Advanced Sensing Techniques

Lecture Material 2

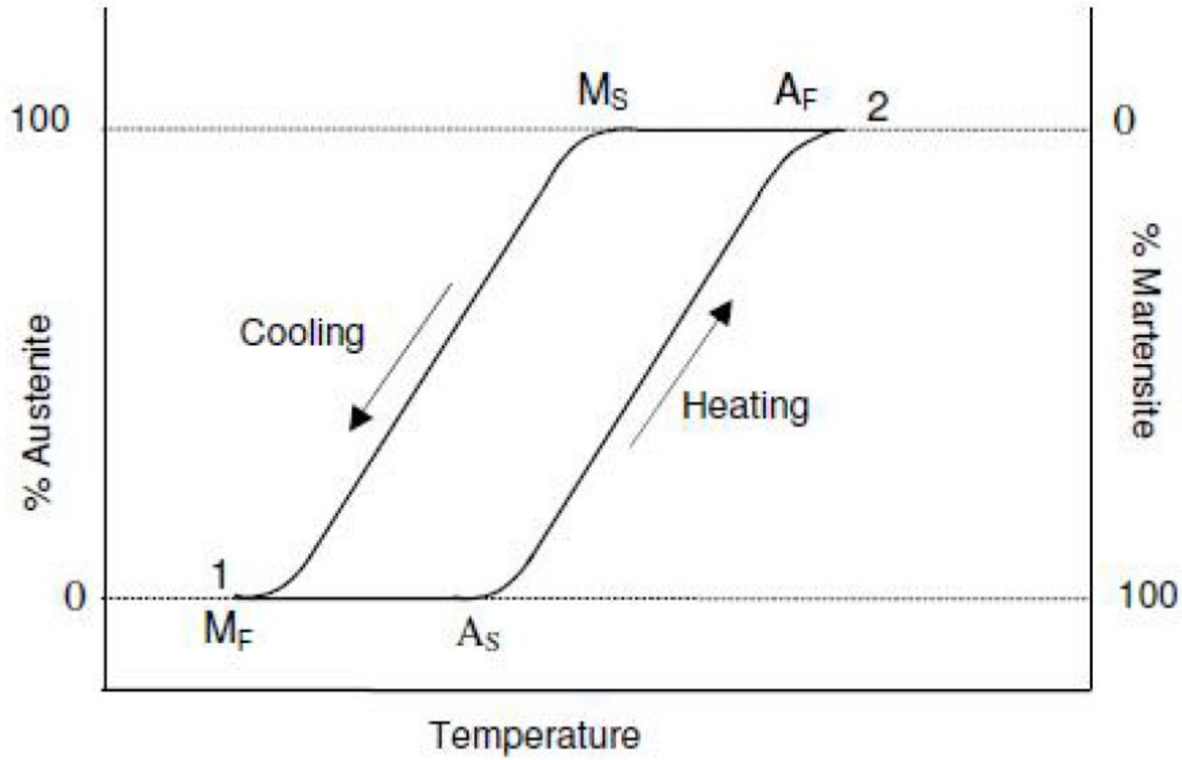
Few references:

1. Fundamentals of Microfabrication by Marc Madou
2. Micro and Smart systems: G . K. Ananthsuresh et al.
3. Couple of Internet sources for Image illustration

Dr. B. Mukherjee & Prof. S. Sen

SMA: Salient Features

- Operates at two states: Martensite (low temperature) and Austentite (high temperature)
- Transformation of states with temperature
- Stress-strain characteristics in two states are different
- Presence of Hysteresis is evident

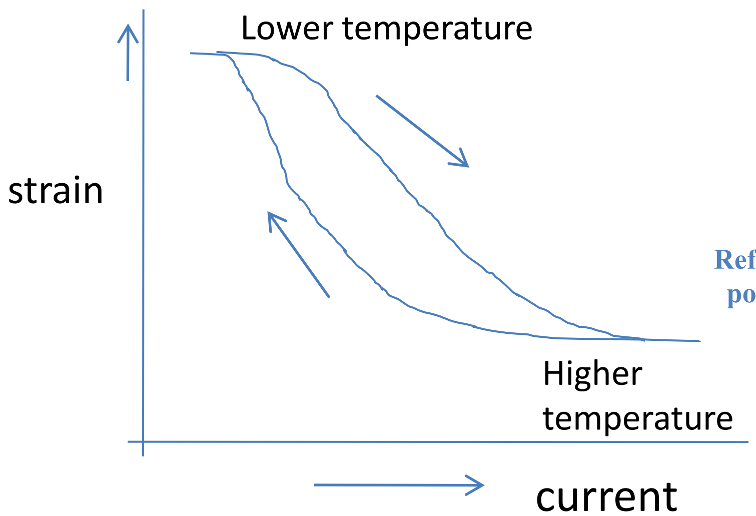


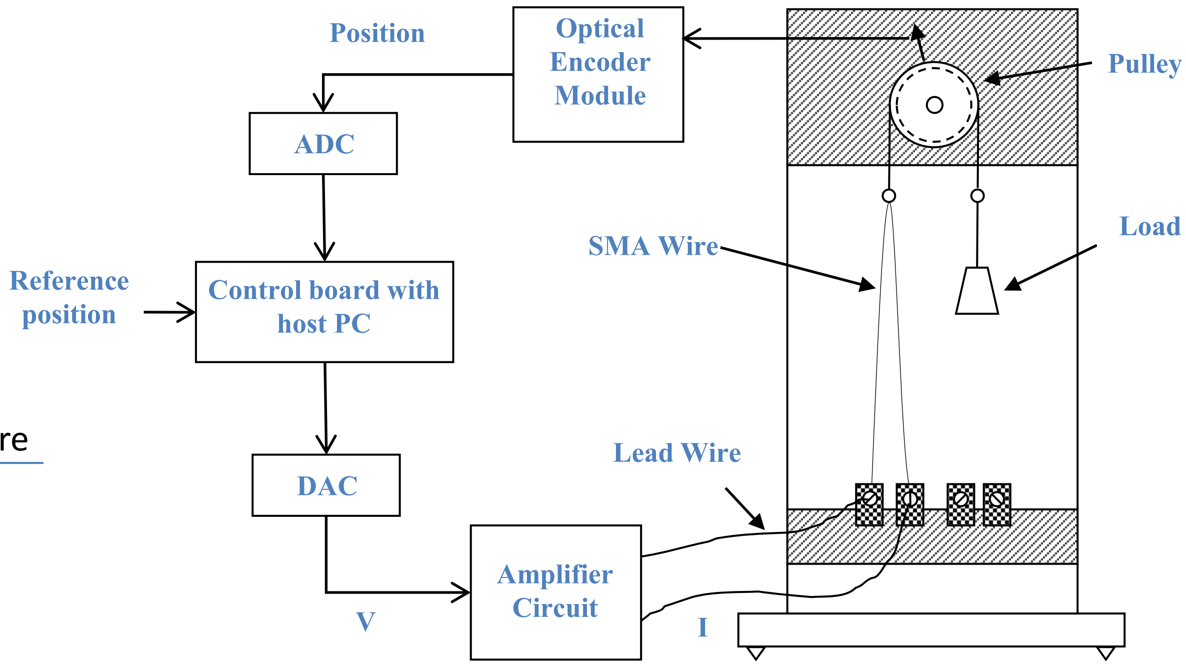
A_s = Austentite start temperature; A_f = Austentite finish temperature
M_s = Martensite start temperature; M_f = Martensite finish temperature

SMA: Applications

Heating: By passing current through SMA wire
If current through the wire is increased, the wire shrinks.

- Position control using SMA actuators





Videos:

https://www.youtube.com/watch?v=f6Iq2B15veA&t=2s

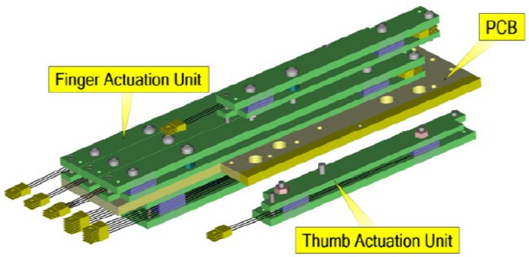
https://www.youtube.com/watch?v=adGxx7OMuNA

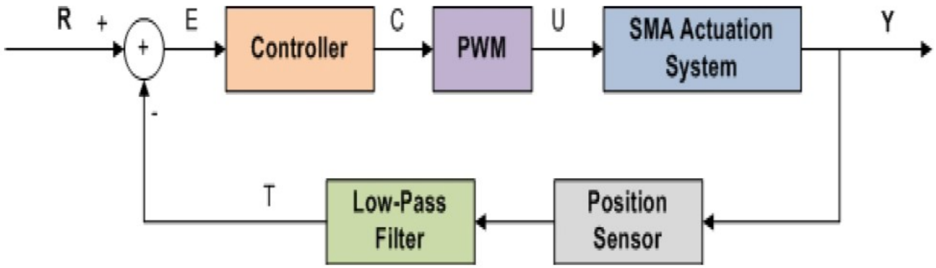
https://www.youtube.com/watch?v=xg_oiVHKqis

https://www.youtube.com/watch?v=-K57cbOhA5g&t=169s

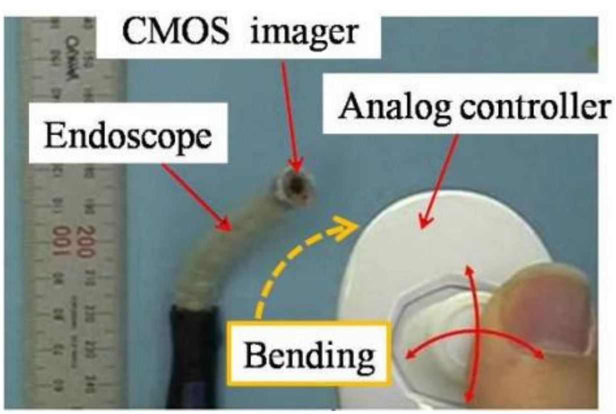
SMA: Applications

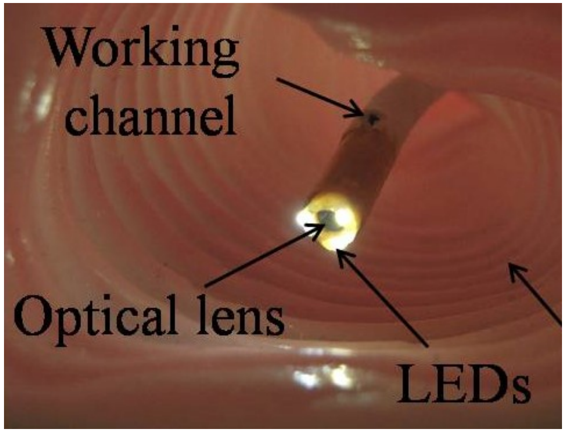
❖ Robotics: e.g. Prosthetic hand





❖ Biomedical: e.g. Active Bending Catheter, Endoscope etc.



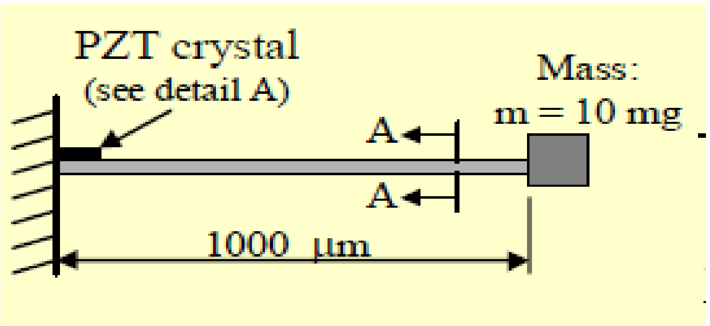


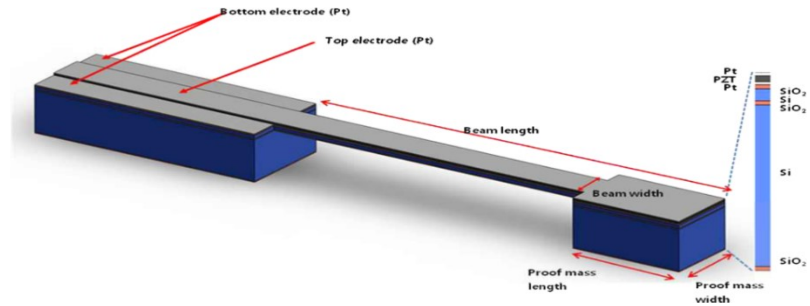
❖ Aerospace, Automotive etc.

Piezoelectric material: Applications in Sensors, Energy Harvester and Actuators

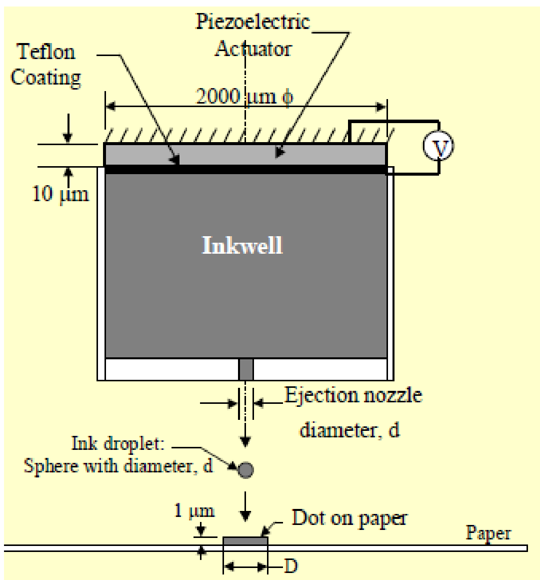
Piezoelectric sensing for accelerometer and energy harvester:

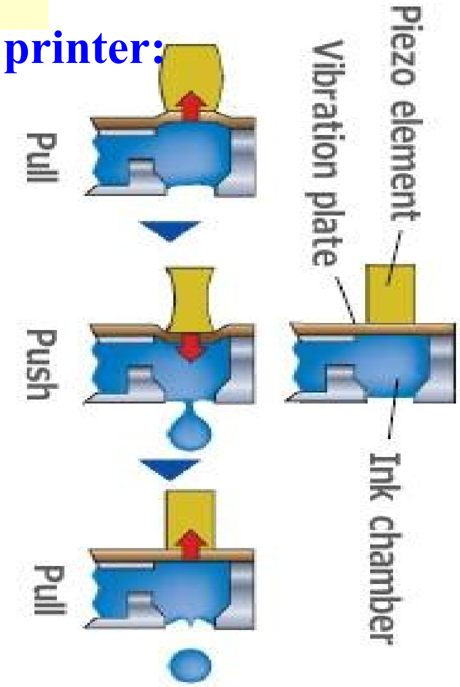
A thin piezoelectric crystal film, **PZT** is used to transduce the signal in a micro accelerometer involving a cantilever beam made of silicon. The accelerometer

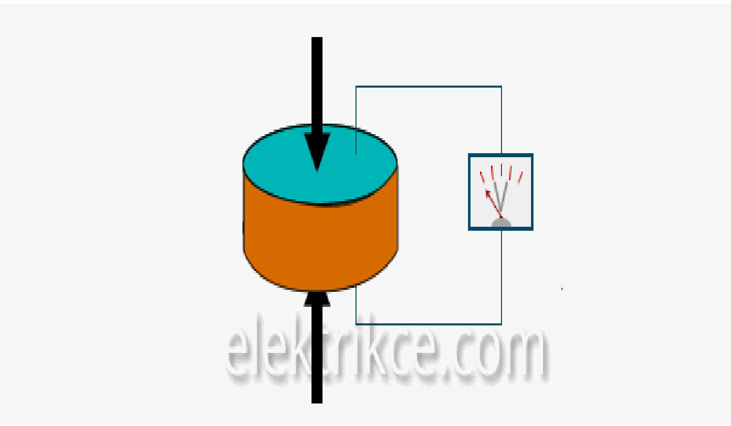




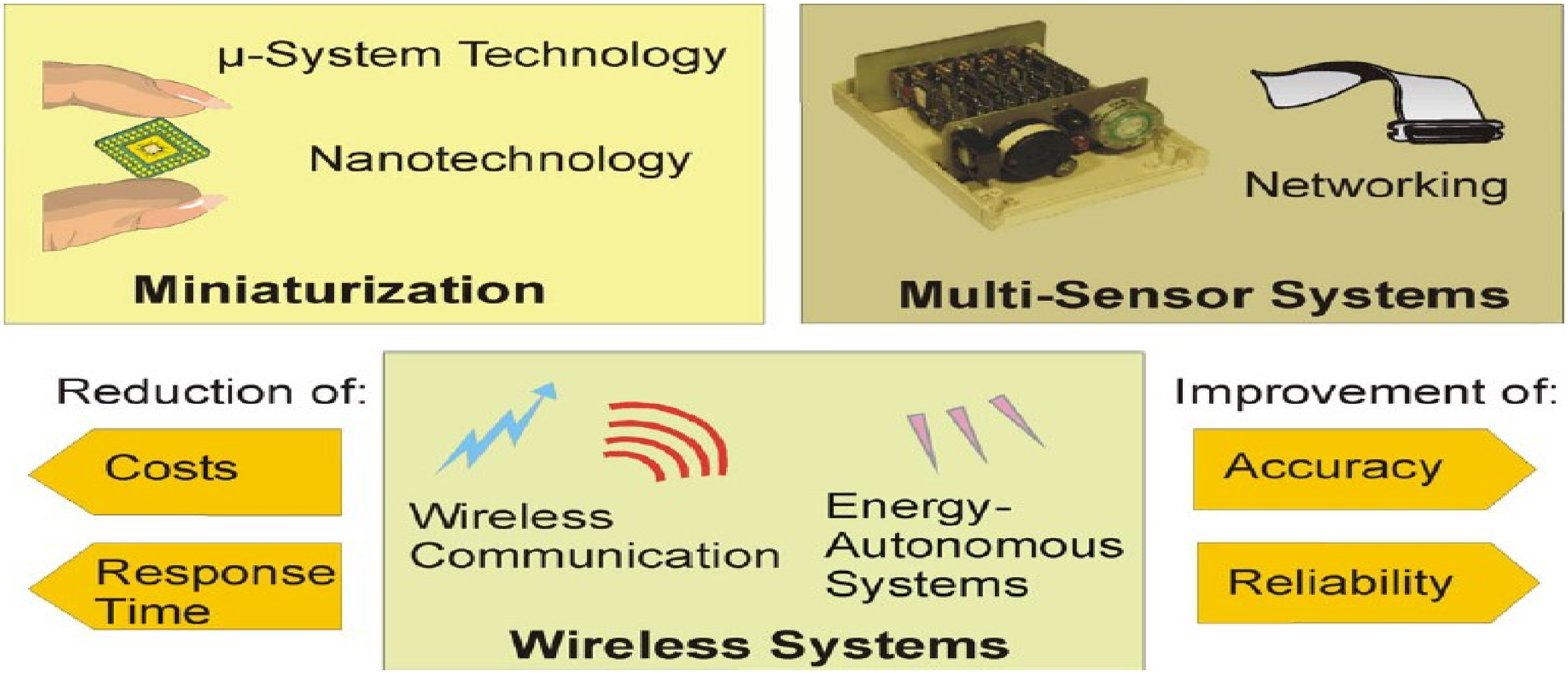
Piezoelectric actuator in inkjet printer:





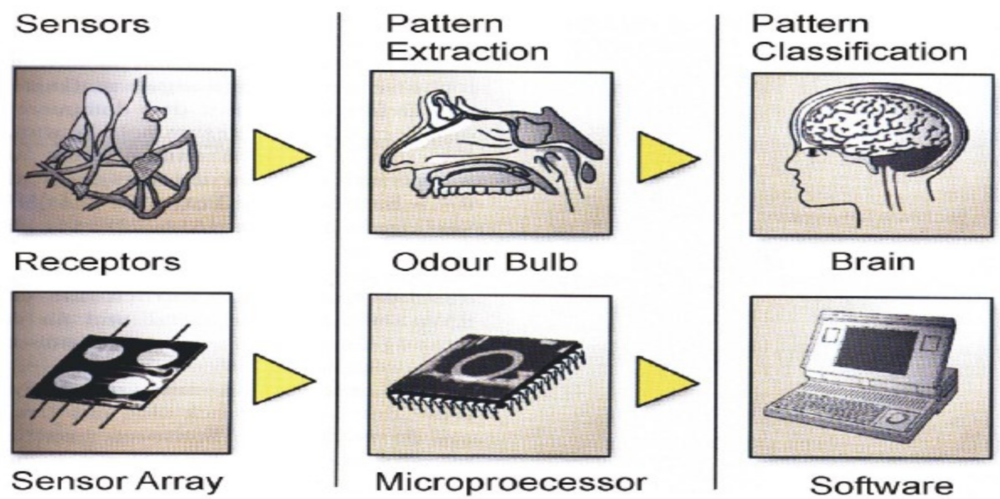


Advancement in Sensing Technology



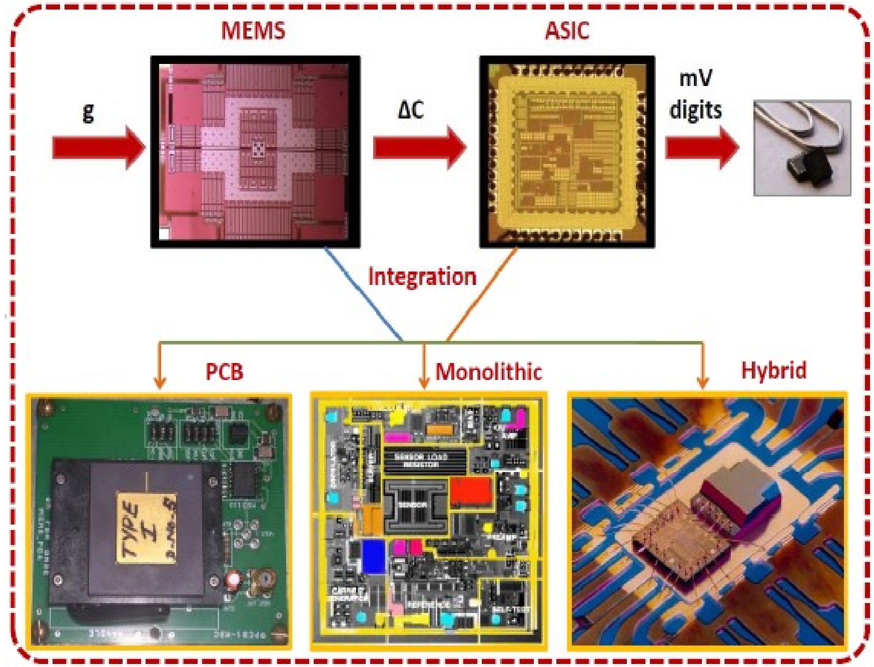
Example: Electronic Nose

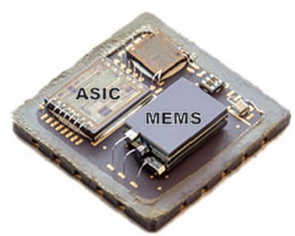
Application: Agriculture; Food, beverage Industry, Chemical process etc.

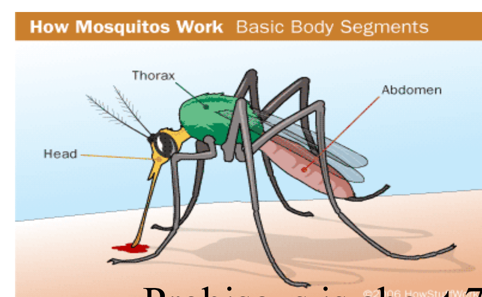


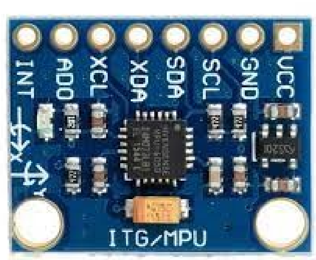
Why miniaturization?

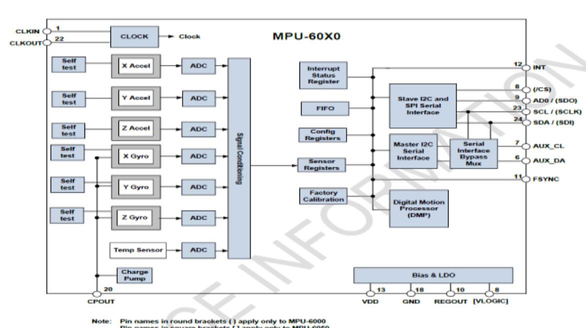
- Small size
- Low Power requirement
- Low Cost
- Improved performance
- Batch fabrication
- Integration with electronics
- Minimal invasive





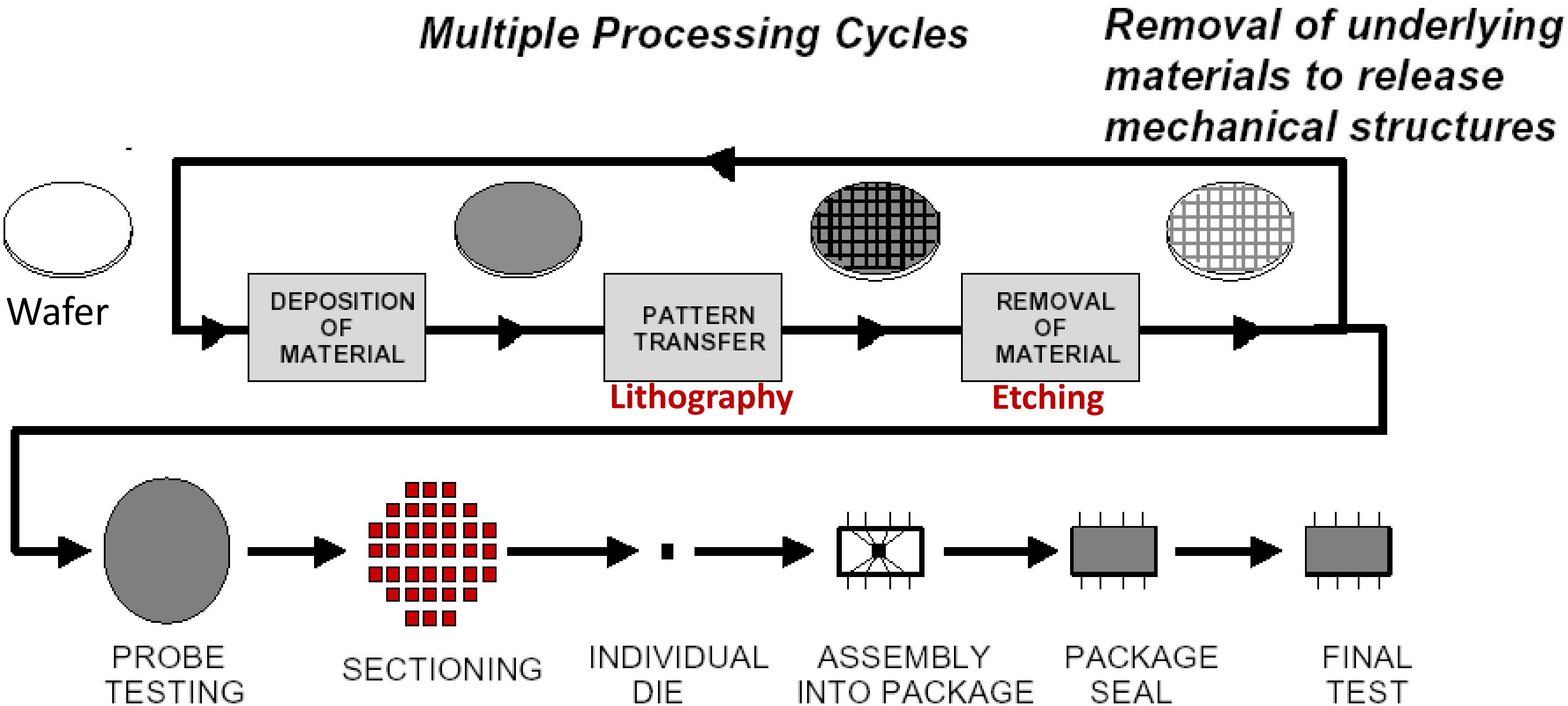






Probiscus is about 75 µm ϕ

Microfabrication Technique



Mostly used material: Silicon

Cleanroom and Various Equipment for Microfabrication

Cleanroom

Sputtering system for material deposition

Mask aligner for Lithography

Dry Etching System

Why Silicon for MEMS?

Major factors that make silicon very attractive for MEMS:

1. Widely used in the fabrication of IC---(Well established technology)

2. Easy integration with CMOS circuit on same chip

3. Excellent mechanical properties: (Young's modulus (Y) comparable to steel, less mass density (d)) (**Si**: **Y= 190 Gpa; d=2.3 g/cc; Steel: Y= 210 Gpa**; d=7.9 g/cc; **Al:** Y= 70 Gpa; **d=2.7 g/cc**).

4. High melting point (MP) (1400°C), about twice as that of Al.

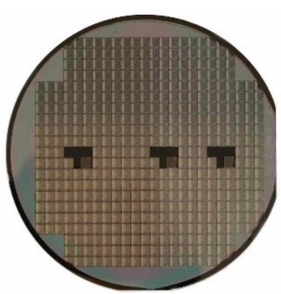
5. Thermal expansion coefficient about 8 times smaller than that of steel, 10 times smaller than that of Al.

6. Silicon and its derivatives (SiO_2, Si_3N_4) are some of the best electrically characterized materials.

Working Environment: Cleanroom

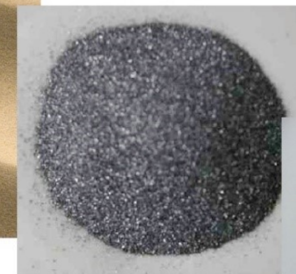
- Controlled environment
  - Temperature (70 F)
  - Humidity (45%)
- Control of particulates
  - Highly filtered air
  - Minimization of certain materials
- Classes of cleanrooms
  - Class 100: Less than 100 particles > 500 nm per ft^3
  - Class 1000: Less than 1000 particles per ft^3

-Class 10: Less than 10 particles/ft3

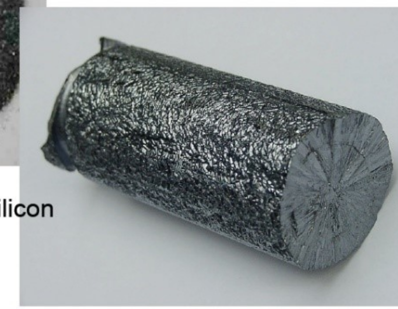


Wafer preparation

Sand

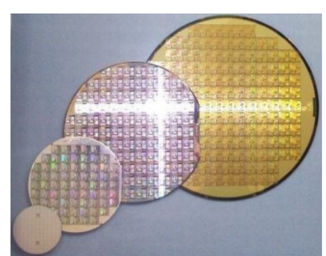


Metallurgical Grade Silicon (MGS)



Electronics Grade Silicon (EGS)

1. SiC with SiO_2 → MGS (purity about 98%)
2. MGS treated chemically to get EGS (99.99%)



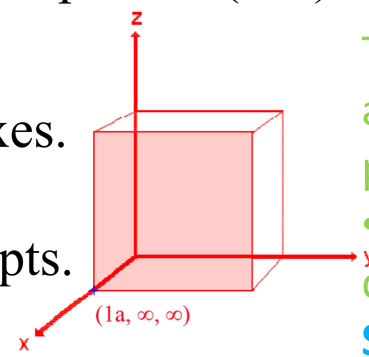
Silicon Crystal Structure and Orientation

Mechanical, Chemical and optical properties of MEMS structure changes with crystal plane and orientation.

Miller indices are used to specify directions and planes. (abc) represents a plane.

Miller Indices for Planes: Procedure::

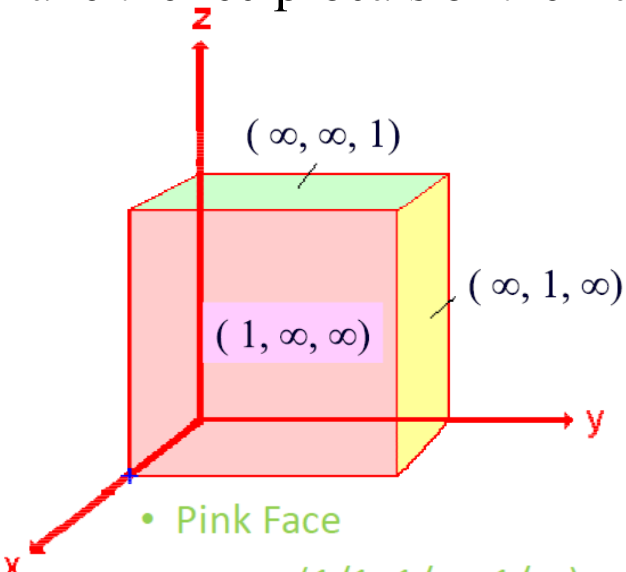
1. Identify the plane intercepts on x, y and z-axes.
2. Specify intercepts in fractional coordinates.
3. Take the reciprocals of the fractional intercepts.



The plane intersects the x-axis at point a. It runs parallel along y and z axes.

- Thus, this plane can be designated as (1,∞,∞)

So Miller indices (100)

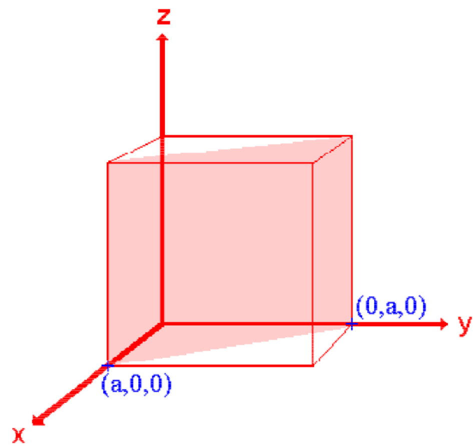


- Pink Face

  = (1/1, 1/∞, 1/∞) = (100)
- Green Face

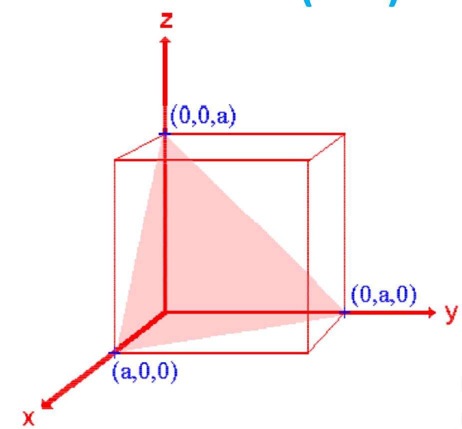
  = (1/∞, 1/∞, 1/1) = (001)
- Yellow Face

  = (1/∞, 1/1, 1/∞) = (010)



Intercepts: (1,1, ∞) → (110)

So Miller indices (110)



This plane cuts all three crystallographic axes.

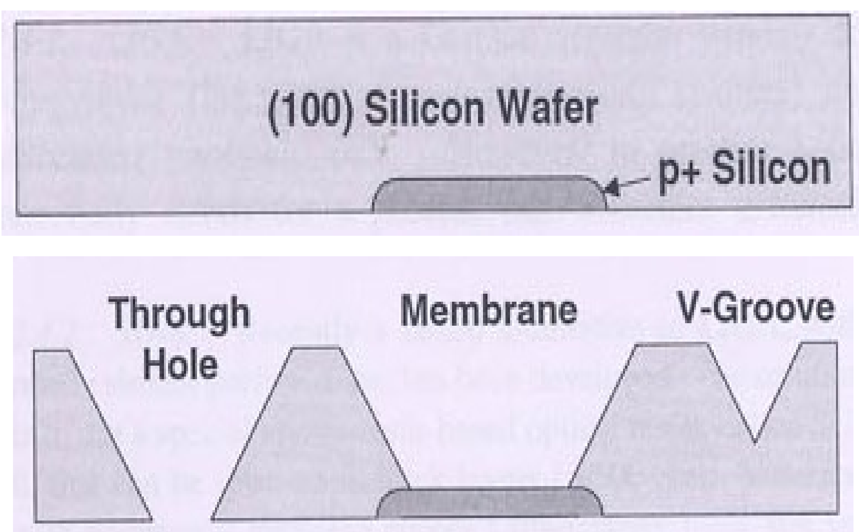
- Intercepts = (1,1,1) →

So Miller indices (111)

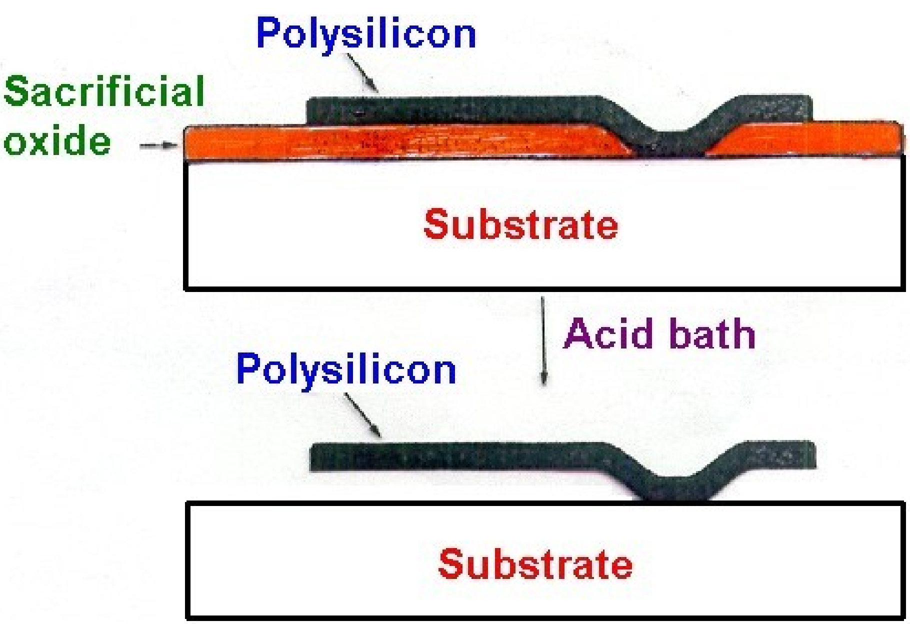
Micromachining Technology

- Micromachining is defined as a process technology for shaping silicon or other materials to realize 3-D MEMS structure
  - Evolved from integrated circuit technology
  - Completely different from conventional machining
- Rapidly emerging technology combining electrical, electronics, mechanical, materials, chemical, optical engineering disciplines for realization of micro-sensors, micro-actuators and microstructures.

Bulk Micromachining



Surface Micromachining



Bulk Micromachining

Using single crystalline silicon wafer, the bulk material of the substrate along thickness direction is dissolved/ etched to realize various 3-D micromechanical structures

➢Device thickness is controlled by etching/ diffusion

Advantages:

➢Well established

➢Rugged structure

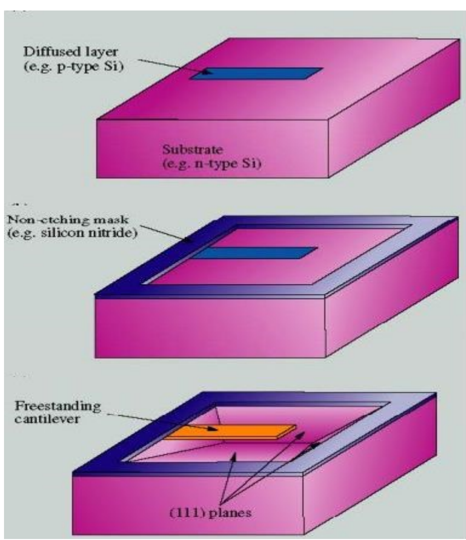
➢Large mass/area suitable for some applications

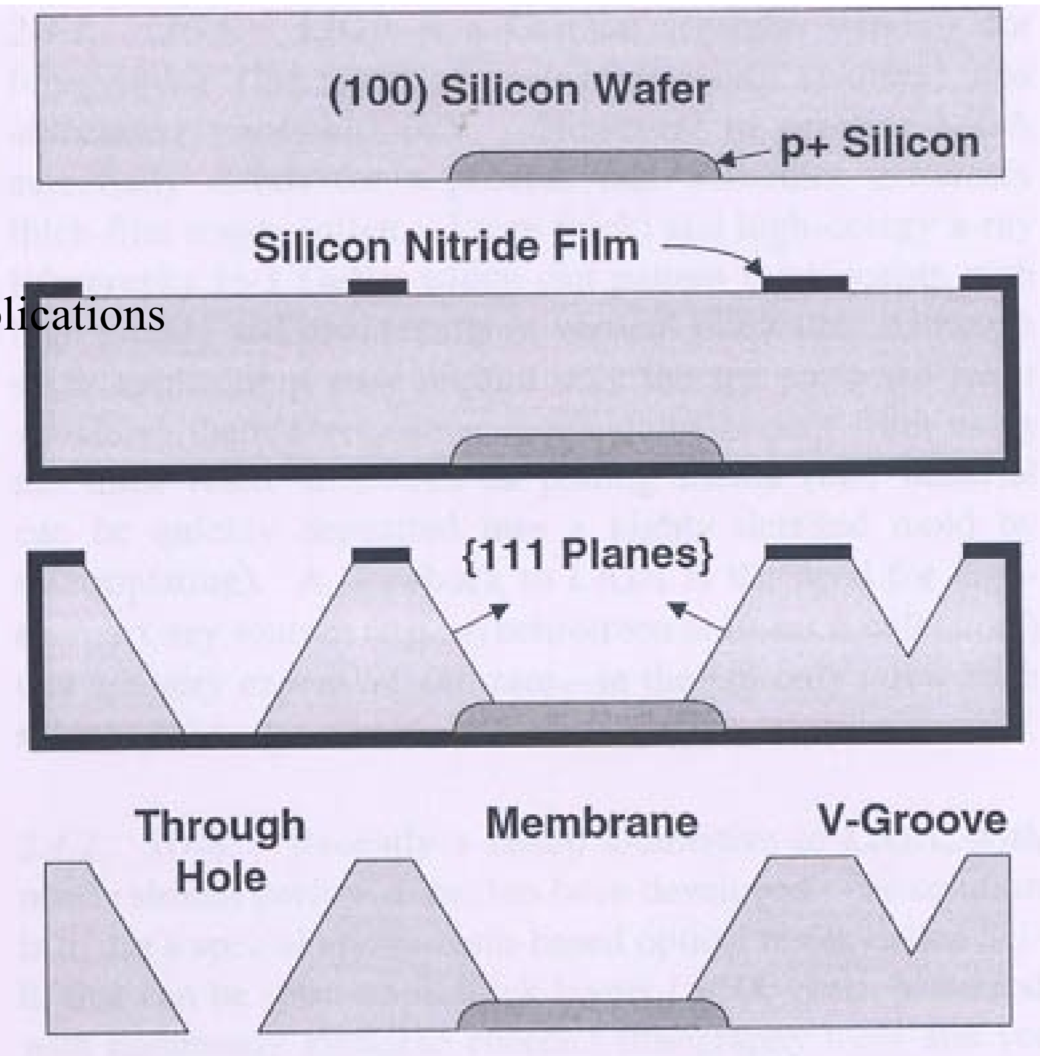
Limitations:

➢Large area: High cost

➢Not fully compatible with IC

➢ Limited structural geometry possible

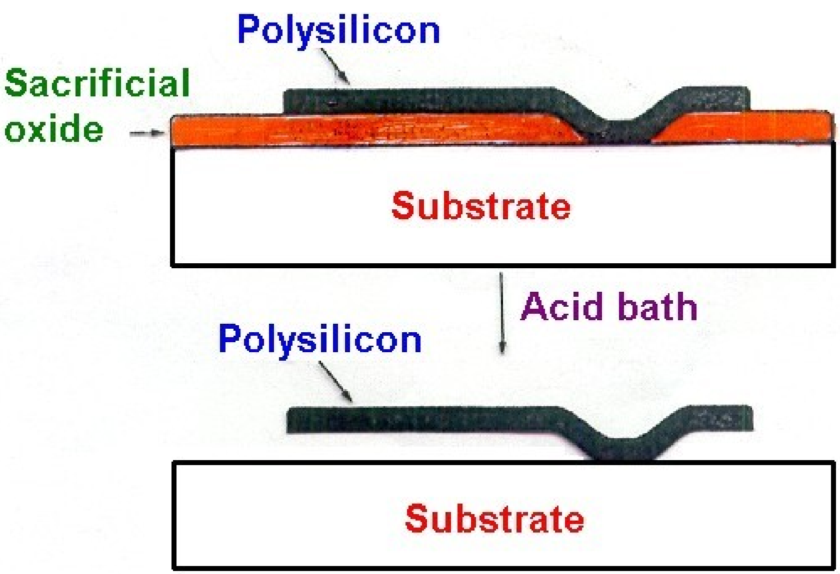




Surface Micromachining

This technology is based on depositing and etching structural and sacrificial films. After deposition of thin film, sacrificial layer is etched away, leaving a completely assembled microstructure. Typically much thinner structures than bulk micromachining

- Maximum possible thickness of the microstructure is limited to that of the deposited film



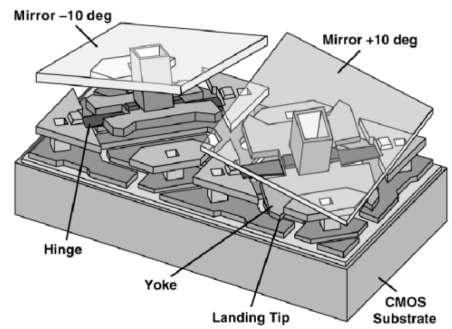
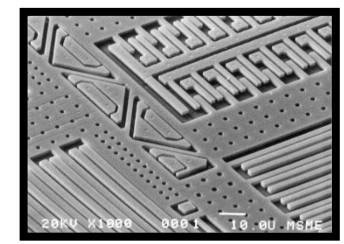


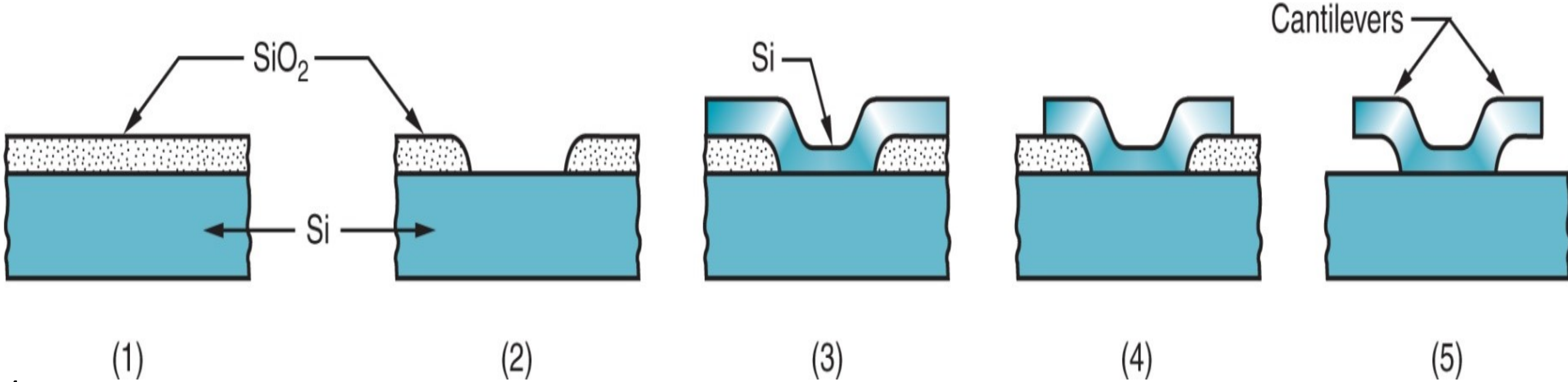
Figure 53. DMD cutaway view showing two mirrors in opposite tilted states.



Examples of devices: accelerometers, pressure sensors, micro mirrors etc.

- Main Advantage: Easy integration with integrated circuit (IC) components, as the same wafer surface can also be processed for IC elements.
- Limitations/Problems:
  - Maximum device thickness is limited to the deposited film.
  - Thermal expansion / induced stress
  - Stiction due to van der Waals force, or capillary forces

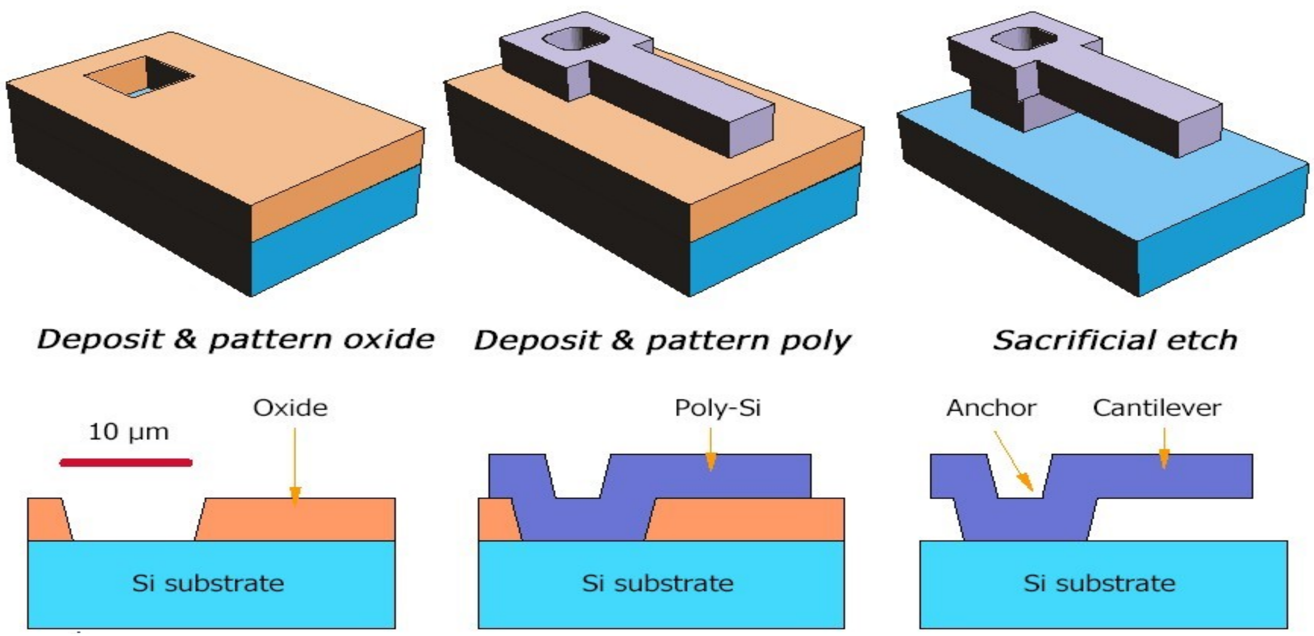
Example: Cantilever structures by surface Micromachining



(1) SiO_2 layer formed on Si substrate ; (2) Patterning of SiO_2 layer using lithography

(3) Deposition of Poly-Si layer; (4) Patterning of poly-Si layer using lithography

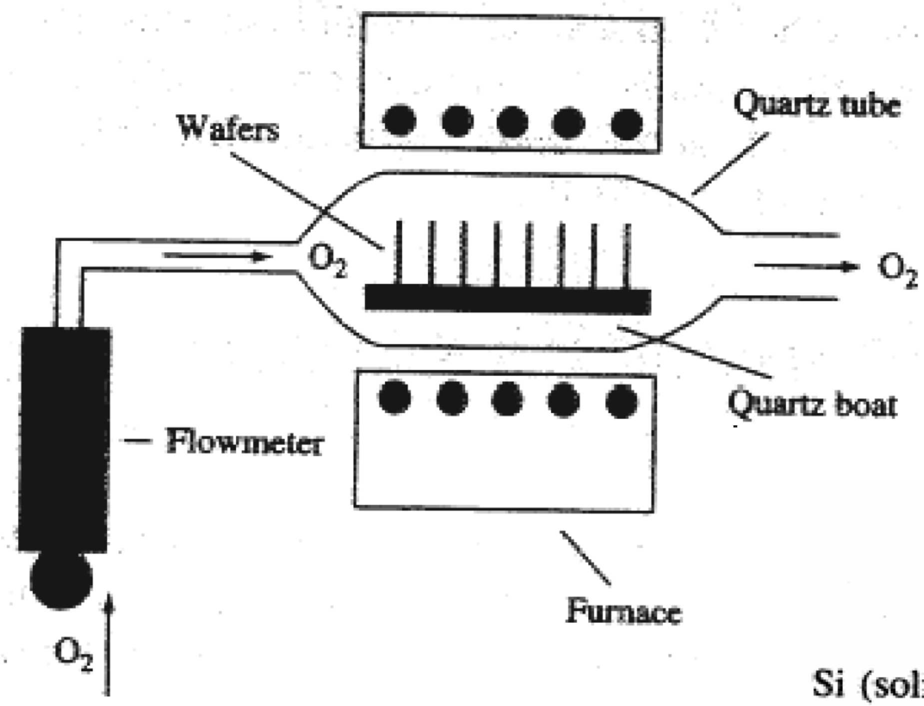
(5) Removal of sacrificial SiO_2 layer beneath the cantilevers by etching



Thin-film Deposition

1. Oxidation
2. Physical Vapour Deposition
3. Chemical Vapour Deposition

Oxidation (Thermal)



➢ Temperature range: 900-1200°C

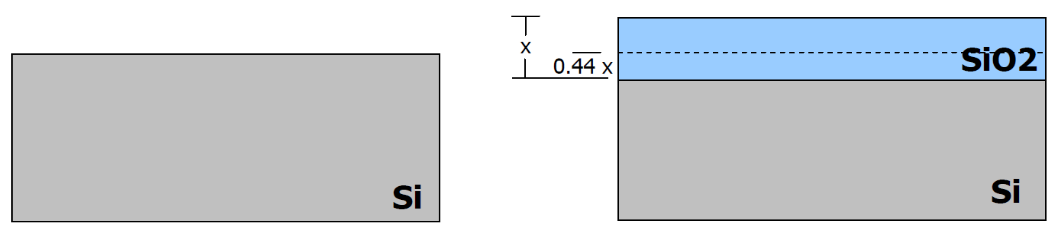
❖ Dry & Wet Oxidation

Oxidation Reactions

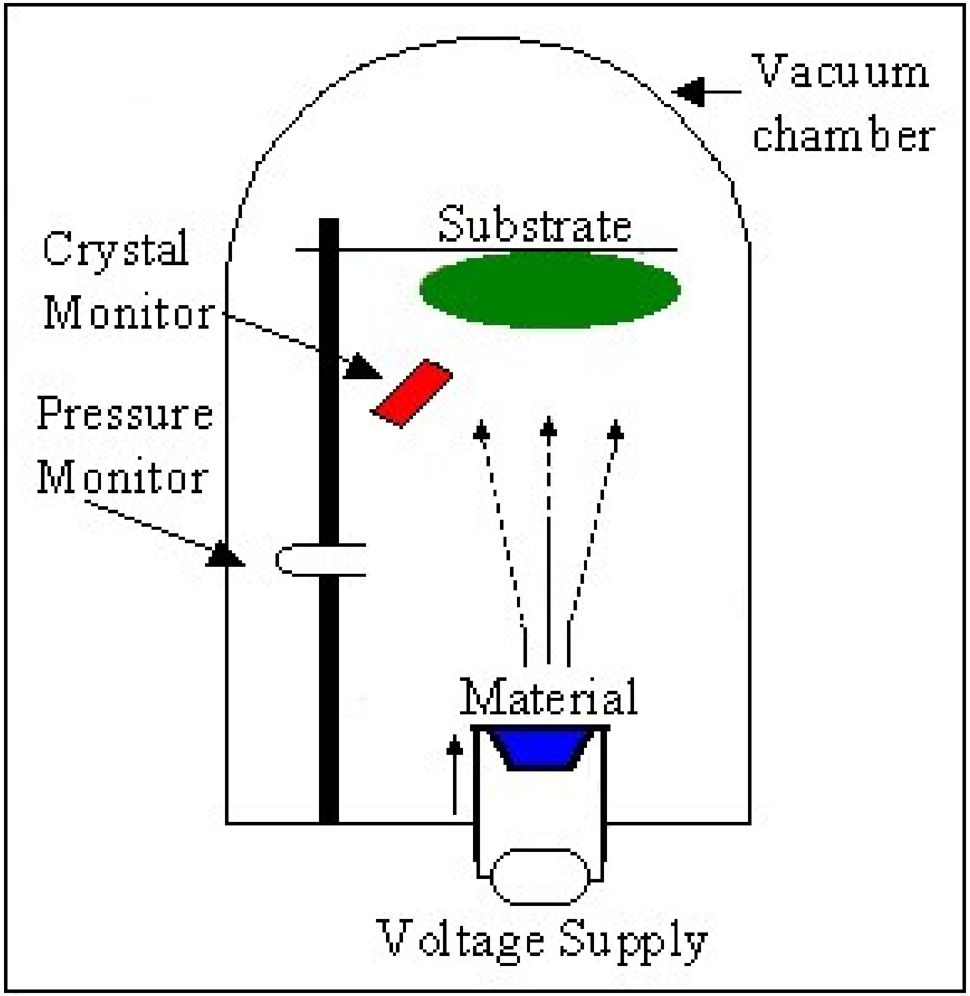
$$\text{Si (solid)} + \text{O}_2 \text{ (gas)} \xrightarrow{900-1200\,^\circ\text{C}} \text{SiO}_2 \text{ (solid)}$$

$$\text{Si (solid)} + 2\text{H}_2\text{O (gas)} \xrightarrow{900-1200\,^\circ\text{C}} \text{SiO}_2 \text{ (solid)} + 2\text{H}_2 \text{ (gas)}$$

The growth of an oxide layer of thickness x will consume 0.44 x of silicon



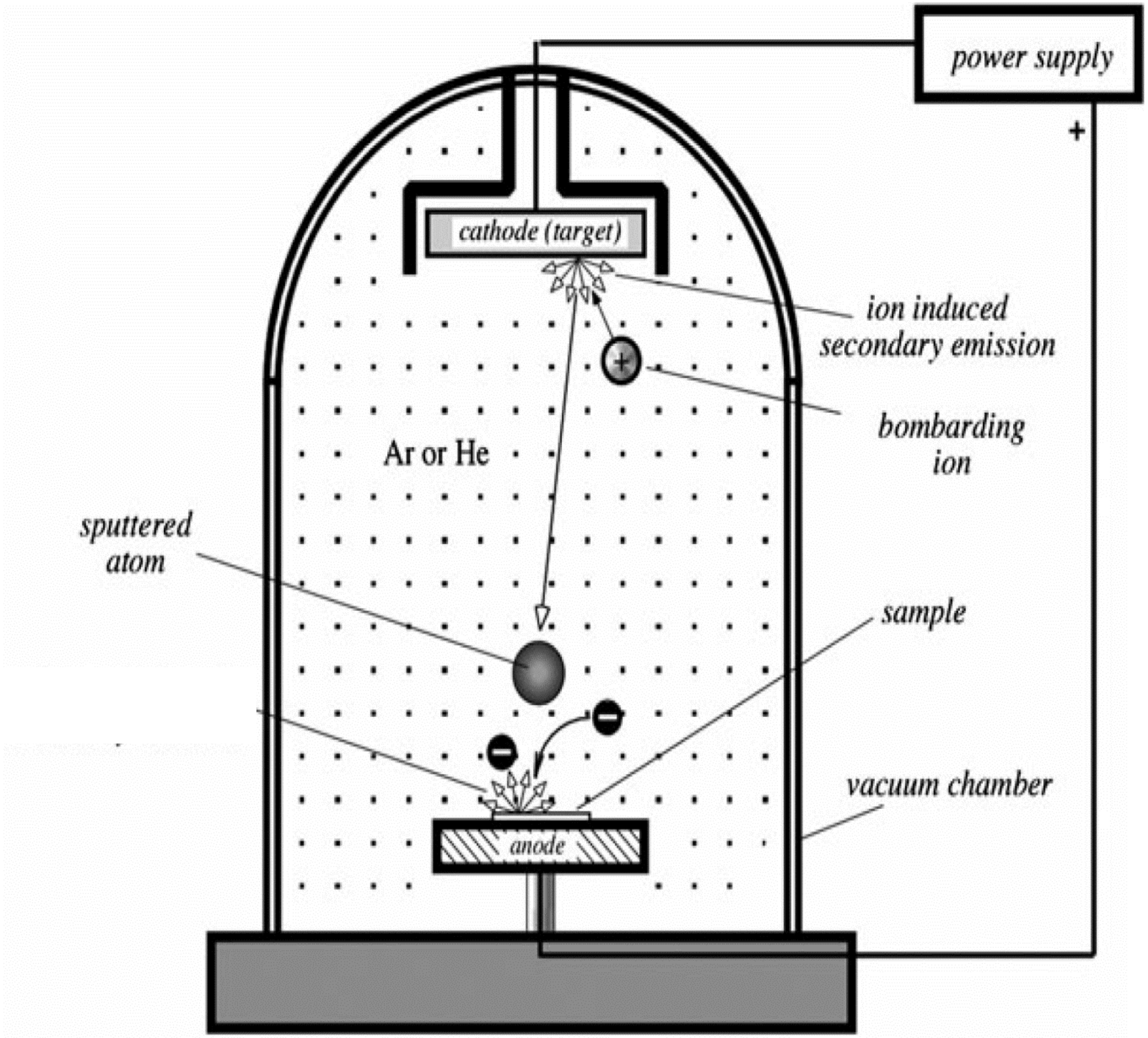
Physical Vapour Deposition: (a) Evaporation



- Vaporization of solid target material
- Condensing of the material on the substrate
- (Heating: passing large current through tungsten)
- Pressure: 10^{-6} - 10^{-7} Torr
- Used mainly for low melting point metal (e.g. Al, Ag, Cu)

Factors: Duration; Distance between source material and substrate; Purity etc.

Physical Vapour Deposition:(b) Sputtering

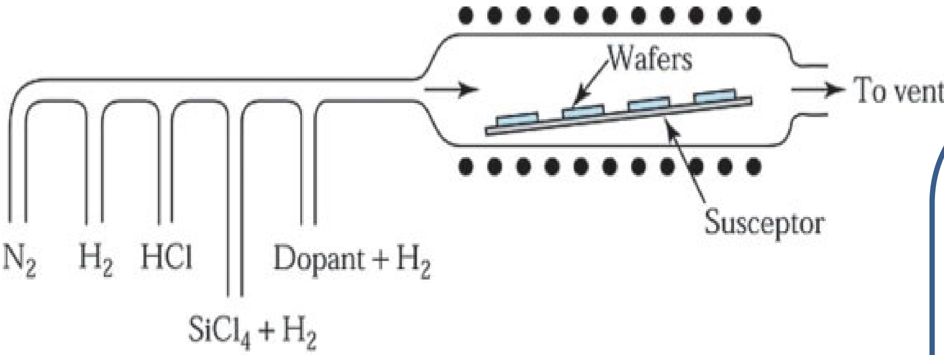


- Vacuum chamber
  (10^{-6} - 10^{-8} Torr)
- Inert gas introduced (He, Ar)
- High voltage Applied – ionization of the inert gas
- Cathode-(target material)
  - hitted by gas ions
  - Releases some atom
- Anode- (Sample/Substrate)
  - Released atoms deposited
- Any material (e.g. Ni, Cr) can be sputtered

Advantages: Uniformity, adhesion to substrate, high deposition rate etc.

Chemical Vapor Deposition

- A chemical reaction occurs on the heated surface of the wafer, resulting in deposition.



For SiO2 : $SiH_4 + O_2 \xrightarrow{500^\circ C} SiO_2 + 2H_2$

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

For Si3N4 : $3SiCl_2H_2 + 4NH_3 \xrightarrow{\sim 800^\circ C} Si_3N_4 + 6HCl + 6H_2$

For Poly-Si: $SiH_4 \xrightarrow{600^\circ C} Si + 2H_2$

Steps in CVD mechanism:

(a) Reactants (e.g. gases and dopants) are transported to substrate region,

(b) Transferred to the substrate surface where they are adsorbed,

(c) Energy supplied by the heated surface triggers the chemical reaction, thus forming thin film over the substrate

(e) reaction by-products are vented out

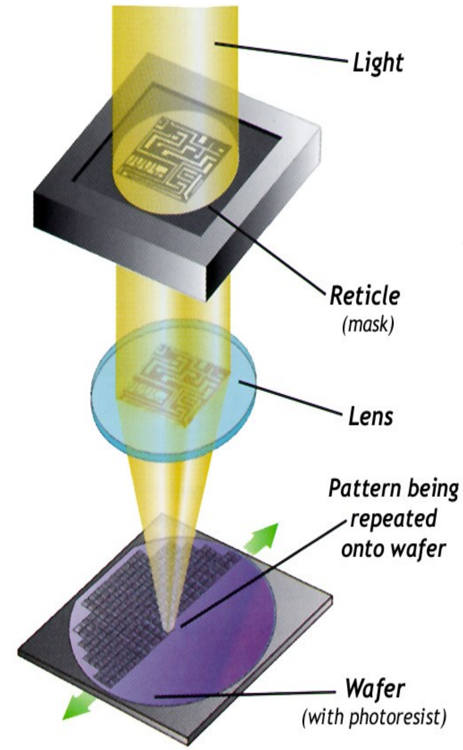
LITHOGRAPHY

Lithography comes from two Greek words, "Lithos" means stone and "Graphein" means write. Lithography means literally "writing a pattern in stone"

Lithography is the heart of integrated circuit processing.

In microelectronics – Lithography is used to describe a process in which a pattern/image from a mask is delineated in a layer of material sensitive to photons, electrons or ions.

The principle is similar to that of a photo camera in which an object is imaged on a photosensitive emulsion film.

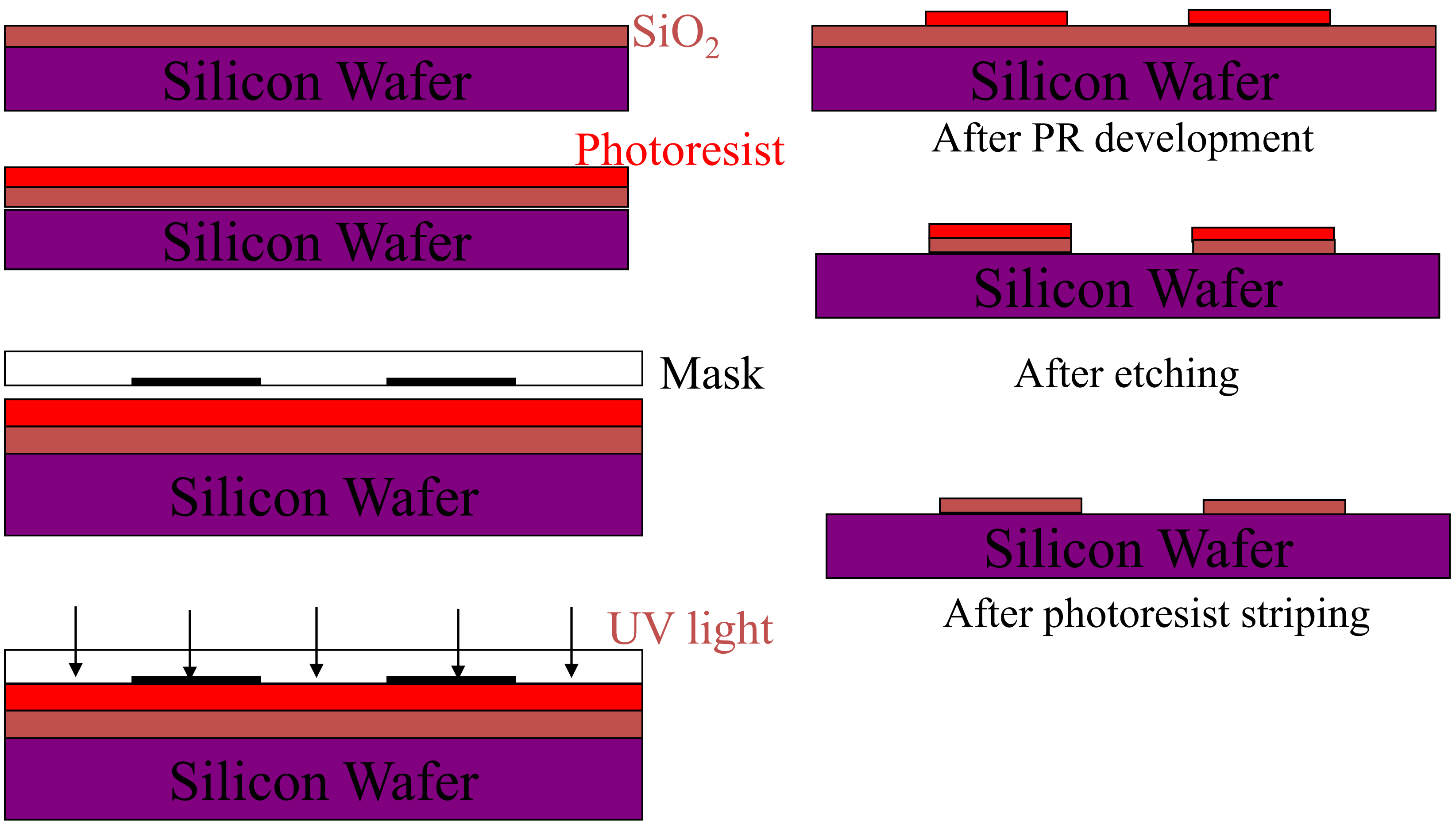


Photolithography

Requirements :

- An Alignment and Exposure Tool
- Masks containing design information
- Photo-sensitive Resist

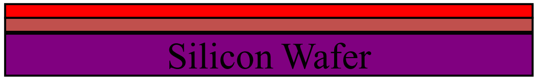
Photolithography process illustration

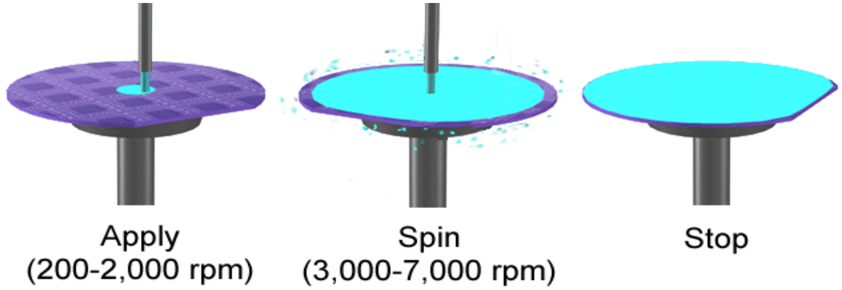


Photolithography process steps detail

1. Spin coating of Photoresist

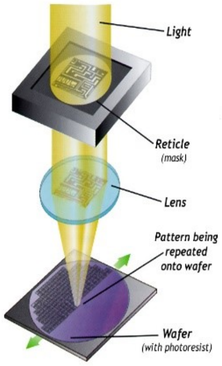
Apply a uniform, defect free film of photoresist over the entire wafer surface by spin coating. Equipment: Spin coater.





2. Pre-Bake (Soft-Bake)

- Heated at typical Temperature 90-100°C for about 10 minutes using Oven or Hot plate.
- Improve adhesion to the substrate

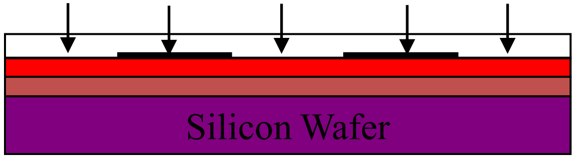


3. UV Exposure

Pattern transfer by UV exposure using mask aligner.

For good results UV exposure should have:

- Proper intensity; Directionality; Radiation uniformity



4. Development

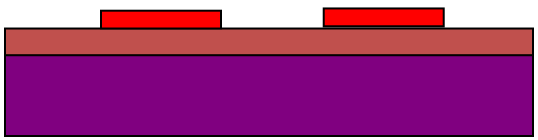
Process steps contd..

Development removes the unwanted photoresist (softened portion)

- Positive Resist - Area exposed to light is removed –(Uses KOH developer)
- Negative Resist - Area unexposed to light is removed - Uses Organic Solvent Developer.

Development Process Includes

- Development by Immersion or Spray; Rinse and Dry

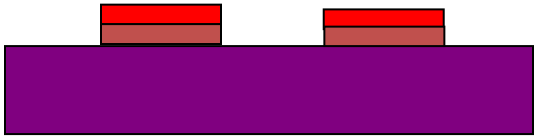


5. Post-Bake (Hard bake)

Temperature applied 120°C for about 20 minutes

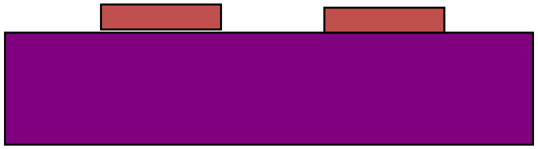
❖ Hardens the remaining photoresist

❖ Improves further adhesion; Removes organic solvents



6. Etch

❖ Removes unwanted material from the substrate through the windows opened after development step



7. Phtoresist strip

❖ After pattern transfer, complete removal of the Photoresist.

❖ Wet Chemical Strip or Dry Plasma Strip used