ME 407 – MECHATRONICS

MODULE III

- Micro Electro Mechanical Systems (MEMS): Fabrication: Deposition, Lithography
- Micromachining methods for MEMS, Deep Reactive Ion Etching (DRIE) and LIGA processes.
- Principle, fabrication and working of MEMS based pressure sensor, accelerometer and gyroscope.

MICRO ELECTRO MECHANICAL SYSTEMS (MEMS)

- Micro electro mechanical systems (MEMS) are a process technology used to create tiny integrated devices or systems that combine mechanical and electrical components.
- They are fabricated using integrated circuit (IC) batch processing techniques and can range in size from a few micrometres to millimetres.
- These devices (or systems) have the ability to sense, control and actuate on the micro scale, and generate effects on the macro scale.
- Typical MEMS consist of components with a size of 1 to 100 μm.
- It usually consists of a central unit that processes data, the microprocessor and several components that interact with the outside such as e.g. pressure sensors, accelerometers or gyroscopes.
- In the most general form, MEMS consist of mechanical microstructures, microsensors, microactuators and microelectronics, all integrated onto the same silicon chip.

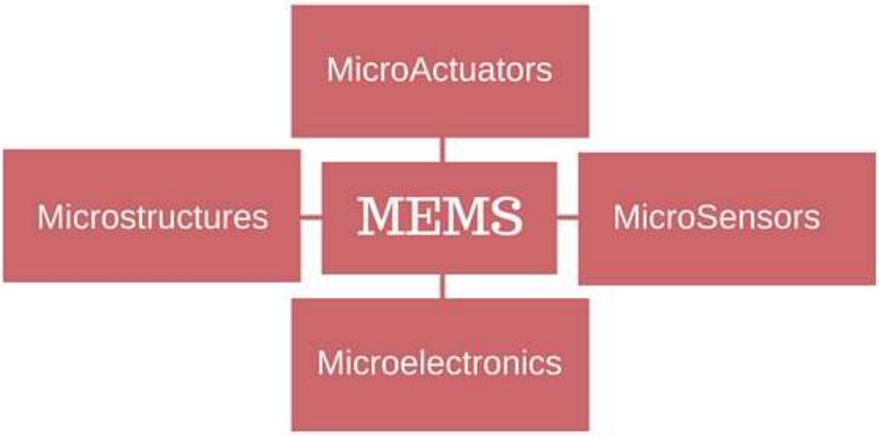


Fig 3.1 MEMS Components

- MEMS devices are very small; their components are usually microscopic. Levers, gears, pistons, as well as motors and even steam engines have all been fabricated by MEMS

DEFINITIONS AND CLASSIFICATIONS

- Although MEMS is also referred to as Micro Systems Technology (MST), strictly speaking, MEMS is a process technology used to create these tiny mechanical devices or systems, and as a result, it is a subset of MST.

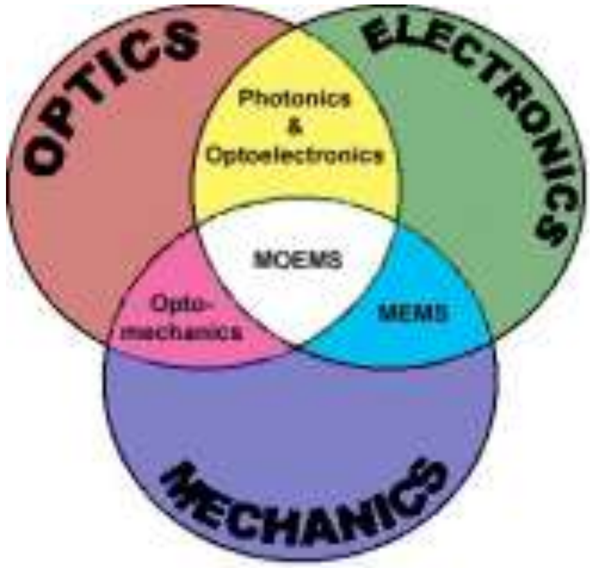


Fig 3.2 Classifications of Microsystems Technology

Transducer:- A transducer is a device that transforms one form of signal or energy into another form. The term transducer can therefore be used to include both sensors and actuators and is the most generic and widely used term in MEMS.

Sensor:- A sensor is a device that measures information from a surrounding environment and provides an electrical output signal in response to the parameter it measured. The major energy domains include:

- Mechanical - force, pressure, velocity, acceleration, position
- Thermal - temperature, entropy, heat, heat flow
- Chemical - concentration, composition, reaction rate
- Radiant - electromagnetic wave intensity, phase, wavelength, polarization reflectance, refractive index, transmittance
- Magnetic - field intensity, flux density, magnetic moment, permeability
- Electrical - voltage, current, charge, resistance, capacitance, polarization

Actuator:- An actuator is a device that converts an electrical signal into an action. It can create a force to manipulate itself, other mechanical devices, or the surrounding environment to perform some useful function.

APPLICATIONS OF MEMS

Automotive:- Automotive airbag sensor**,** Internal navigation sensors**,** Brake force sensor and suspension control accelerometers**,** Fuel level and vapour pressure sensor.

Electronics:- Disk drive heads**,** Earthquake sensors**,** Inkjet printer head**,** Overhead projection display.

Medical:- Medical pressure sensor**,** Implanted pressure sensor**,** Pacemakers

Communications:- Fibre – optic network components**,** RF relay switches and filters**,** Splitters and couplers**,** Voltage controlled oscillators

Defence:- Aircraft control**,** Embedded sensors**,** Data storage**,** Arming systems**,** Surveillance

MEMS FABRICATION

MATERIALS USED IN MEMS FABRICATION

SILICON

- Silicon is the material used to create most integrated circuits used in consumer electronics in the modern world. It is also an attractive material for the production of MEMS, as it displays many advantageous mechanical and chemical properties.
- Single crystalline silicon is an almost perfect Hookean material. This means that when silicon is bent there is virtually no hysteresis and hence almost no energy loss.
- This property makes it to the ideal material, where many small motions and high reliability are demanded, as silicon displays very little fatigue and can achieve service lifetimes in the range of billions to trillions of cycles.

POLYMERS

- Even though the electronics industry provides an economy of scale for the silicon industry, crystalline silicon is still a complex and relatively expensive material to be produced. Polymers on the other hand can be produced in huge volumes, with a great variety of material characteristics.
- MEMS devices can be made from polymers by processes such as injection moulding, embossing or stereolithography and are especially well suited to micro fluidic applications such as disposable blood testing cartridges.

METALS

- Metals can also be used to create MEMS elements. While metals do not have some of the advantages displayed by silicon in terms of mechanical properties, when used within their limitations, metals can exhibit very high degrees of reliability.
- Metals can be deposited by electroplating, evaporation, and sputtering processes. Commonly used metals include gold, nickel, aluminium, copper, chromium, titanium, tungsten, platinum, and silver.

CERAMICS

- The nitrides of silicon, aluminium and titanium as well as silicon carbide and other ceramics are increasingly applied in MEMS fabrication due to advantageous combinations of material properties.

OTHER MATERIALS

- Besides silicon also some metals and polymers can be used to form MEMS elements or functional layers.
- The common fabrication processes for metals such as gold, nickel, copper, titanium, silver and several more are electroplating, evaporation and sputter deposition.
- Polymeric MEMS can be produced by using injection moulding, embossing or stereo lithography. These MEMS devices are especially well suited to micro fluidic applications such as disposable blood testing cartridge.

FABRICATION METHODS FOR MEMS

1. Deposition
    - Chemical vapour deposition
    - Physical vapour deposition
    - Deposition by expitaxy
2. Patterning
    - Lithography
        - Photolithography
3. Ion implantation
4. Diffusion
5. Oxidation
6. Etching (Bulk Micromachining)
    - Wet
    - Dry

LITHOGRAPHY

- **Photolithography** is the photographic technique to transfer copies of a master pattern, usually a circuit layout in IC applications, onto the surface of a substrate of some material (usually a silicon wafer). Various steps in photo lithography are
    - Wafer cleaning
    - Barrier layer application
    - Photoresist application
    - Prebaking/ soft baking
    - Mask alignment
    - Exposure
    - Development
    - Hard baking
    - Etching
    - Stripping
- **Wafer cleaning -** Surface conditioning prepares the wafer to accept the photoresist by providing a clean surface. The wafers are chemically cleaned to remove organic, ionic and metallic impurities.
- **Barrier layer application -** The substrate is covered with a thin film of some material, usually silicon dioxide (SiO2), in the case of silicon wafers, on which a pattern of holes will be formed.
- **Photoresist application -** A thin layer of an organic polymer, which is sensitive to ultraviolet radiation, is then deposited on the oxide layer; this is called a photoresist. It is applied on to the wafer surface by high speed centrifugal spinning known as spin coating. It

produces a thin layer of photoresist on the wafer surface. Chemicals commonly used as photoresists are; poly methyl methacrylate (PMMA), polymethyl glutarimide (PMGI) etc.

Two types of photo resists are used,

- **Positive Photoresist** – in these resists exposure to the uv light changes the chemical structure of the resist so that it becomes more soluble in the developer. The exposed resist is then washed away by the developer solution.
- **Negative Photoresist** – Exposure to UV light causes the negative resist to become polymerized and more difficult to dissolve. It remains on the surface wherever it is exposed and the developer removes only the unexposed portions.

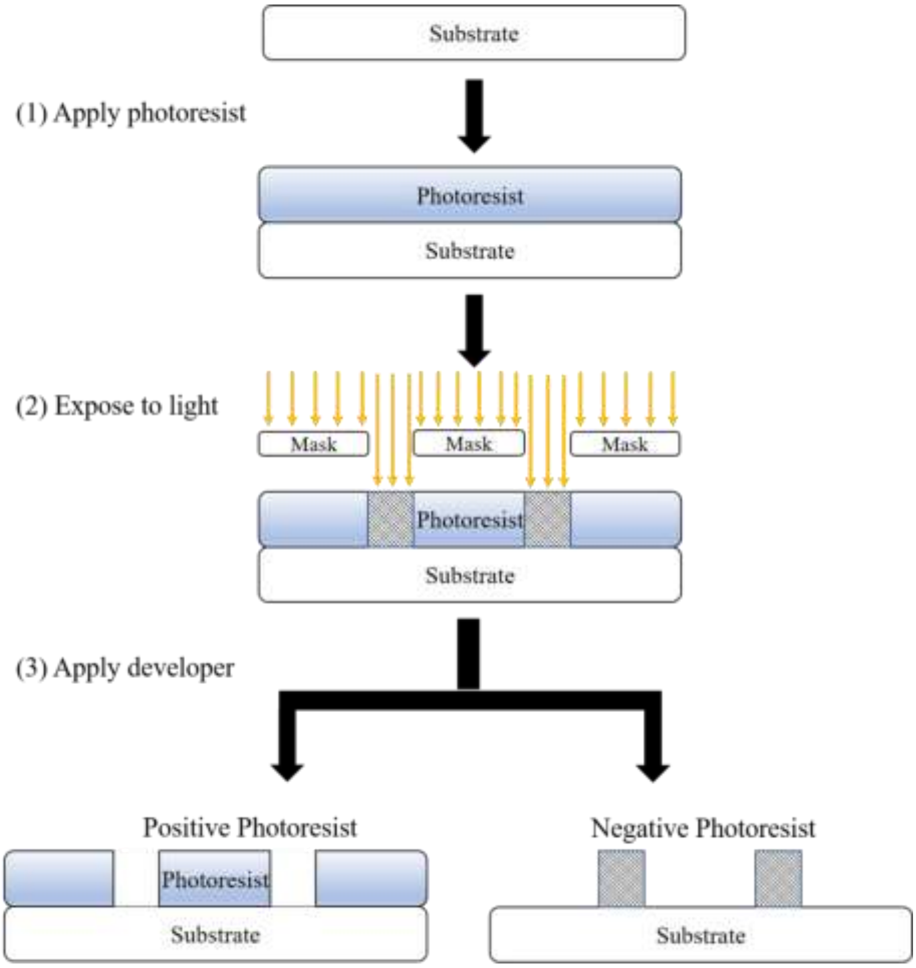


Fig 3.3 Photolithography

- **Prebaking/ Softbaking** – After applying the photoresist to the desired thickness, a softbake is used to remove the residual solvents of the photoresist. Photoresist is prebaked at 90^{0}C to 100^{0}C for 5 – 30 minutes. After the softbaking, the wafer is cooled to room temperature.
- **Mask alignment -** A photomask, consisting of a glass plate (transparent) coated with a chromium pattern (opaque), is then placed in contact with the photoresist coated surface. "Align" is one of the most critical steps in the entire microsystems fabrication process. A misalignment of one micron or smaller can destroy the device and all the devices on the wafer. Each layer must be aligned properly and within specifications to the previous layers and subsequent layers

- **Exposure -** The wafer is exposed to the ultraviolet radiation transferring the pattern on the mask to the photoresist. The wafer is exposed by UV (ultraviolet) from a light source traveling through the mask to the resist. A chemical reaction occurs between the resist and the light. Only those areas not protected by the mask undergo a chemical reaction.
- **Development -** Portions of the photoresist are dissolved by a chemical developer. With positive resist, the exposed resist is dissolved while the unexposed resist remains on the wafer. With negative resist, the unexposed resist is dissolved while the exposed resist remains. Most commonly used developer is tetra methyl ammonium hydroxide.
- **Hard Baking –** It hardens the photoresist for the next process. The temperature of the hardbaking is higher than that of the softbaking after coat (120^0C – 150^0C). After the hardbaking the wafer is cooled to room temperature.
- **Etching –** It is performed either using wet chemicals such as acids or using dry etching. The photoresist wall resists the etching and protects the material covered by the resist.
- **Stripping –** After etching the remaining photoresist is removed by wet or dry stripping. Commonly used stripping medium are phenol based organic compounds like acetone.

DEPOSITION

CHEMICAL VAPOUR DEPOSITION

- Chemical vapour deposition (CVD) is the most important process in microfabrication. It is used extensively for producing thin films by depositing many different kind of foreign materials over the surface of silicon substrates, or over other thin films that have already been deposited to the silicon substrate.
- CVD usually takes place at elevated temperatures and in vacuum in high class clean rooms.
- Materials for CVD may include:

  (a) Metals: Al, Ag, Au, W, Cu, Pt and Sn.

  (b) Organic materials: Al2O3, polysilicon, SiO2, Si3N4, piezoelectric ZnO, SMA TiNi

- There are three available CVD processes in microfabrication:
  - APCVD: (Atmospheric-pressure CVD)
  - LPCVD (Low-pressure CVD), and
  - PECVD (Plasma-enhanced CVD)

Working principle of CVD:

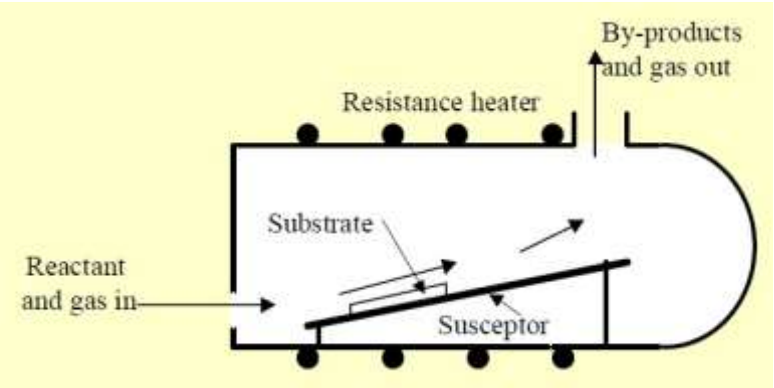


Fig 3.4 Horizontal Reactor

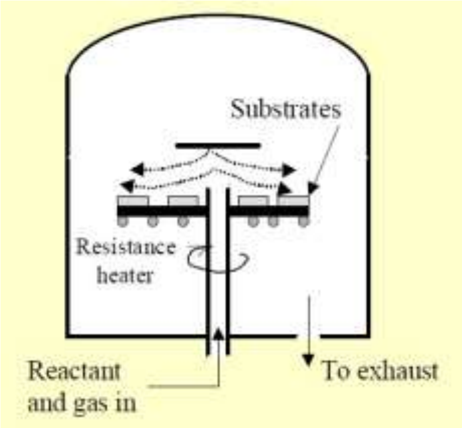


Fig 3.5 Vertical Reactor

- CVD involves the flow of a gas containing diffused reactants (normally in vapor form) over the hot substrate surface.
- The gas that carries the reactants is called "*carrier gas*".
- The "diffused" reactants are foreign material that needed to be deposited on the substrate surface.

  The carrier gas and the reactant flow over the hot substrate surface, the energy supplied by the surface temperature provoke chemical reactions of the reactants that form films during and after the reactions.
- The by-products of the chemical reactions are then let to the vent.
- Various types of CVD reactors are built to perform the CVD processes (horizontal and vertical).

PHYSICAL VAPOUR DEPOSITION

EVAPORATION

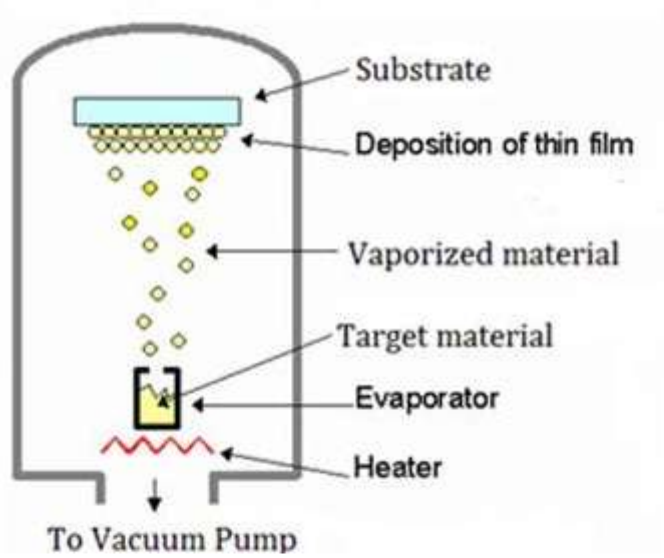


Fig 3.6 Evaporation

- Evaporation involves two basic processes: a hot source material evaporates and condenses on the substrate. It resembles the familiar process by which liquid water appears on the lid of a boiling pot.

- Evaporation takes place in a vacuum, i.e. vapours other than the source material are almost entirely removed before the process begins. In high vacuum (with a long mean free path), evaporated particles can travel directly to the deposition target without colliding with the background gas.
- Resistive heating method is used for heating the target material. Voltage and current is manually controlled.
- Electron beam can also be used for heating the target material.

SPUTTERING

- PVD is used to deposit titanium, titanium nitrate, tantalum, tantalum nitrate, aluminum and a very thin film of copper called seed layer.
- The PVD equipment will be about 4 ft in height and 4 ft in diameter. The material to be deposited (e.g. titanium) will be at the top, as shown in schematic Fig 3.6.

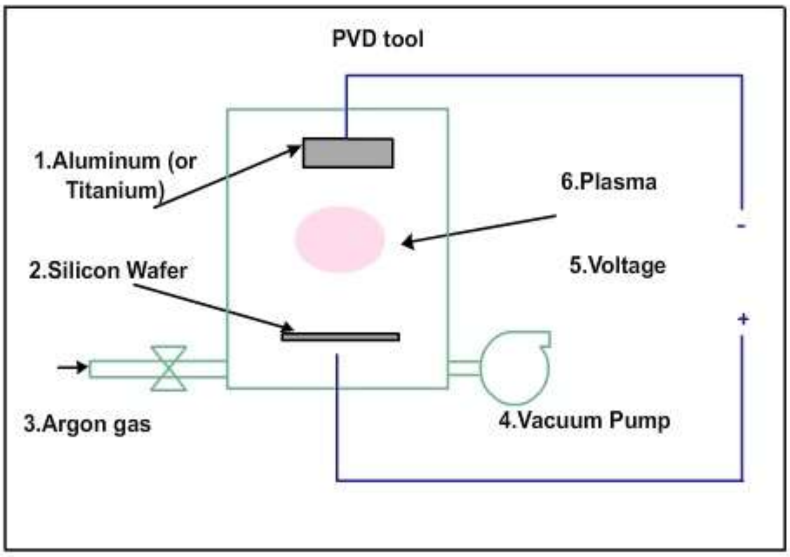


Fig 3.7 Schematic of PVD Chamber

- The tungsten will be in the form of a disc of 1 inch thickness and 5 or 6 inches diameter. At the bottom, silicon wafer will be kept.
- Apart from these, there will be facilities to allow gases into the chamber and to evacuate the chamber with vacuum pump and electrical connections to apply very high voltage (of the order of 10000 V).
- The negative plate will be near the tungsten and the positive plate will be near the wafer.
- Tungsten (or any other material in its place) is called *target*.
- First the air in the chamber must be removed and vacuum must be created. Then argon gas sent inside and a low pressure will be maintained.
- If high voltage is applied to the plates, a plasma will be generated. The plasma will have electrons and positive argon ions. The plasma cannot be generated by normal 230 volts.
- The positive argon ions will be attracted towards the negative plate. They will move towards the negative plates and hit the tungsten with high force. That is why tungsten is called target in this process.

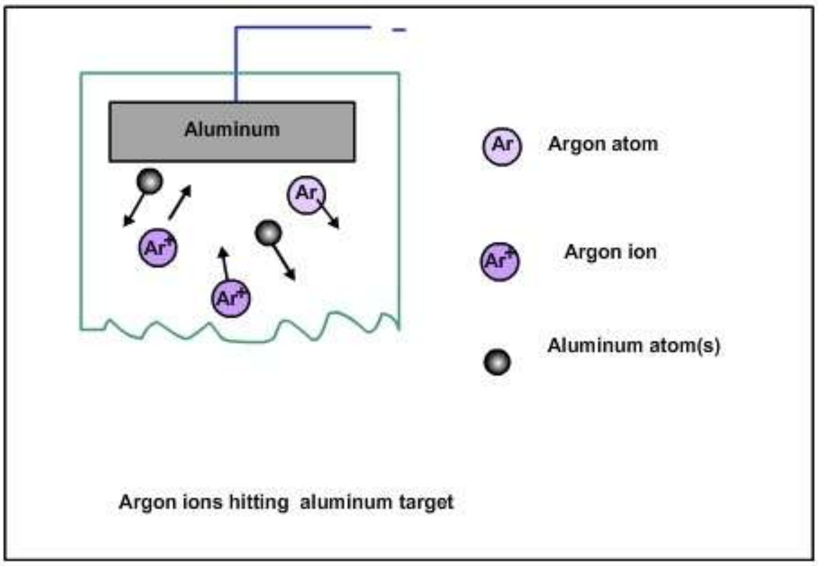


Fig 3.8 Argon Ions Hitting Aluminium Target

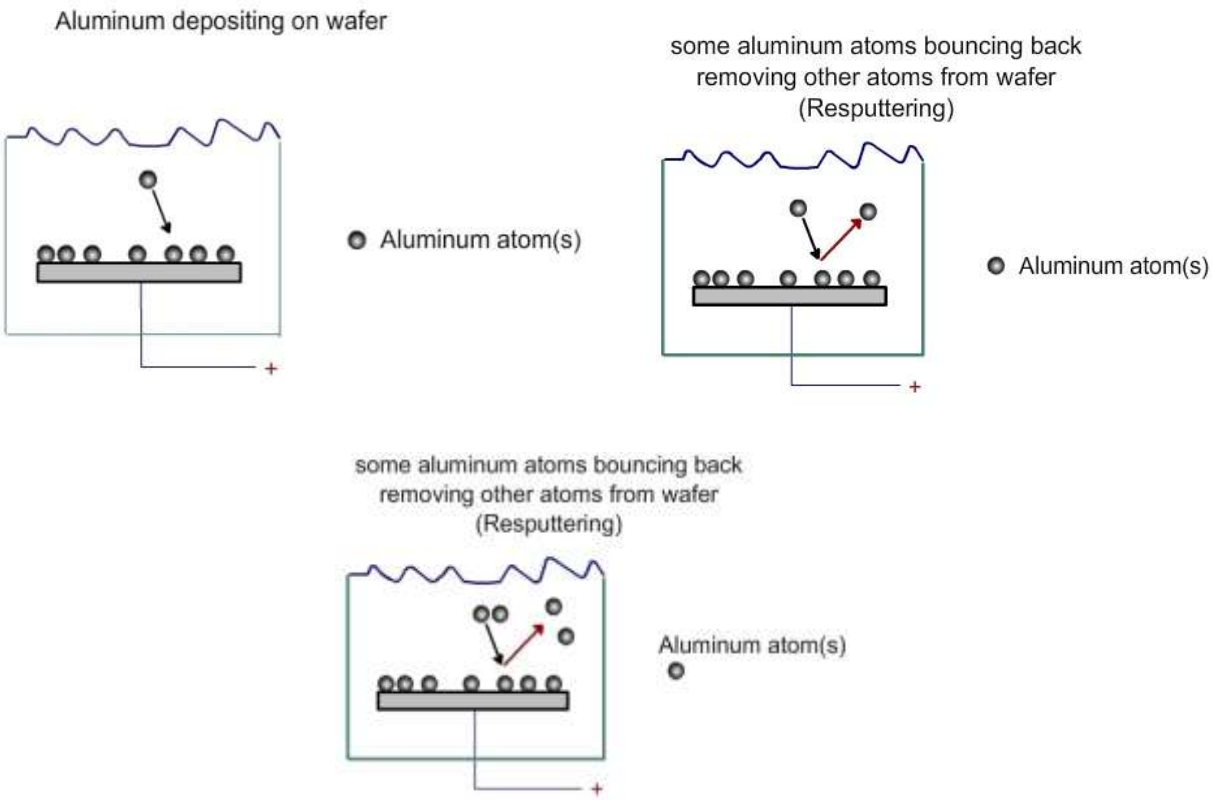


Fig 3.9 PVD Process Near Wafer

- Since the argon ions impinge on the target with large force, some of the target atoms will break and come out, as shown in Fig 3.7.
- The number of tungsten atoms bounce back for each argon ion hitting the target is called sputtering yield. It depends on the speed of the argon ions, the angle of the impact and also on the bond strength of the target.

- The atoms from the target will come towards the wafer with some force. Not all of them will deposit on the wafer. Some will be deposited, while some will bounce back. Some may even bounce back and remove some of the materials already deposited on the wafer.

- Among the tungsten atoms that fall on the wafer, the fraction that stick to the wafer is called sticking coefficient. If all the atoms that fall on the wafer stick to it, then the sticking coefficient is one. If none of them stick, then the sticking coefficient is zero. Typically, the sticking coefficient is about 0.7 to 0.8.

DEPOSITION BY EXPITAXY

- Both CVD and PVD processes are used to deposit dissimilar materials on the silicon substrate surfaces. Epitaxy deposition process is used to deposit **polysilicon** films on **silicon substrate** surfaces.
- Most polisilicons are doped pure silicon crystals randomly oriented. They are used to conduct electricity at desired locations on silicon substrates.
- This process is similar to CVD with carrier gas with reactants that release the same material as the substrates.
- Reactor is very similar to those used in CVD, except that many of the carrier gas used is **H2**. For safety reason, **N2** gas is used to drive out any O**2** gas in the system before the process begins.

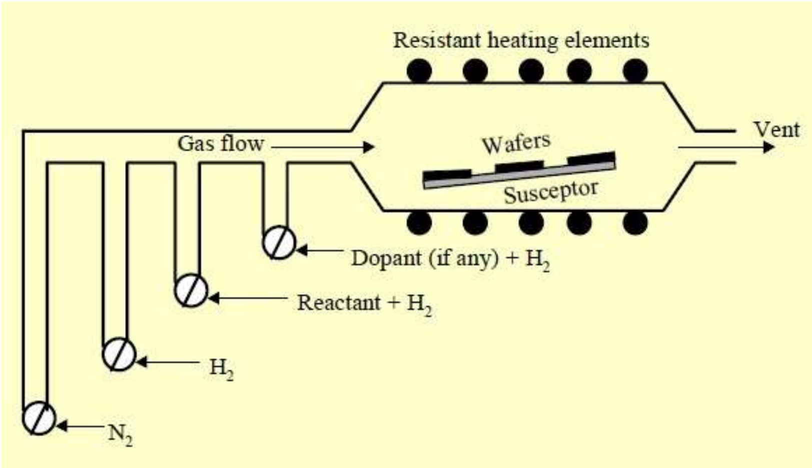


Fig 3.10 Horizontal Reactor

ETCHING

- Bulk micromachining involves the removal of part of the bulk substrate. It is a subtractive process that uses wet anisotropic etching or a dry etching method such as reactive ion etching (RIE), to create large pits, grooves and channels.
- Materials typically used for wet etching include silicon and quartz, while dry etching is typically used with silicon, metals, plastics and ceramics.

WET ETCHING

- Wet Etching is an etching process that utilizes liquid chemicals or etchants to remove materials from the wafer, usually in specific patterns defined by photoresist masks on the wafer.

- In wet etching, the wafers are immersed in a tank of the etchant (mix of chemicals. There is a chemical reaction between the wafer surface and the etchants that helps in material removal.
- Either a photoresist layer or a hard mask like oxide or nitride layer is used to protect the rest of the wafer.
- The time for etching depends on the amount and type of material that needs to be removed.
- KOH (potassium hydroxide) is a common etchant used to remove Si. Usually, 30% KOH solution is used, which has a etch rate of ∼ 100 μm/hr at 90 ◦C.
- After etching, the wafers are rinsed, usually in DI water, for removal of etchant and then finally dried.

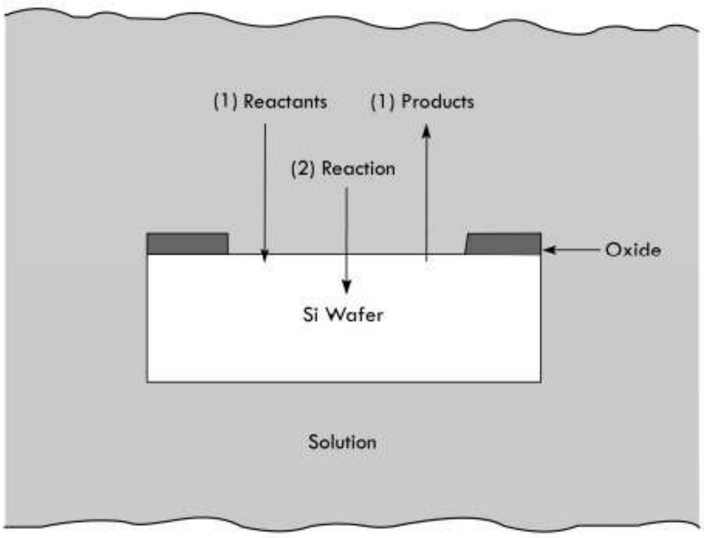


Fig 3.11 Wet Etching

DRY ETCHING

- Dry etching refers to the removal of material, typically a masked pattern of semiconductor material, by exposing the material to a bombardment of ions (usually a plasma of reactive gases such as fluorocarbons, oxygen, chlorine, boron trichloride; sometimes with addition of nitrogen, argon, helium and other gases) that dislodge portions of the material from the exposed surface.

DEEP REACTIVE ION ETCHING (DRIE)

- Dry etching relies on vapour phase or plasma-based methods of etching using suitably reactive gases or vapours usually at high temperatures.
- The most common form for MEMS is reactive ion etching (RIE) which utilizes additional energy in the form of radio frequency (RF) power to drive the chemical reaction.
- Energetic ions are accelerated towards the material to be etched within a plasma phase supplying the additional energy needed for the reaction.
- As a result the etching can occur at much lower temperatures (typically 150º - 250ºC, sometimes room temperature) than those usually needed (above 1000ºC).
- RIE is not limited by the crystal planes in the silicon, and as a result, deep trenches and pits, or arbitrary shapes with vertical walls can be etched.

- Deep Reactive Ion Etching (DRIE) is a much higher-aspect-ratio etching method that involves an alternating process of high-density plasma etching (as in RIE) and protective polymer deposition to achieve greater aspect ratios.
- Etch rates depend on time, concentration, temperature and material to be etched. To date there are no universally accepted master equations to predict etch performance and behaviour.

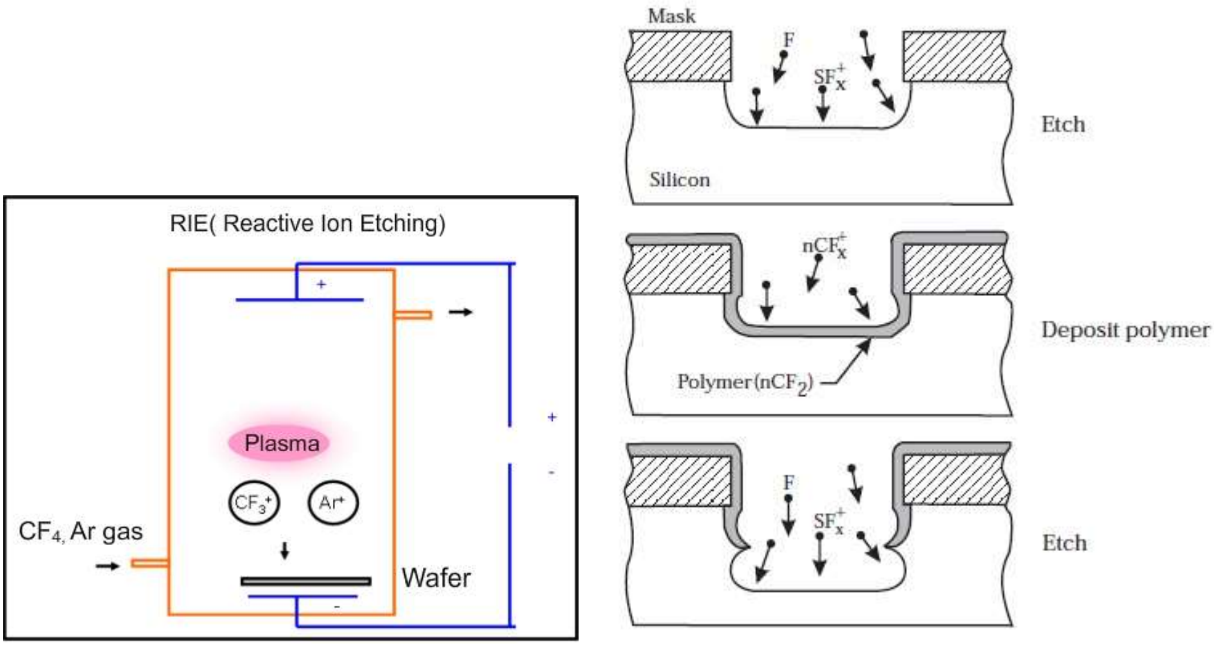


Fig 3.12 Deep Reactive Ion Etching

<u>Advantages of DRIE</u>

- ✓ Fine resolution
- ✓ High aspect ratio
- ✓ High etch rate
- ✓ High sensitivity and precision

<u>Disadvantages of DRIE</u>

- Usage of high plasma power
- Single wafer at a time
- Specialized hardwares are required and hence expensive

<u>Applications of DRIE</u>

- Sensors and actuators
- Printer heads
- Accelerometer for air bags
- Capacitor in DRAM memory circuits

ION IMPLANTATION

- It is physical process used to dope silicon substrates.
- It involves "forcing" free charge-carrying ionized atoms of boron, Phosphorous or Arsenic into silicon crystals.
- These ions associated with sufficiently high kinetic energy will be penetrated into the silicon substrate. Physical process is illustrated as follows:

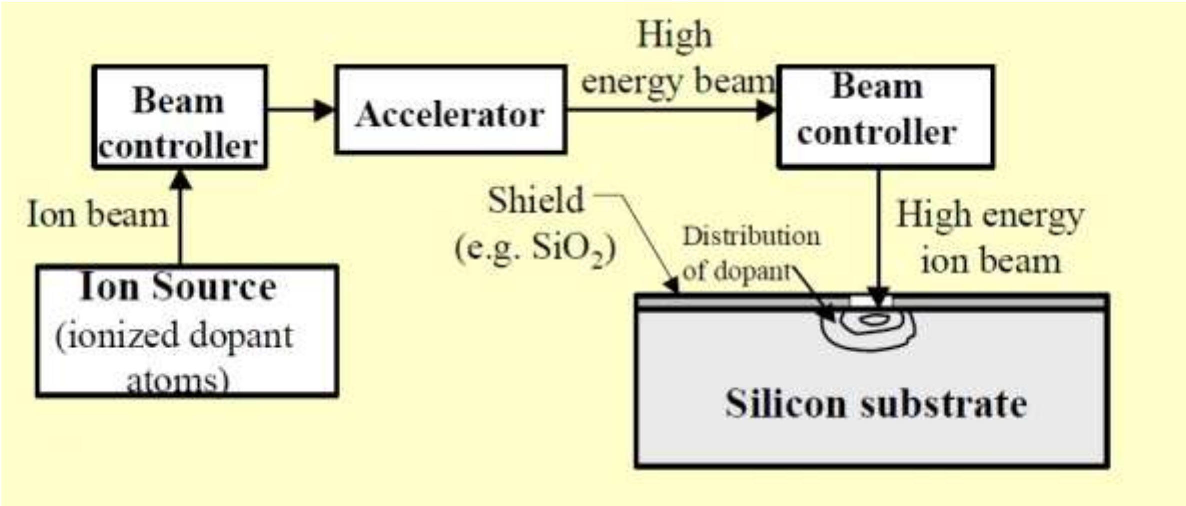


FIG 3.13 Ion Implantation

DIFFUSION

- Diffusion is another common technique for doping silicon substrates. Unlike ion implantation, diffusion takes place at high temperature.
- Diffusion is a chemical process. The profile of the spread of dopant in silicon by diffusion is different from that by ion implantation:

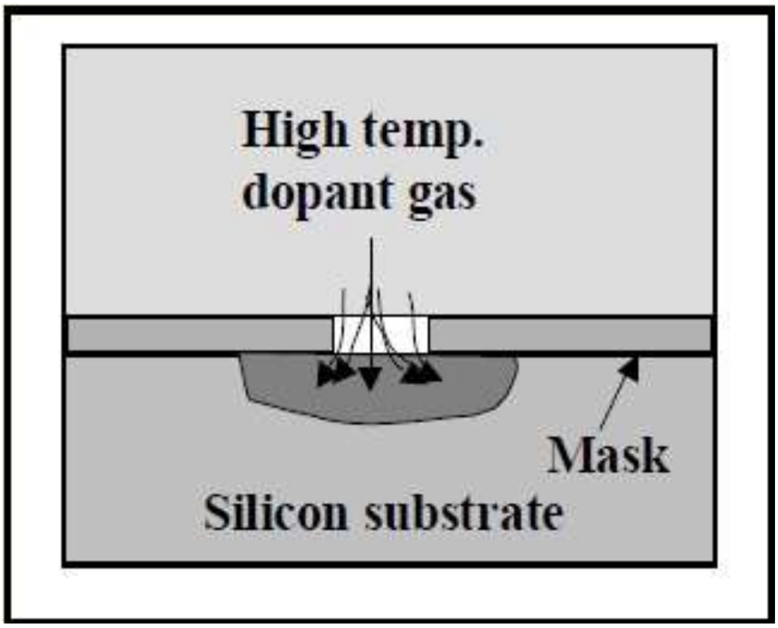


Fig 3.14 Diffusion

OXIDATION

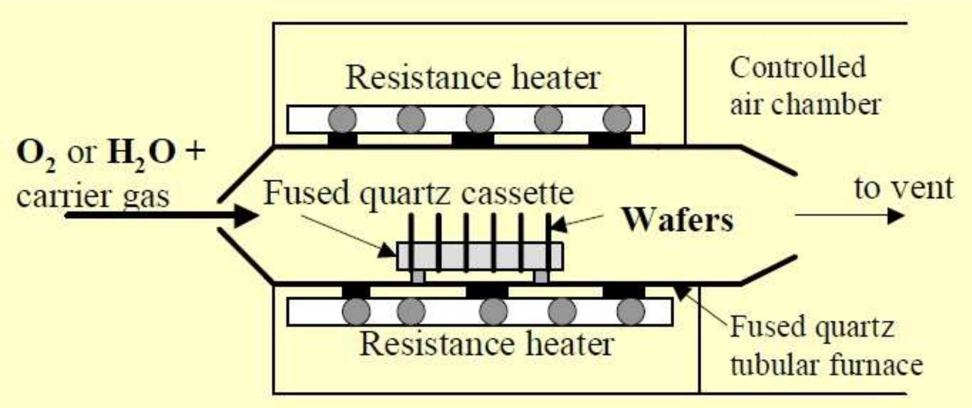


Fig 3.15 Oxidation

- SiO2 is an important element in MEMS and microsystems. Major application of SiO2 layers or films are:
    - To be used as thermal insulation media
    - To be used as dielectric layers for electrical insulation
- SiO2 can be produced over the surface of silicon substrates either by:
    - Chemical vapor deposition (CVD)
    - Growing SiO2 with dry O2 in the air, or wet steam by the following two chemical reactions at high temperature:
        - Si (solid) + O2 (gas) → SiO2 (solid)
        - Si (solid) + 2H2O (steam) → SiO2 (solid) + 2H2 (gas)

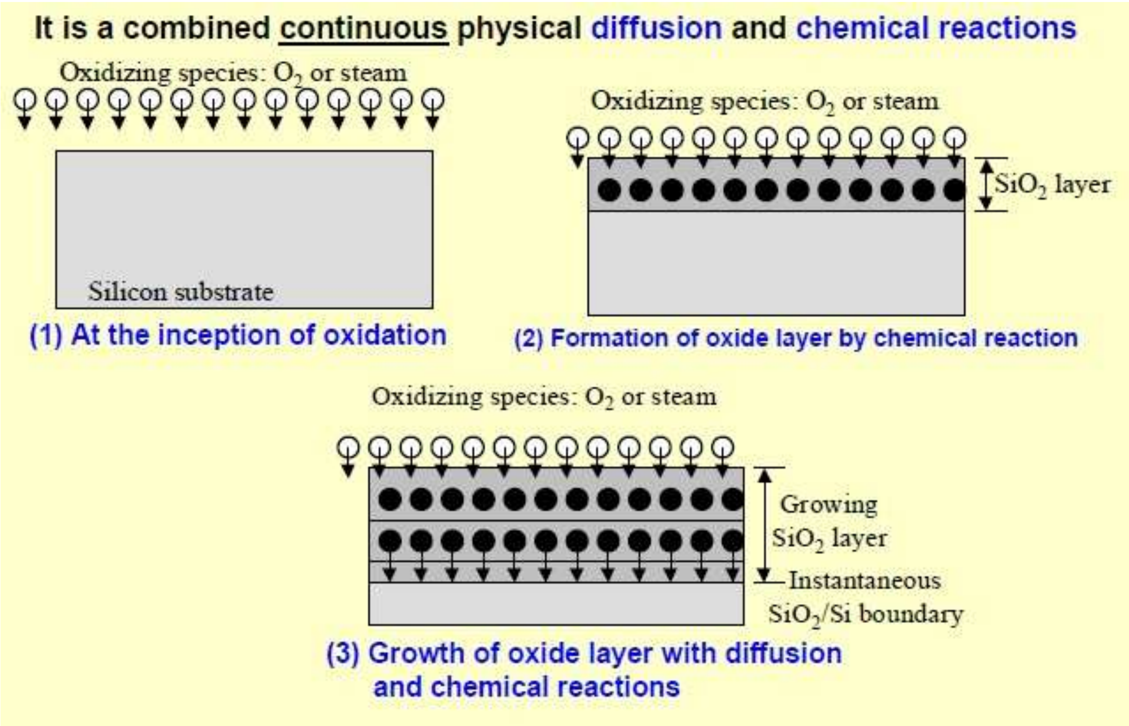


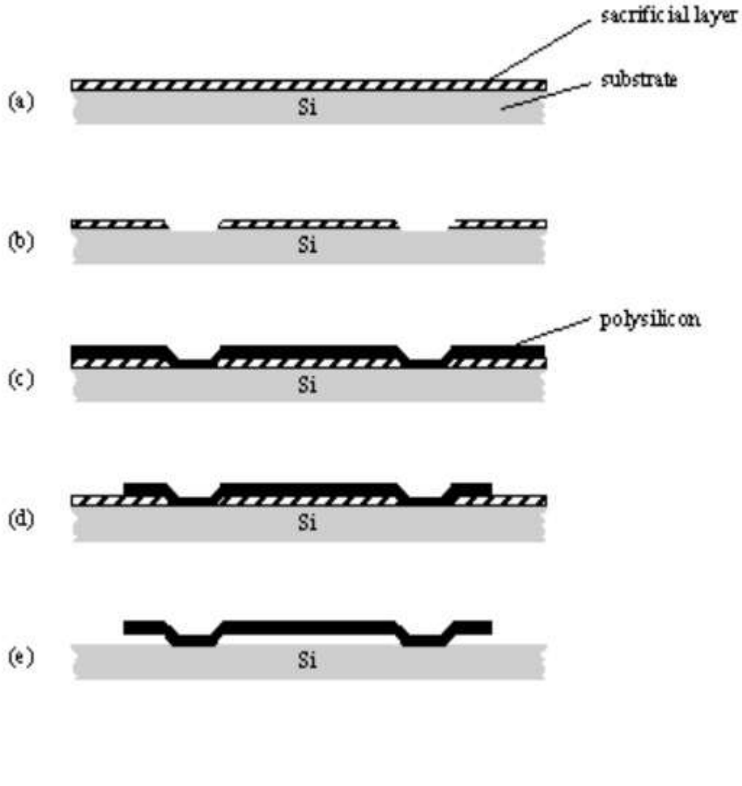
Fig 3.16 Principle of Thermal Oxidation

MICROMACHINING METHODS FOR MEMS

- Bulk Micromachining
- Surface Micromachining
- LIGA

SURFACE MICROMACHINING

- Surface micromachining is a process that uses thin film layers deposited on the surface of a substrate to construct structural components for MEMS. Unlike bulk micromachining that builds components within a substrate, surface micromachining builds on top of the substrate.
- Most commonly used materials for surface micromachining:
  Substrate: silicon
  Sacrificial material: SiO2 or phosphosilicate glass (PSG) s
  Structural material: polysilicon
- The dimensions of these surface micromachined structures can be several orders of magnitude smaller than bulk-micromachined structures.
- The prime advantage of surface-micromachined structures is their easy integration with IC components, because the wafer is also the working area for IC elements.



: Basic surface micromachining process. (a) Spacer layer deposition. (b) Pattering of the spacer layer. (c) Deposition of the microstructure layer. (d) Patterning of desired structure. (e) Stripping of the spacer layer resolves final structure

Fig 3.17 Surface Micromachining

- It should be noted that as miniaturization is immensely increased by surface micromachining, the small mass structure involved may be insufficient for a number of mechanical sensing and actuation applications.

- Surface micromachining requires a compatible set of structural materials, sacrificial materials, and chemical etchants. The structural materials must possess the physical and chemical properties that are suitable for the desired application. In addition, they must have satisfactory mechanical properties.
- The sacrificial materials must have good mechanical properties to avoid device failure during fabrication. These properties include good adhesion and low-residual stresses to eliminate device failure by delamination and/or cracking.
- The etchants to remove the sacrificial materials must have excellent etch selectivity and they must be able to etch off the sacrificial materials without affecting the structural ones. In addition, the etchants must have proper viscosity and surface tension characteristics.

LIGA PROCESS

- LIGA is a Germal acronym for Lithographie (Lithography), Galvanoformung (Electroplating), Abformung (Molding).
- 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.
- The LIGA process involves the following steps:
    - A very thick (up to hundreds of microns) resist layer of polymethylmethacrylate (PMMA) is deposited onto a primary substrate.
    - The PMMA is exposed to columnated X-rays and is developed.
    - Metal is electrodeposited onto the primary substrate.
    - The PMMA is removed or stripped, resulting in a freestanding metal structure.
    - Plastic injection molding takes place.
- The LIGA-fabrication process is composed of:
    - Exposure
    - Development
    - Electroforming
    - Stripping
    - Replication

Steps in LIGA Process

Step-1

- Coat thick photoresist (300 m to > 500 m) on a substrate with an electrically conductive surface.

Step-2 Irradiation

- X-ray lithography with extended exposure from highly collimated X-radiation to penetrate thick Resist with well- defined sidewalls.
- Irradiation involves exposing a thick layer of resist to high-energy beam of x-rays from a synchrotron.
- The mask membrane is normally a low atomic number material such as diamond, beryllium, or a thin membrane of a higher atomic number material such as silicon or silicon carbide.

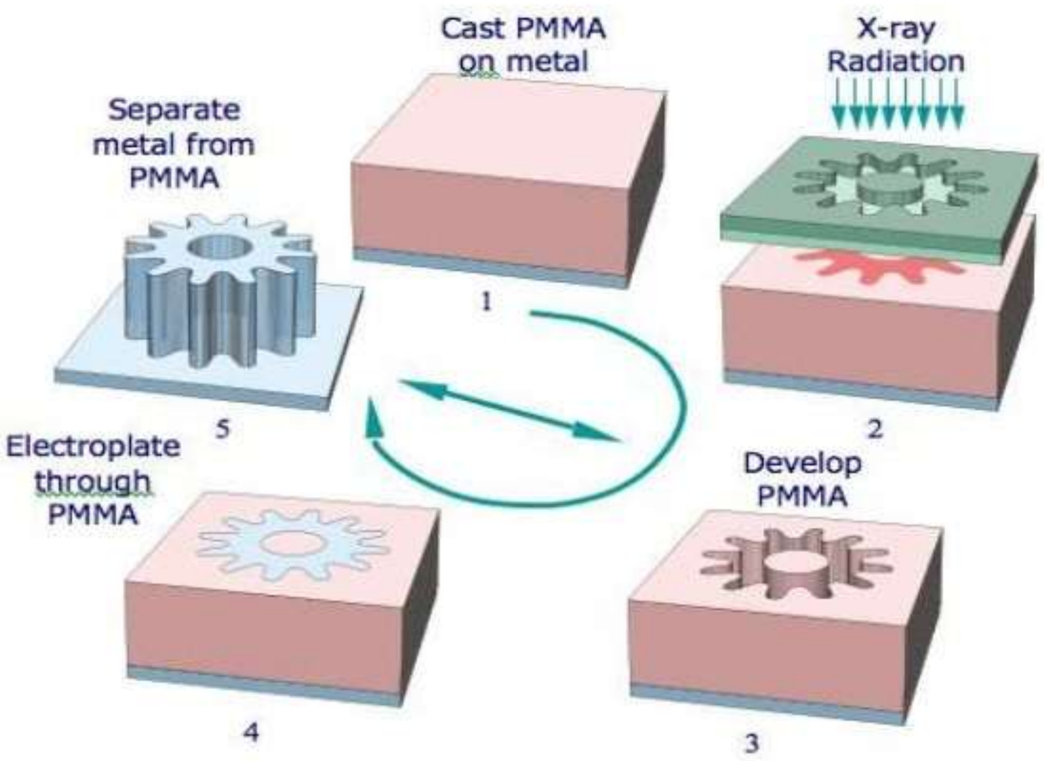


Fig 3.18 Steps in LIGA Process

Step-3: Development

- In this step the pattern is etched into the resist substrate by the use of x- rays and desired structure are formed.

Step-4: Electroforming

- Metal electroplated on the exposed conductive substrate surface. Electroforming is the same as electroplating.
- Electroforming suggests that the plating is used to create an actual metal component

Step-5

- After photoresist removal, metal structure formed may be used as mold.
- Sacrificial techniques are combined with the basic LIGA process to create partially freed, flexure-suspended structure or completely freed devices.

<u>Advantages of LIGA</u>

- No diffraction effect
- Simple to use
- Uniform refraction pattern
- High resolution for small feature size

Disadvantages of LIGA

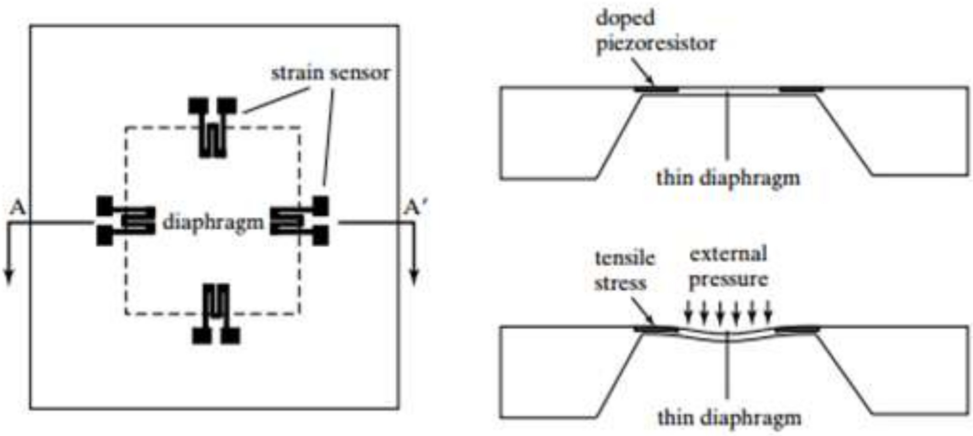
- Distortion in absorber
- Mask is expensive to produce
- Slow and complicated process

Applications of LIGA

- Sensors and actuators
- Projectors
- Micro optical components
- Mass spectrometers

MEMS BASED PRESSURE SENSOR

- The basic structure of a piezoresistive pressure sensor consists of four sense elements in a Wheatstone bridge configuration to measure stress within a thin, crystalline silicon membrane.



Pressure Sensor

Fig 3.19 MEMS Pressure Sensor

- The stress is a direct consequence of the membrane deflecting in response to an applied pressure differential across the front and back sides of the sensor. The stress is, to a first order approximation, linearly proportional to the applied pressure differential.
- The membrane deflection is typically less than one micrometre. The output at full-scale applied pressure is a few millivolts per volt of bridge excitation (the supply voltage to the bridge).
- The output normalized to input applied pressure is known as sensitivity [(mV/V)/Pa]. The thickness and geometrical dimensions of the membrane affect the sensitivity, and consequently, the pressure range of the sensor.
- Devices rated for low pressure (less than 10 kPa) usually incorporate complex membrane structures, such as central bosses, to improve sensitivity.
- A common design layout positions the four diffused piezoresistive sense elements at the points of highest stress, which occur at the center edges of the diaphragm.

- Two elements have their primary axes parallel to the membrane edge, resulting in a decrease in resistance with membrane bending. The other two resistors have their axes perpendicular to the edge, which causes the resistance to increase with the pressure load.
- It is necessary that the four piezoresistors have identical resistances *in the* absence of applied pressure. Any mismatch in resistance, even one caused by temperature, causes an imbalance in the Wheatstone bridge. The resulting output reading is known as zero offset, and is undesirable.

FABRICATION OF MEMS BASED PRESSURE SENSOR

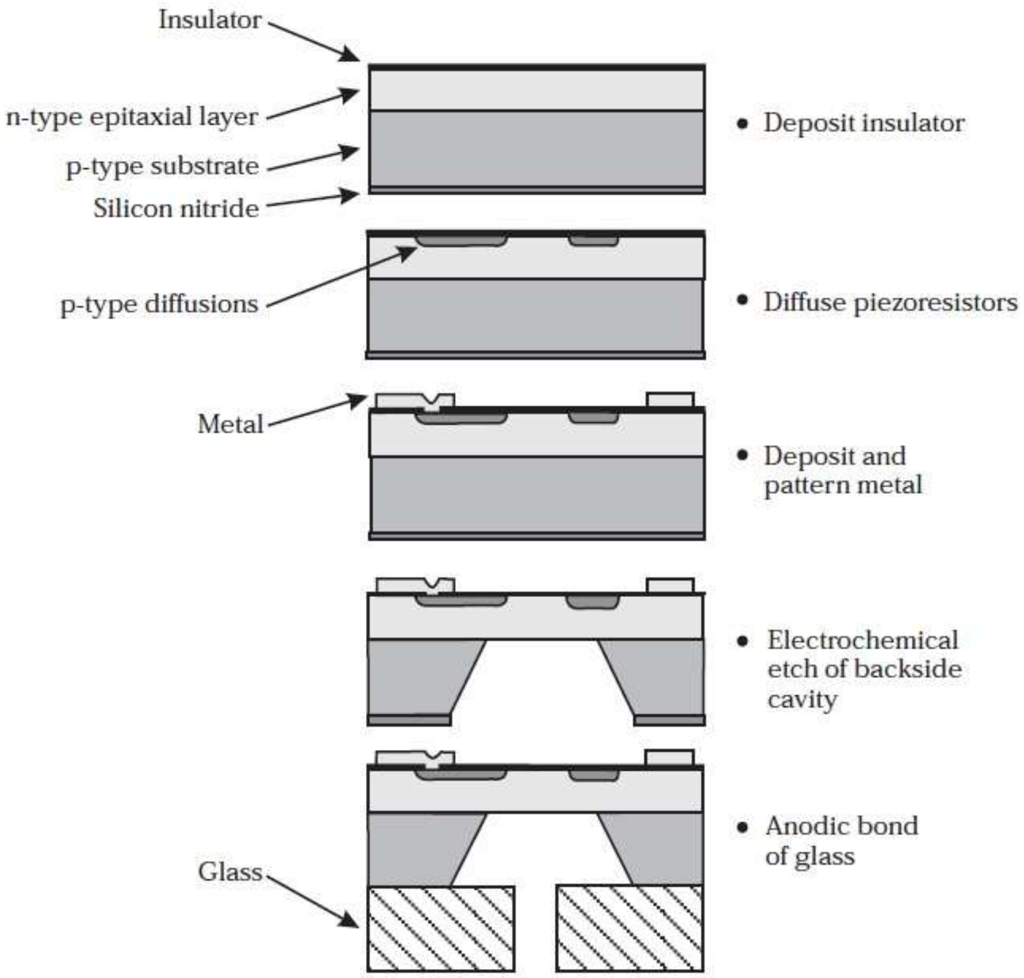


Fig 3.20 Fabrication of MEMS Based Pressure Sensor

- The fabrication of a silicon-fusion-bonded sensor begins with the etching of a cavity in a bottom handle wafer. Silicon-fusion bonding of a second top wafer encapsulates and seals the cavity. Electrochemical etching or standard polishing thins down the top bonded wafer to form a membrane of appropriate thickness.
- A Clear wafer is placed on the surface. The surface should have the ability to rotate. On the surface of the wafer, deposition of silicon nitride take place.
- After a few seconds, photoresist coat is applied to the surface and is allowed to undergo the photoresist exposure by UV light through a mask with the desired pattern. After some time photoresist development is occurred by tetra methyl ammonium hydroxide solution.
- Next etching process is taken place by reactive ions like Ar, CF3, CF4 etc. Finally photoresist strip can be made by piranha clean method.

- After completing front surface, we need to rotate the wafer and the same process is repeated to the other side also. Lift off resist coat is poured and by rotating the surface, it allows to spread all along the surface.
- Photo resist coating is done by the same as above and then it is undergone in to a LOR and PR exposure by UV light through a mask and then rinsed in the developer solution (LOR and PR develop.).
- Then, deposition process takes place by chrome and gold disposition. It is a physical vapour deposition method. Then PR strip lift of by acetone solution is done and then LOR strip off is done finally through KOH anisotropic etching method.
- MEMS pressure sensor is created/ fabricated by placing a pyrex 7740 glass anodic bonding on the surface.

MEMS BASED ACCELEROMETER

- Accelerometer is an instrument for measuring the acceleration of a moving or vibrating body.
- An accelerometer generally consists of a proof mass suspended by compliant beams anchored to a fixed frame.
- The proof mass has a mass of m, the suspension beams have an effective spring constant stiffness **k** and there is a damping factor (b) affecting the dynamic movement of the mass generated by the air structure interaction.
- The accelerometer can be modelled by a second-order Mass-damper-spring system, External acceleration displaces the support frame relative to the proof mass, which in turn changes the internal stress in the suspension spring.
- Both this relative displacement and the suspension-beam stress can be used as a measure of the external acceleration.

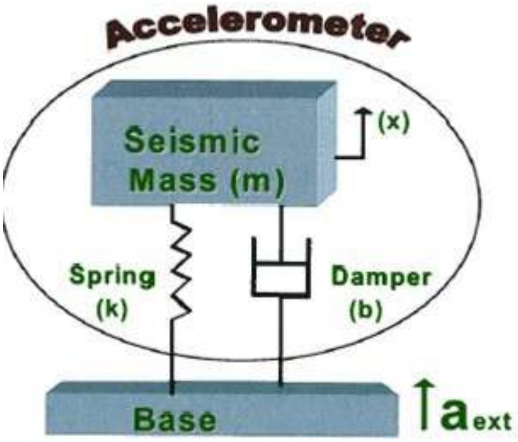


Fig 3.21 MEMS Accelerometer - Principle

- The mass develops a force which is given by the D'Alembert's inertial force equation

  F= m*a.
- This force displaces the spring by a distance x. Hence the total force externally is balanced by the sum of internal forces given by,

$$F_{external} = F_{inertial} + F_{damping} + F_{spring}$$

- Stress is the defined as the force per unit area acting on the surface of a differential volume element of a solid body.

$$\text{Stress}(\sigma) = \frac{F}{A}\ [N/m^2]$$

- The strain, which can be defined as the deformation resulting from;

$$\varepsilon = \frac{\text{Change in the amount of Deformation}}{\text{Original Dimension}} = \frac{\delta}{L}$$

- Spring Constant (proportionality constant) that relates the force and the displacement in Hooke's law. By increasing or decreasing the spring constant we can alter the movement of the proof mass in the corresponding direction

$$F = -kx$$

CAPACITANCE ACCELEROMETER

- One of the most commonly used MEMS accelerometer is the capacitive type. The capacitive MEMS accelerometer is famous for its high sensitivity and its accuracy at high temperatures.
- The device does not change values depending on the base materials used and depends only on the capacitive value that occurs due to the change in distance between the plates.
- If two plates are kept parallel to each other and are separated by a distance'd', and if 'E' is the permitivity of the separating material, then capacitance produced can be written as;

  $\mathbf{C_0 = E_0.E\ A/d = E_A/d}$

  $\mathbf{E_A = E_0EA}$

  A – Area of the electrodes
- A change in the values of E, A or d will help in finding the change in capacitance and thus helps in the working of the MEMS transducer.
- Accelerometer values mainly depend on the change of values of d or A.
- A typical MEMS accelerometer is shown in the figure below. It can also be called a simple one-axis accelerometer.
- If more sets of capacitors are kept in 90 degrees to each other you can design 2 or 3-axis accelerometer.
- A simple MEMS transducer mainly consists of a movable microstructure or a proof mass that is connected to a mechanical suspension system and thus on to a reference frame.
- The movable plates and the fixed outer plates act as the capacitor plates. When acceleration is applied, the proof mass moves accordingly. This produces a capacitance between the movable and the fixed outer plates.
- When acceleration is applied, the distance between the two plates displace as X1 and X2, and they turn out to be a function of the capacitance produced.

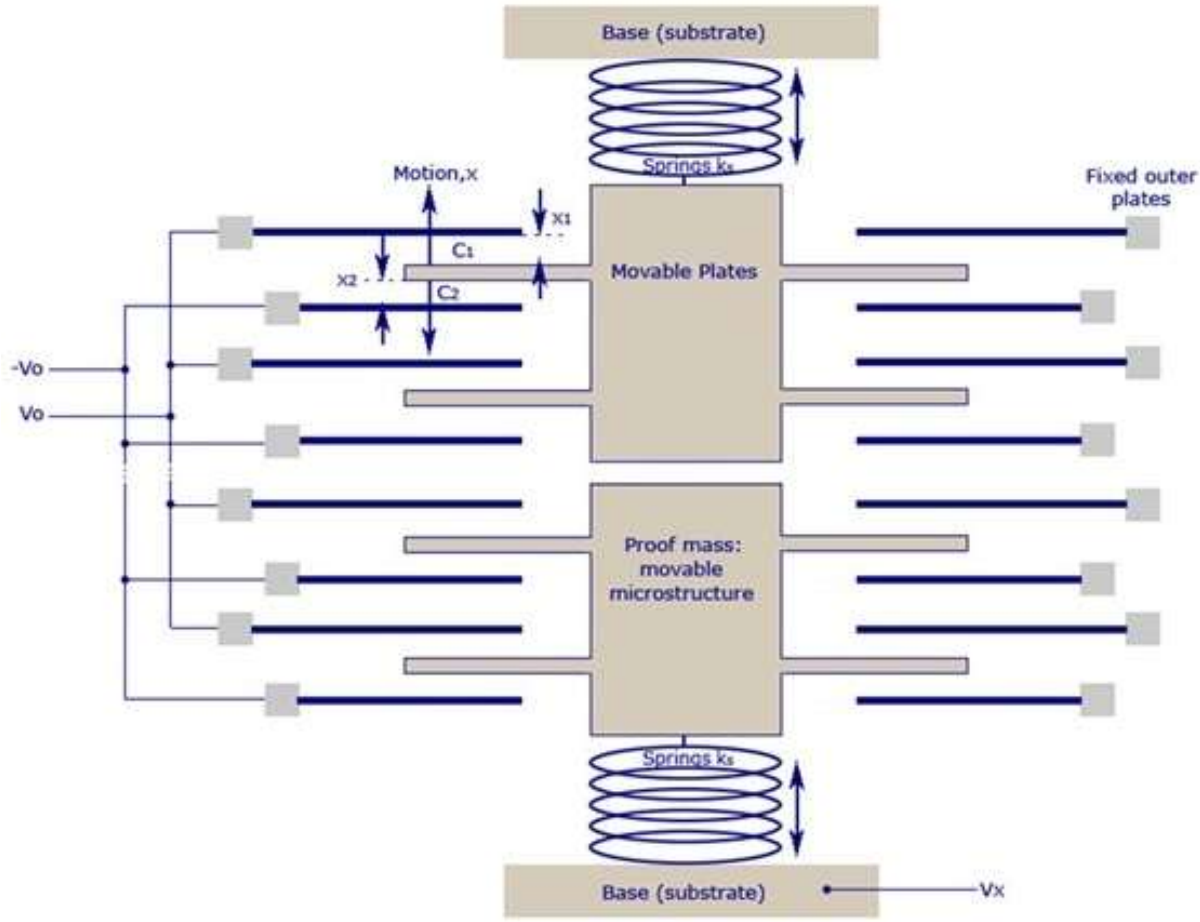


Fig 3.22 MEMS Capacitive Accelerometer

FABRICATION OF MEMS ACCELEROMETER

Various steps involved in fabrication of MEMS accelerometer are;

- Deposition of silicon on wafer
- Oxidation
- Photolithography
- SiO2 Etching
- Silicon Etching
- SiO2 removal
- Metallization

- Two silicon layers are added to wafer oxide. One on above and another below. Then oxidation process takes place on both sides. By photolithography, photoresist is placed on the surface and allow UV light to pass through it for 15 to 20 sec through a mask followed by photoresist development of TMAH (Tetramethyl Ammonium Hydroxide).
- After a while SiO2 and silicon etching process takes place and so PR layer is removed. Finally we get V-groove formation by SiO2 removal method. Oxide layer is removed from the surface and the structure is obtained finally by metallization process. 2^{nd} level mask is deposited by Al at a temperature of 650^0C.

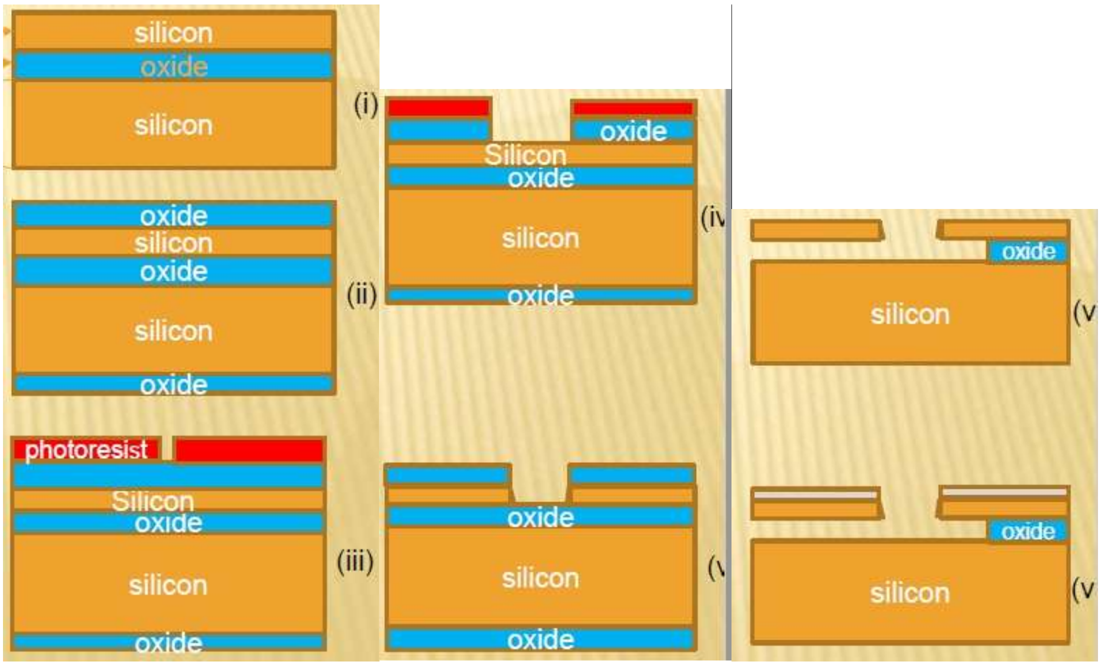


Fig 3.23 Fabrication of MEMS Accelerometer

Advantages of MEMS Accelerometer

- High sensitivity.
- Easy readout circuitry.
- Independent of temperature variation.
- Easy fabrication (two level mask).
- Large noise margin.
- Fabrication on silicon.
- Compatible with CMOS technology.

Applications of MEMS Accelerometer

- Automotive
    - Crash detection & Air bag deployment.
- Consumer Electronics
    - hard disk protection(laptops)
    - screen rotation (mobile)
    - Image stabilization (camera)
- Industrial
    - Vibration detection (machine)
    - crack detection (pulley)
- Aerospace & Defence
    - Navigation
    - Missile guidance
    - Thrust detection

MEMS BASED GYROSCOPE

- Gyroscope is a device used for measuring and maintaining orientation based on principle of angular momentum.
- Mechanically, gyroscope is a spinning wheel/ disc mounted on axle and axle is free to assume any direction.
- MEMS gyroscopes generally use a vibrating mechanical element as a sensing element for detecting the angular velocity. They do not have rotating parts that require bearings and this allows an easy miniaturization and the use of the manufacturing techniques typical of MEMS devices.

Working Principle

- All MEMS gyroscopes with vibrating element are based on the transfer of energy between two vibration modes caused by the acceleration of Coriolis.
- **Corioli's effect** – an effect where by a mass moving in a rotating system experiences a force (Corioli's force) acting perpendicular to the direction of motion and to the axis of rotation.

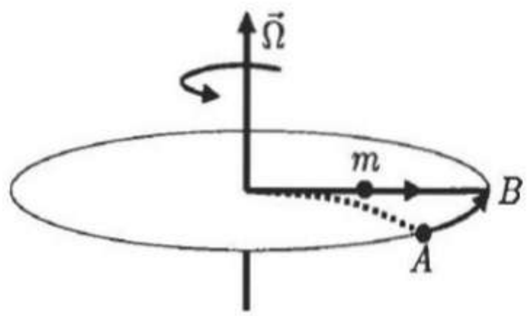


Fig 3.24 Illustration of Corioli's Principle

- **Corioli's Acceleration** – It is an apparent acceleration that arises in rotating frame of reference. It is proportional to the rate of rotation Ω.

$$\vec{a}_{cor} = 2(\vec{V} \times \vec{\Omega})$$

- **Corioli's force** is given by;

$$\vec{F_c} = -2m(\vec{\Omega} \times \vec{v})$$

FABRICATION OF MEMS GYROSCOPE

- Silicon wafer is taken with implanted etch to stop on the bottom surface. Processing takes place only on the top surface of the wafer. Anisotropic KOH etching is taken place on the wafer surface and sacrificial layer is added on to it. An oxide layer is added on top. Through etching process, the sacrificial layer is etched out.
- Sputter thin aluminium layer, pattern with PR mask. Then etch away aluminium from the substrate to create leads.

- Use sol – gel method to add 2 micron layer of PZT and use another mask PR and etchant to create piezo electric sheet. Sputter more aluminium leads and pattern with a third mask, photoresist and etchant.

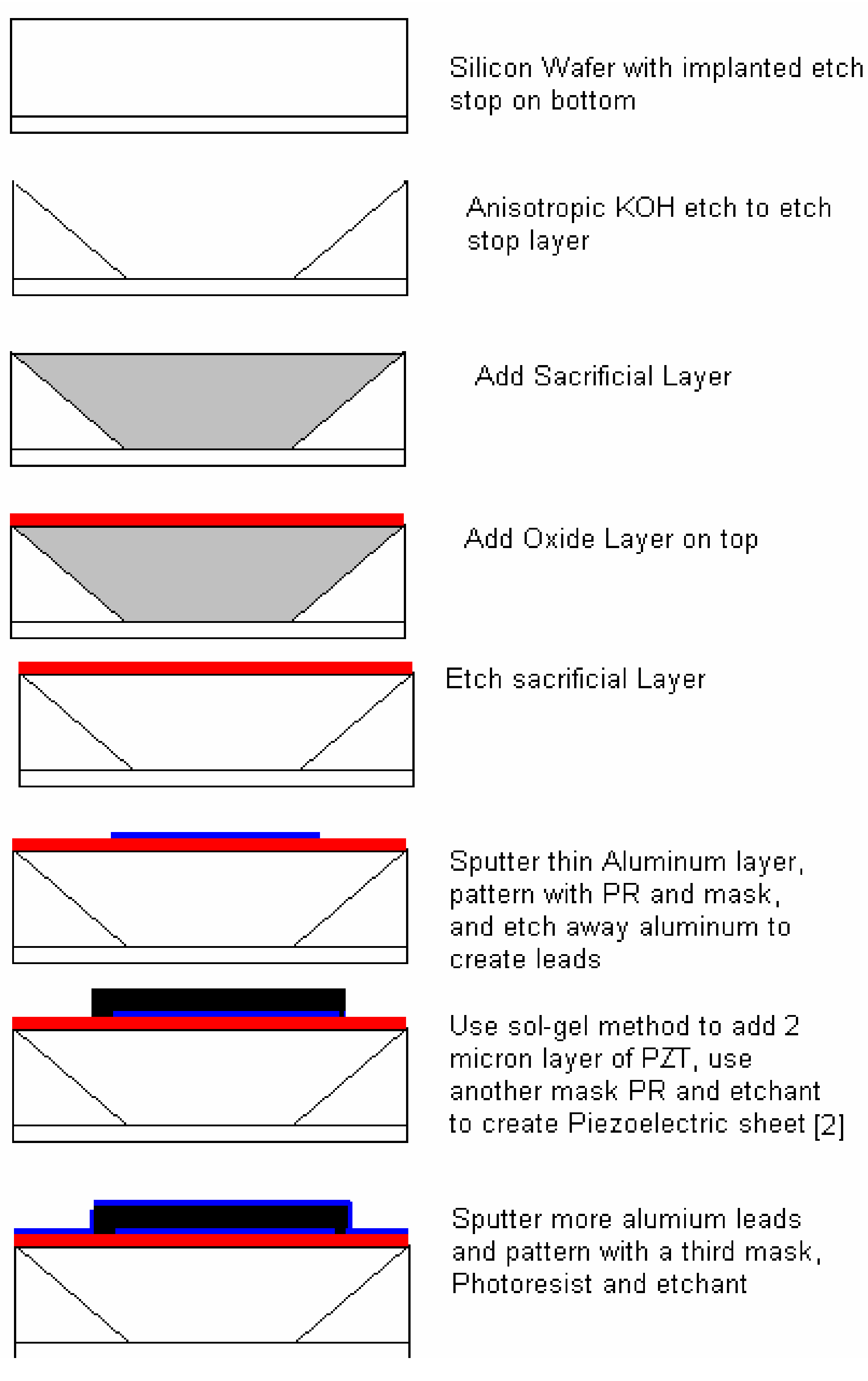


Fig 3.25 Fabrication of MEMS Gyroscope

- DC source creates an electrostatic force that moves the disc. Proper control of these electrodes can put the system into resonance. Similarly, the sensing electrodes change to gauge system change.

Advantages of MEMS Gyroscope

- Improved sensitivity
- Improved accuracy and reliability
- Easier to alter the parts of device as compared to its macro counter part

Disadvantages of MEMS Gyroscope

- Poly silicon is a brittle material
- Design complexity

Applications of MEMS Gyroscope

- Optical image stabilization
- Aircrafts, ships, satellites, missiles etc
- Automotive application – Air bag safety system, vehicle security system, Braking system etc.