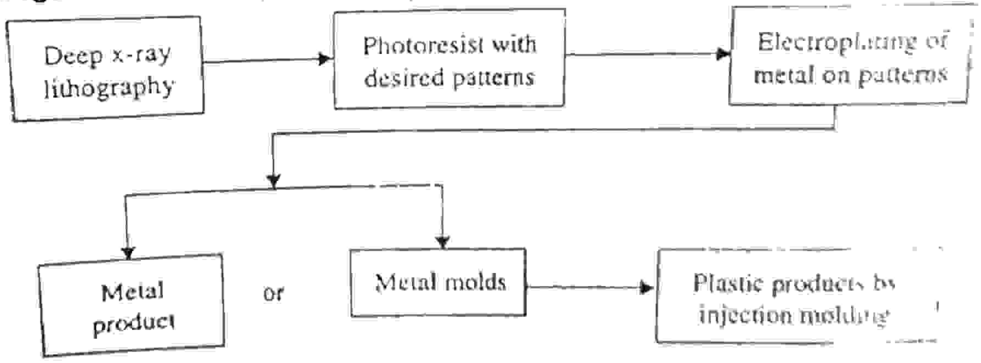
LIGA Process.

LIGA is an acronym for the German terms Lithography (Lithographie), Electroforming (Galvanoformung) and molding (Abformung).

LIGA fabrication is used to create high-aspect ratio structures through the use of X-rays produced by a synchrotron or relatively low aspect ratio structures through the use of UV (ultraviolet) light.

General Description of the LIGA Process.

Figure 9.14 | Major fabrication steps in the LIGA process.



- LIGA process begins with deep X-ray lithography that sets the desired patterns on a thick film of photoresist. X-rays are used as the light source in photolithography.

- X rays have its advantage of short wave length which provides higher penetration power into the photoresist materials.

- This penetration power is necessary for high resolution in lithography and for a high aspect ratio in the depth.

- Then electroplating of metal creates a pattern and it produce a metal product or metal molds. we can produce plastic products by the use of injection molding.

LIGA process involves the following steps.

Step 1 : A very thick (up to 100 microns) photoresist layer of Polymethylmethacrylate (PMMA) is deposited onto a primary substrate.

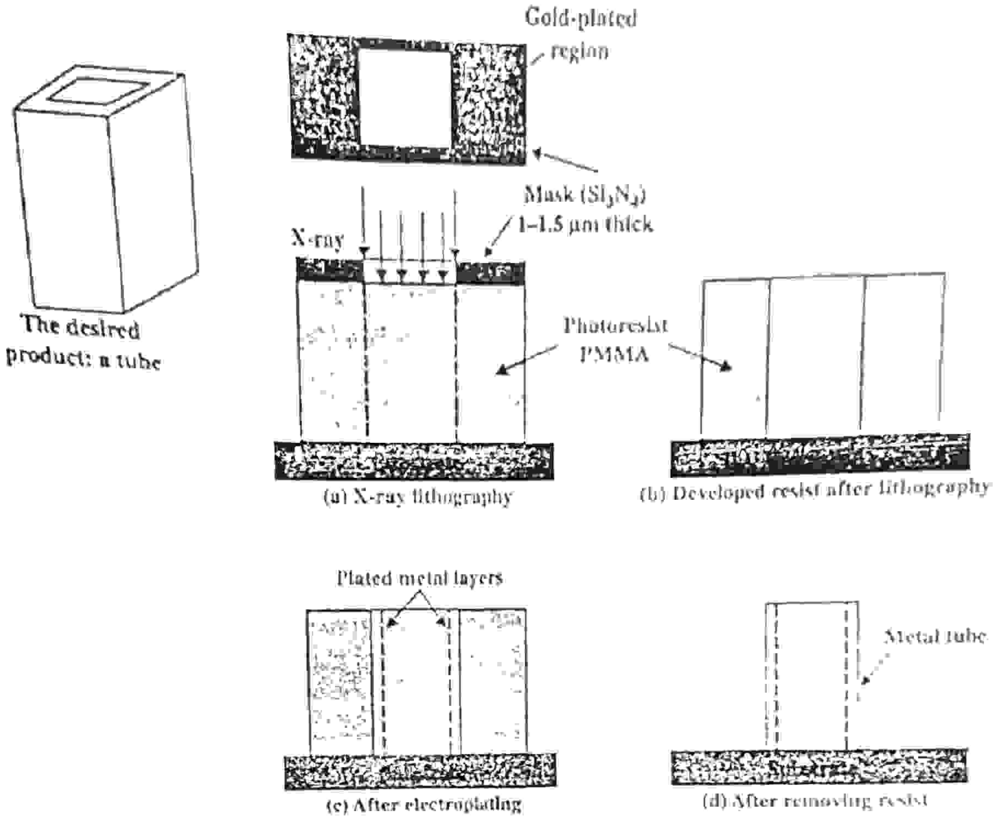
Step 2 : The PMMA is exposed to columnated X-rays and is developed.

Step 3 : Metal is electrodeposited onto the primary substrate

Step 4 : The PMMA is removed or stripped, resulting in a free standing metal structure.

Step 5: plastic injection (20) molding takes place.

Figure 9.15 | Major steps in the LIGA process.



The LIGA - fabrication process is composed of
(1) Exposure (2) Development (3) Electro forming
(4) Stripping and (5) Replication.

(Exposure) Step 1. Coat or depositing a thick photoresist material as a substrate. photoresist material used is PMMA.

Masks are made of diamond, beryllium, Silicon or silicon carbide and they are transparent to X-rays, so it is necessary to apply a thin film of gold to the area that will block X-ray transmission to X-radiation.

Then exposed

Step 2: Development:

In this step the pattern is etched into the resist substrate by the use of X-rays and desired structure are formed. The PMMA photoresist after the development will have the outline of the product (ie, outside profile of the tube)

Step 3: Electroforming

It is same as electroplating. Metal electroplates on the exposed conductive surface. It suggests that the plating is used to create an actual metal component. ∴ Metal gets deposited over the outlined square structure.

Step 4: Stripping and Replication

Stripping is nothing but photoresist removal and finally metal structure is formed according to the desired shape and may be used as mold for replication.

Here our final product is the "Micro thin metal tube' of square cross-section.

Materials for LIGA process

Substrate Material.

Substrate used in the LIGA process is often called the 'base plate'.

The substrate must be an electrical conductor or an insulator coated with electrically conductive materials.
- Electrical conductivity of the substrate is necessary in order to facilitate electroplating.
- Suitable materials include: Austenite steel, Silicon wafers with a thin titanium or Ag/Cr layer top, Copper plated with gold, titanium and Nickel, Glass plate with thin metal plating.

[In short, the starting material is a flat substrate such as silicon wafer or a polished disc of beryllium, Copper, titanium etc. The substrate must be electrically conductive].

Photoresist material.

Basic requirements: → It must be sensitive to X-ray radiation.
→ It must have resolution as well as high resistence to dry and wet etching.
→ It must have thermal stability up to 140°C.
→ It must exhibit very good adhesion to the substrate during electroplating.

Materials:

Based on the above requirements, PMMA is the optimal choice of photoresist material.

Electroplating materials: Nickel is the common metal used

Other metals: Cu, AU, NiFe and NiW. [NiFe (Nickel Iron Alloy), NiW (Ni + Tungsten)]

Major Advantage:

→ Virtually unlimited aspect ratio of the microstructure geometry.

→ flexible micro structure configurations and geometry

→ protection of metallic microstructure.

→ Best of 3 manufacturing process for mass production, with the provision for injection molding

---

[In the previous page in Step 3: Electroforming we can include Electroplating notes, below.]

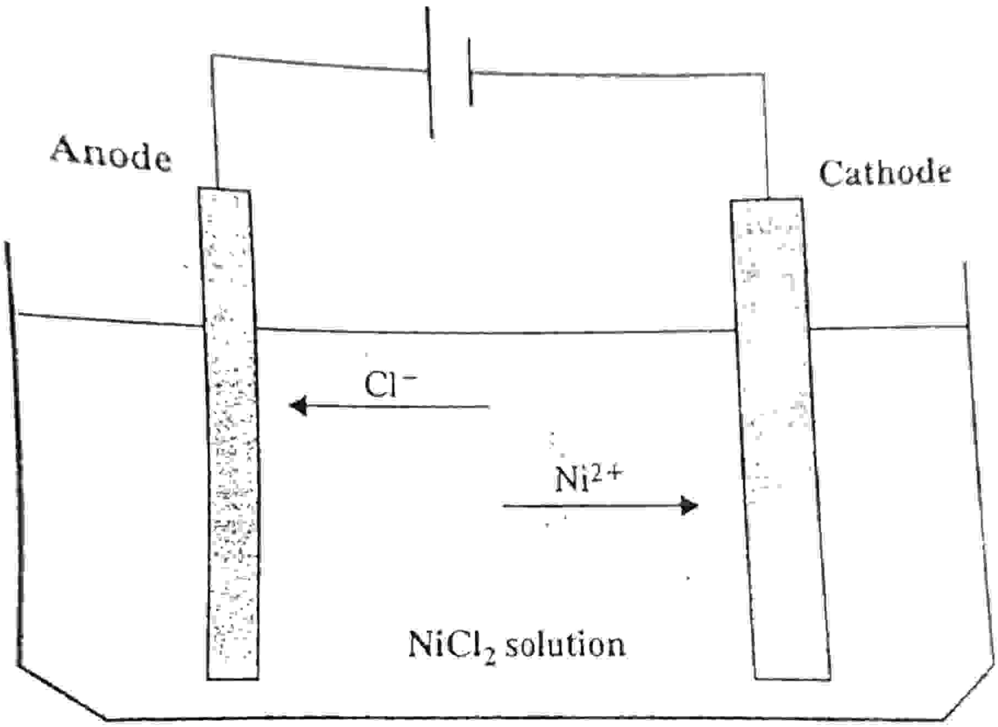
Electroplating: Electroplating is an important step in LIGA process. Nickel is the common metal to be electroplated on the photoresists walls. Electroplating taking place in an electrolytic cell, the current density, temperature and solution are carefully controlled to ensure proper plating.

fig: See next page.

Electroplating works on the principle that the Nickel ions Ni^{2+} from the nickel chloride ($NiCl_2$) solution react with the electrons at the cathode to yield nickel.

$$Ni^{2+} + 2e^- \rightarrow Ni.$$

Figure 9.16 | An electroplating process of nickel.



→ To avoid damage of the plated surfaces by Hydrogen bubbles, we need to control the PH of the solution, the temperature and the current density in the electrolysis.