

Lectures on MEMS and Microsystems Design and Manufacture

Chapter 7

Materials for MEMS and Microsystems

This chapter will cover the materials used in “**silicon-based**” MEMS and microsystems. As such, **silicon** will be the principal material to be studied.

Other materials to be dealt with are silicon compounds such as: SiO_2 , **SiC**, **Si₃N₄** and **polysilicon**.

Also will be covered are electrically conducting of **silicon piezoresistors** and **piezoelectric crystals** for electromechanical actuations and signal transductions.

An overview of **polymers**, which are the “rising stars” to be used as MEMS and microsystems substrate materials, will be studied too.

Silicon – an ideal substrate material for MEMS

- Silicon (Si) is the most **abundant material on earth**. It almost always exists in compounds with other elements.
- Single crystal silicon is the most widely used substrate material for MEMS and microsystems.
- The popularity of silicon for such application is primarily for the following reasons:
 - (1) It is **mechanically stable** and it is feasible to be integrated into electronics on the same substrate (b/c it is a semiconducting material).
 - (2) Electronics for signal transduction such as the **p or n-type piezoresistive** can be readily integrated with the Si substrate-ideal for transistors.
 - (3) Silicon is almost an **ideal structure material**. It has about the same Young's modulus as steel ($\sim 2 \times 10^5$ MPa), but is as light as aluminum with a density of about 2.3 g/cm^3 .

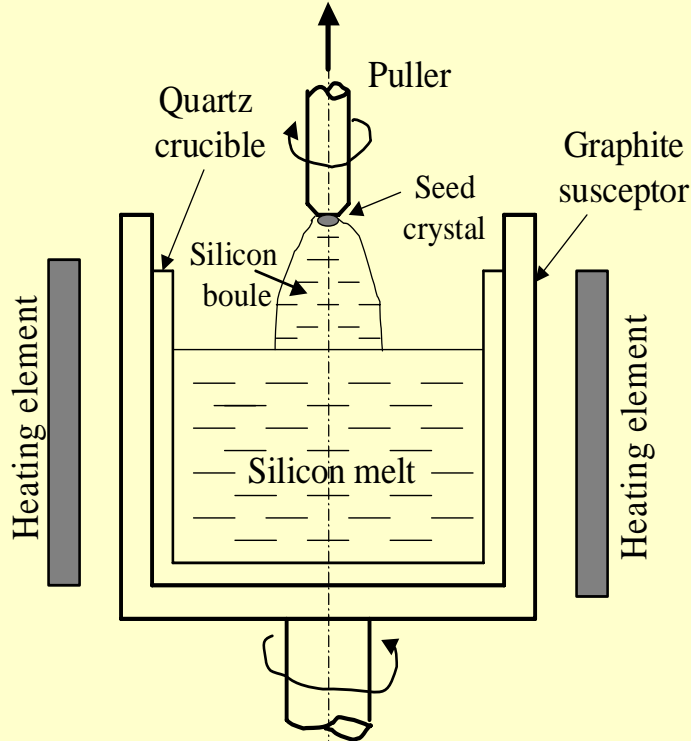
Silicon – an ideal substrate material for MEMS-Cont'd

- (4) It has a melting point at 1400°C, which is about twice higher than that of aluminum. This high melting point makes silicon dimensionally stable even at elevated temperature.**
- (5) Its thermal expansion coefficient is about 8 times smaller than that of steel, and is more than 10 times smaller than that of aluminum.**
- (6) Silicon shows virtually no mechanical hysteresis. It is thus an ideal candidate material for sensors and actuators.**
- (7) Silicon wafers are extremely flat for coatings and additional thin film layers for either being integral structural parts, or performing precise electromechanical functions.**
- (8) There is a greater flexibility in design and manufacture with silicon than with other substrate materials. Treatments and fabrication processes for silicon substrates are well established and documented.**

Single-Crystal Silicon

- For silicon to be used as a substrate material in integrated circuits and MEMS, it has to be in a **pure single-crystal form**.
- The most commonly used method of producing single-crystal silicon is the **Czochralski (CZ) method**.

The Czochralski method for producing single-crystal silicon



Equipment: a crucible and a “puller”.

Procedure:

- (1) **Raw Si** (quartzite) + coal, coke, woodchips) are melted in the crucible.
- (2) A **“seed” crystal** is brought to be in contact with molten Si to form larger crystal.
- (3) The “puller” slowly pulls the molten Si up to form **pure Si “boule”** after the solidification.
- (4) The diameters of the “bologna-like” boules vary from **100 mm (4”) to 300 mm (12”) in diameters**.

Chemical reaction for the process: $\text{SiC} + \text{SiO}_2 \rightarrow \text{Si} + \text{CO} + \text{SiO}$

Pure silicon wafers

Pure silicon boules of 300 mm diameter and **30 ft long**, can weigh up to **400 Kg**.

These boules are sliced into thin disks (wafers) using diamond saws.

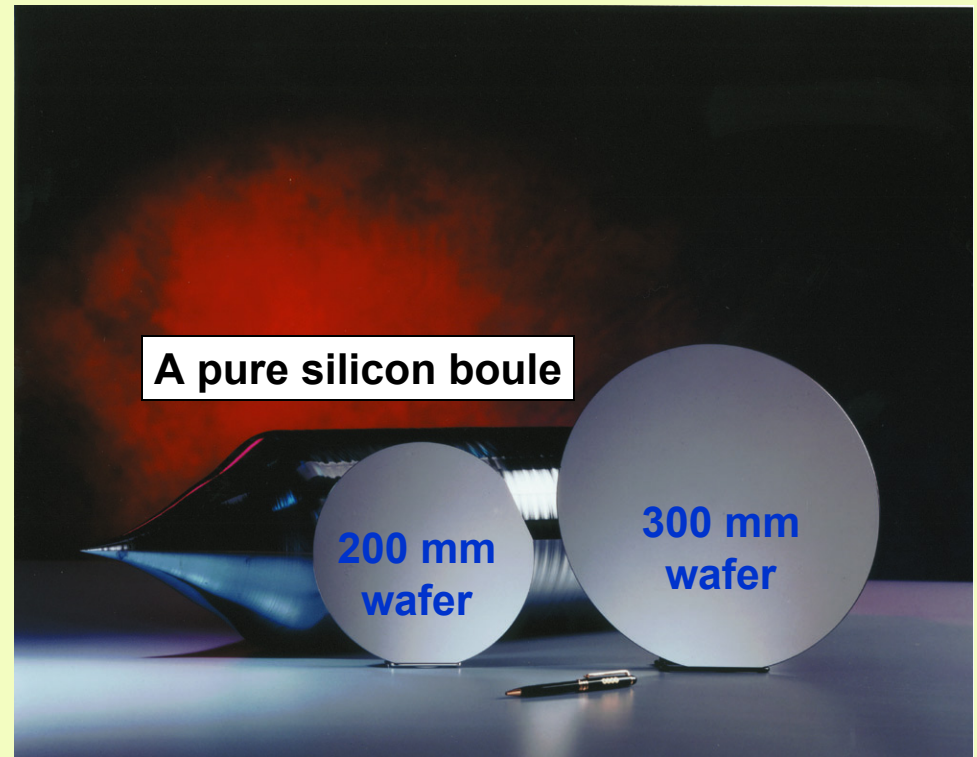
Standard sizes of wafers are:

100 mm (4") diameter x 500 μm thick.

150 mm (6") diameter x 750 μm thick.

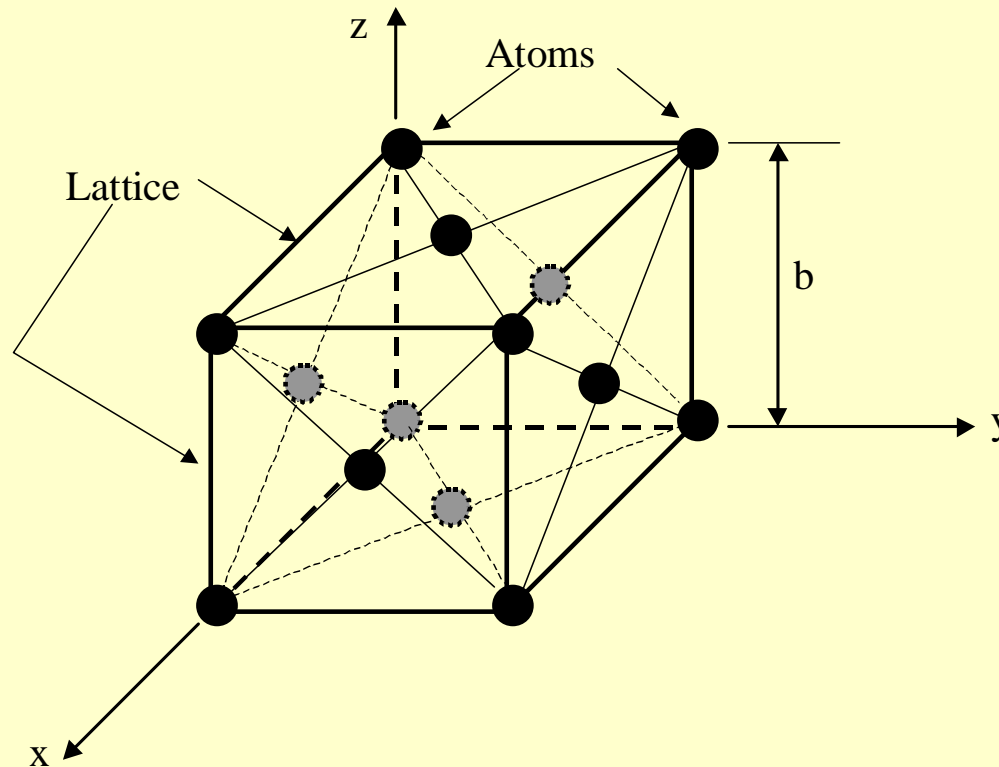
200 mm (8") diameter x 1 mm thick

300 mm (12") diameter x 750 μm thick (tentative).



Single Silicon Crystal Structure

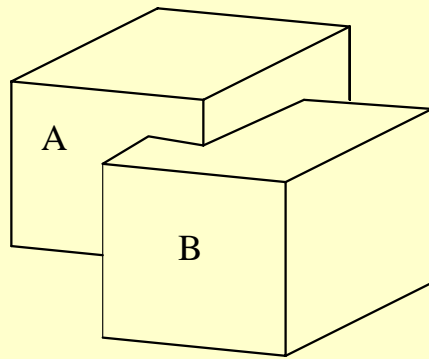
- Single silicon crystals are basically of “face-cubic-center” (FCC) structure.
- The crystal structure of a typical FCC crystal is shown below:



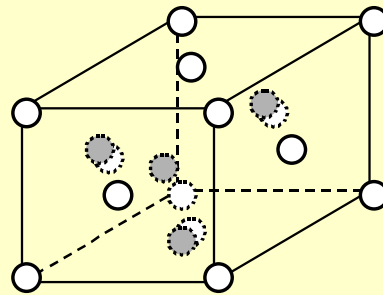
Note: Total number of atoms: 8 at corners and 6 at faces = **14 atoms**

Single Silicon Crystal Structure-Cont'd

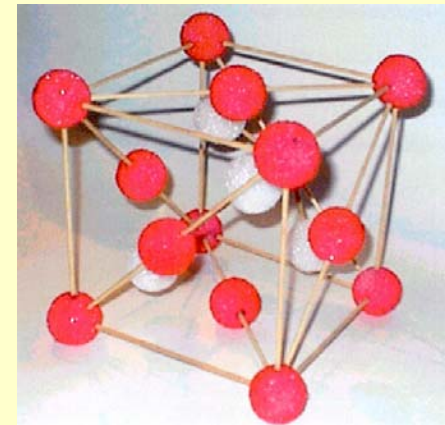
- Single crystal silicon, however has 4 extra atoms in the interior.
- The situation is like to merge two FCC crystals together as shown below:



(a) Merger of two FCC



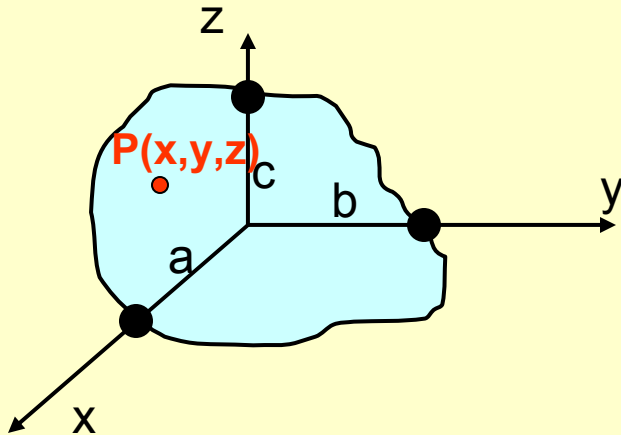
(b) Merged crystal structure



- Total no. of atoms in a single silicon crystal = 18.
- The unsymmetrical distribution of atoms within the crystal make pure silicon anisotropic in its mechanical properties.
- In general, however, we treat silicon as an isotropic material.

The Miller Indices

- Miller indices are commonly use to describe the **faces** of crystalline materials.



- A plane intersects x, y and z-coordinates at a, b and c.
- A point on the plane located at P(x,y,z)
- The equation defines the P(x,y,z) is:

$$\frac{x}{a} + \frac{y}{b} + \frac{z}{c} = 1 \quad (7.1)$$

Express Eq. (7.1) in a different form:

$$hx + ky + mz = 1 \quad (7.2)$$

in which $h = 1/a$, $k = 1/b$ and $k = 1/c$.

- Miller indices involve:

(hkm) = designation of a “face”, or a **plane**;

<hkm> = designation of a **direction** that is perpendicular to the (hkm) plane.

- **NOTE:** In a cubic crystal, such as silicon, $a = b = c = 1$

The 3 Distinct Planes of a Cubic Crystal

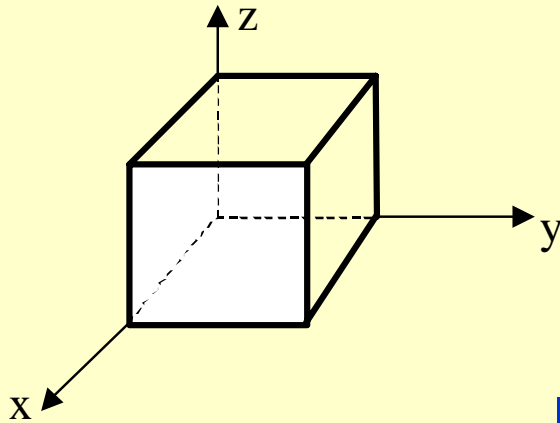


Figure A

Top face: Plane (001)

Right face: Plane (010)

Front face: **Plane (100)**

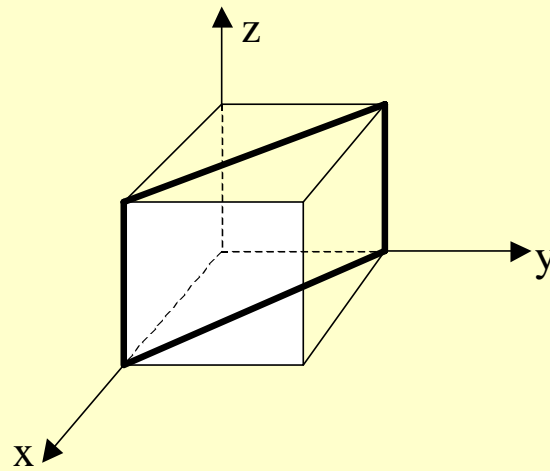


Figure B

Diagonal face: **Plane (110)**

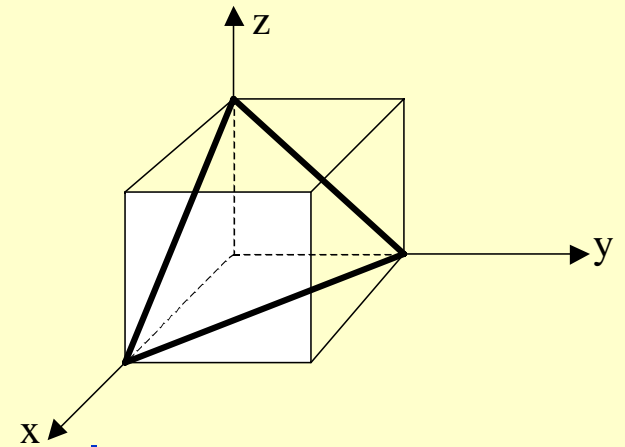
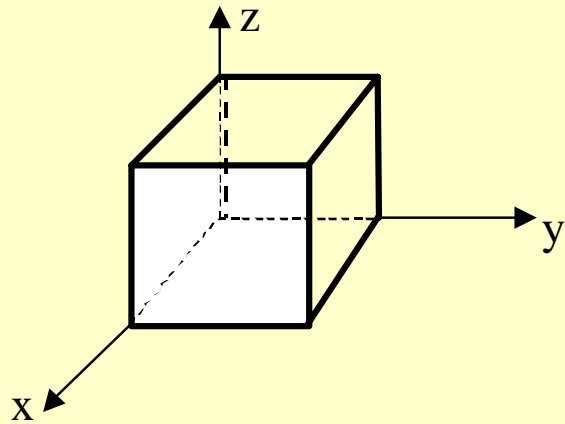


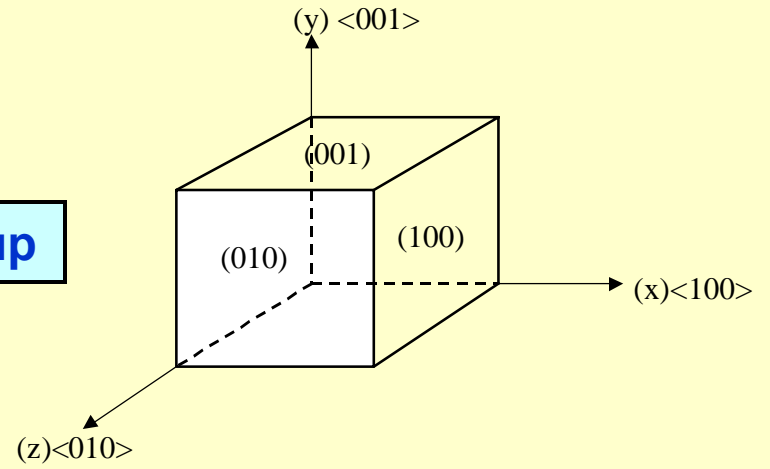
Figure C

Incline face:
Plane (111)

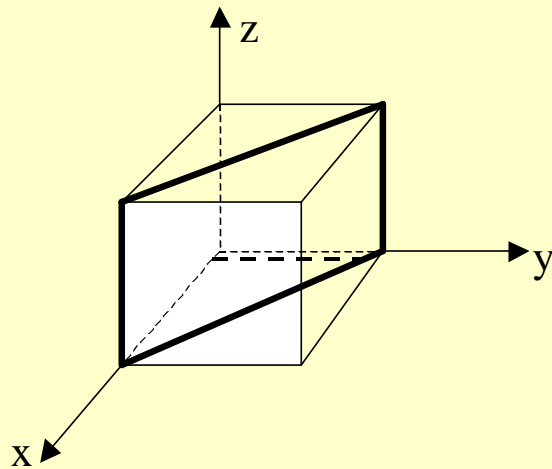
The 3 Principal Planes of a Silicon Crystal



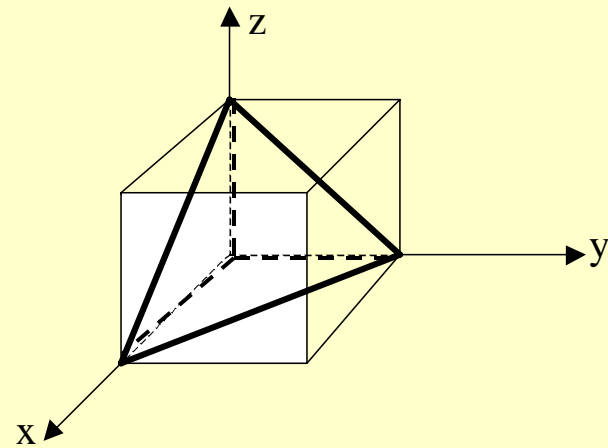
The (100) group



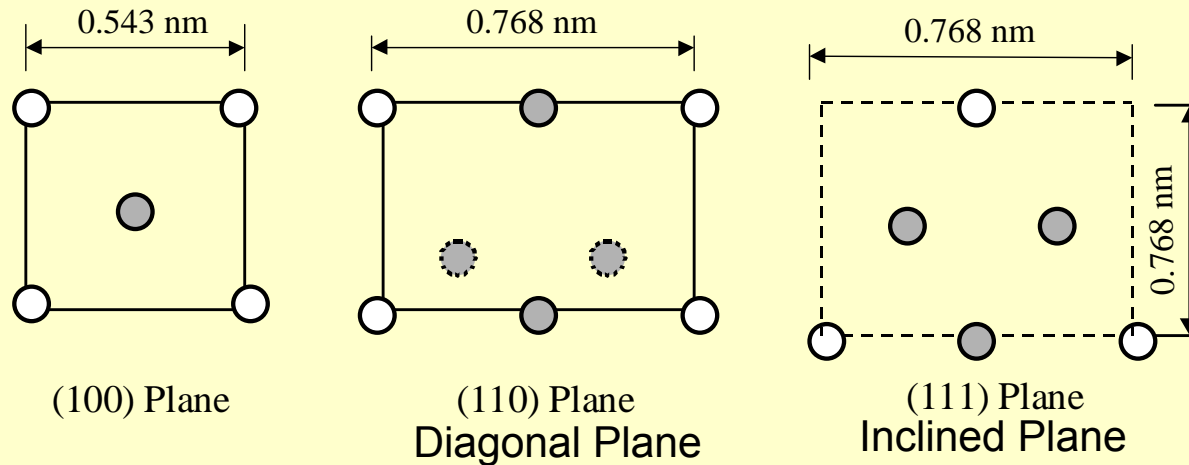
The (110) group



The (111) group



The 3 Principal Planes of a Silicon Crystal-Cont'd



• Characteristics of silicon by principal planes:

- (1) The **(100)** planes contain least number of atoms → the weakest plane → **easiest to work with**.
- (2) The **(110)** planes offers the **cleanest surfaces** in micro fabrications.
- (3) The **(111)** contains shortest bonds between atoms → **strongest plane** → toughest to work with.

Miller Index for Orientation	Young's Modulus, E (GPa)	Shear Modulus, G (GPa)
<100>	129.5	79.0
<110>	168.0	61.7
<111>	186.5	57.5

NOTE: The **(100)** plane makes an angle of **54.74°** with the **(111)** plane.

(Bulk) Mechanical and Thermophysical Properties of Silicon

Legend: σ_y = yield strength; E = Young's modulus; ρ = mass density; C = specific heat;
 k = thermal conductivity; α = coefficient of thermal expansion, T_M = melting point.

	σ_y (10^9 N/m ²)	E (10^{11} N/m ²)	ρ (g/cm ³)	C (J/g-°C)	k (W/cm-°C)	α ($10^{-6}/^\circ\text{C}$)	T_M (°C)
Si	7.00	1.90	2.30	0.70	1.57	2.33	1400
SiC	21.00	7.00	3.20	0.67	3.50	3.30	2300
Si ₃ N ₄	14.00	3.85	3.10	0.69	0.19	0.80	1930
SiO ₂	8.40	0.73	2.27	1.00	0.014	0.50	1700
Aluminum	0.17	0.70	2.70	0.942	2.36	25	660
Stainless Steel	2.10	2.00	7.90	0.47	0.329	17.30	1500
Copper	0.07	0.11	8.9	0.386	3.93	16.56	1080
GaAs	2.70	0.75	5.30	0.35	0.50	6.86	1238
Ge		1.03	5.32	0.31	0.60	5.80	937
Quartz	0.5-0.7	0.76-0.97	2.66	0.82-1.20	0.067-0.12	7.10	1710

* Principal source for semiconductor material properties: "Fundamentals of Microfabrication", Marc Madou, CRC Press, 1997

Silicon Compounds

There are **3** principal silicon compounds used in MEMS and microsystems: Silicon dioxide (**SiO₂**), Silicon carbide (**SiC**) and silicon nitride (**Si₃N₄**) – each Has distinct characteristic and unique applications.

Silicon dioxide (SiO₂)

- It is **least expensive** material to offer good thermal and electrical insulation.
- Also used a low-cost material for “**masks**” in micro fabrication processes such as etching, deposition and diffusion.
- Used as **sacrificial material** in “surface micromachining”.
- Above all, it is very **easy to produce**:
 - by dry heating of silicon: $\text{Si} + \text{O}_2 \rightarrow \text{SiO}_2$
 - or by oxide silicon in wet steam: $\text{Si} + 2\text{H}_2\text{O} \rightarrow \text{SiO}_2 + 2\text{H}_2$

Silicon dioxide (SiO₂) – cont'd

Properties	Values
Density (g/cm ³)	2.27
Resistivity (Ω-cm)	≥10 ¹⁶
Dielectric constant	3.9
Melting point (°C)	~1700
Specific heat (J/g/°C)	1.0
Thermal conductivity (W/cm/°C)	0.014
Coefficient of thermal expansion (ppm/°C)	0.5

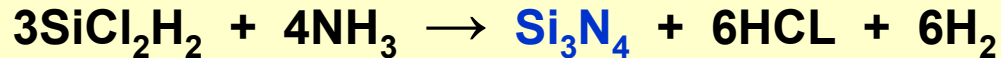
Silicon carbide (SiC)

Its very **high melting point** and resistance to chemical reactions make it ideal candidate material for being masks in micro fabrication processes.

It has **superior dimensional stability**.

Silicon nitride (Si₃N₄)

- Produced by **chemical reaction**:



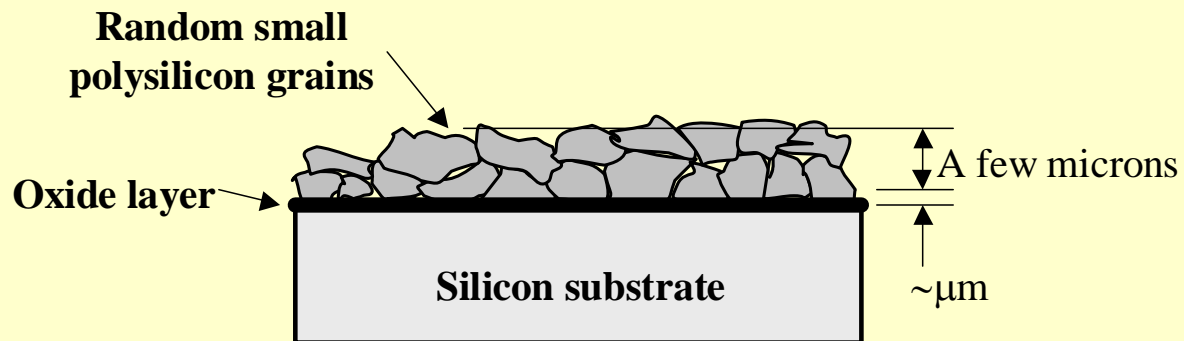
- Used as **excellent barrier to diffusion** to water and ions.
- Its ultra strong resistance to oxidation and many etchants make it a superior material for **masks in deep etching**.
- Also used as high strength **electric insulators**.
- Selected properties **Si₃N₄ films** are as follows:

Properties	LPCVD*	PECVD**
Deposition temperature (°C)	700-800	250-350
Density (g/cm ³)	2.9-3.2	2.4-2.8
Film quality	Excellent	Poor
Dielectric constant	6-7	6-9
Resistivity (Ω-cm)	10 ¹⁶	10 ⁶ -10 ¹⁵
Refractive index	2.01	1.8-2.5
Atom % H	4-8	20-25
Etch rate in concentrated HF	200 Å/min	
Etch rate in boiling HF	5-10Å/min	
Poisson's ratio	0.27	
Young's modulus (GPa)	385	
Coefficient of thermal expansion, ppm/°C	1.6	

* Low pressure chemical vapor deposition; ** Plasma enhanced chemical vapor deposition

Polycrystalline silicon

- It is usually called “**Polysilicon**”.
- It is an aggregation of pure silicon crystals with **randomly orientations** deposited on the top of silicon substrates:



- These polysilicon usually are **highly doped** silicon.
- They are deposited to the substrate surfaces to produce localized “**resistors**” and “**gates for transistors**”
- Being randomly oriented, polysilicon is even **stronger** than single silicon crystals.

Polycrystalline silicon – cont'd

Comparison of Mechanical Properties of Polysilicon with Other Materials

Materials	Young's modulus (GPa)	Poisson's ratio	Coefficient of thermal expansion (ppm/°C)
<u>As substrates:</u>			
Silicon	190	0.23	2.6
Alumina	415		8.7
Silica	73	0.17	0.4
<u>As thin films:</u>			
<i>Polysilicon</i>	<i>160</i>	<i>0.23</i>	<i>2.8</i>
Thermal SiO ₂	70	0.2	0.35
LPCVD SiO ₂	270	0.27	1.6
PACVD SiO ₂			2.3
Aluminum	70	0.35	25
Tungsten	410	0.28	4.3
Polymide	3.2	0.42	20-70

Silicon Piezoresistors

Piezoresistance = a change in electrical resistance of solids when subjected to stress fields. **Doped silicon are piezoresistors (p-type or n-type).**

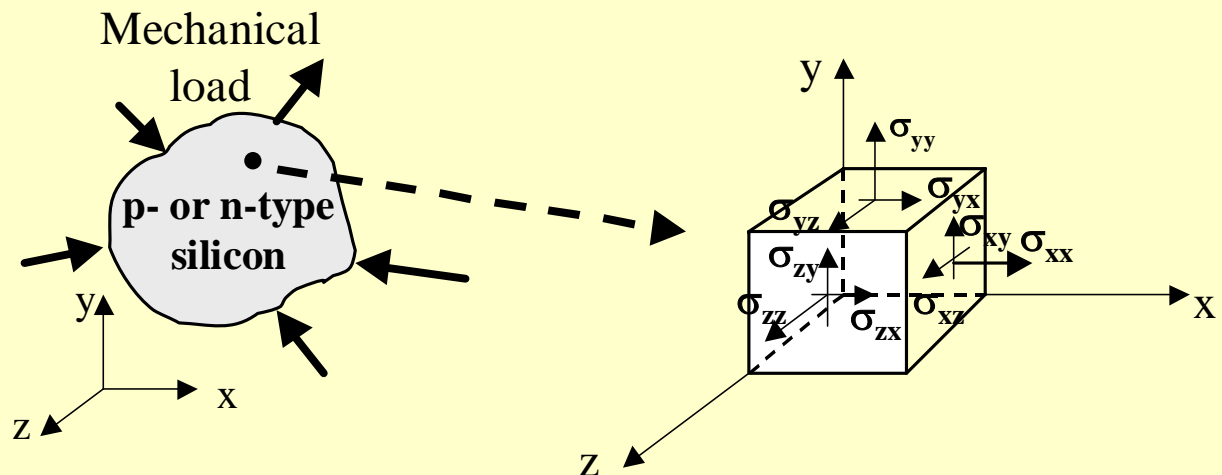
Relationship between change of resistance $\{\Delta R\}$ and stresses $\{\sigma\}$:

$$\{\Delta R\} = [\pi] \{\sigma\} \quad (7-6)$$

where $\{\Delta R\} = \{\Delta R_{xx} \ \Delta R_{yy} \ \Delta R_{zz} \ \Delta R_{xy} \ \Delta R_{xz} \ \Delta R_{yz}\}^T$ represents the change of resistances in an infinitesimally small cubic piezoresistive crystal element with corresponding stress components:

$\{\sigma\} = \{\sigma_{xx} \ \sigma_{yy} \ \sigma_{zz} \ \sigma_{xy} \ \sigma_{xz} \ \sigma_{yz}\}^T$ and $[\pi] =$ **piezoresistive coefficient matrix.**

A silicon piezoresistance subjected to a stress field:



Silicon Piezoresistors – Cont'd

- Due to equilibrium condition, there are six independent stress components: 3 normal stress components and 3 shearing stress components.
- Consequently, the **piezoresistive coefficient matrix** has the components:

$$[\pi] = \begin{bmatrix} \pi_{11} & \pi_{12} & \pi_{12} & 0 & 0 & 0 \\ \pi_{12} & \pi_{11} & \pi_{12} & 0 & 0 & 0 \\ \pi_{12} & \pi_{12} & \pi_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & \pi_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & \pi_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & \pi_{44} \end{bmatrix} \quad (7.7)$$

- Expanding Eq. (7.6) result in the following:

$$\Delta R_{xx} = \pi_{11} \sigma_{xx} + \pi_{12} (\sigma_{yy} + \sigma_{zz})$$

$$\Delta R_{xy} = \pi_{44} \sigma_{xy}$$

$$\Delta R_{yy} = \pi_{11} \sigma_{yy} + \pi_{12} (\sigma_{xx} + \sigma_{zz})$$

$$\Delta R_{xz} = \pi_{44} \sigma_{xz}$$

$$\Delta R_{zz} = \pi_{11} \sigma_{zz} + \pi_{12} (\sigma_{xx} + \sigma_{yy})$$

$$\Delta R_{yz} = \pi_{44} \sigma_{yz}$$

- Note: Only **3** piezoresistive coefficients are required; π_{11} and π_{12} associated with normal stresses and π_{44} with shearing stresses.

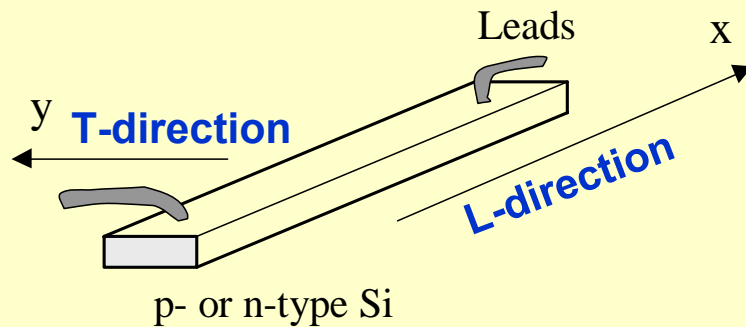
Silicon Piezoresistors – Cont'd

Numerical values of piezoresistive coefficients

Silicon piezoresistors at room temperature

Materials	Resistivity (Ω -cm)	π_{11}^*	π_{12}^*	π_{44}^*
p-silicon	7.8	+6.6	-1.1	+138.1
n-silicon	11.7	-102.2	+53.4	-13.6

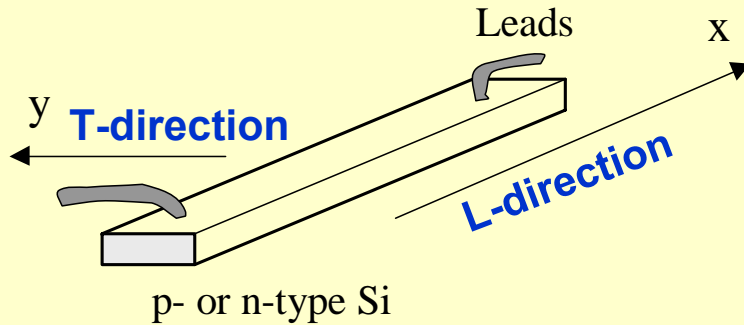
Silicon piezoresistors



$$\frac{\Delta R}{R} = \pi_L \sigma_L + \pi_T \sigma_T$$

Silicon Piezoresistors – Cont'd

Numerical values of piezoresistive coefficients



$$\frac{\Delta R}{R} = \pi_L \sigma_L + \pi_T \sigma_T$$

Piezoresistive coefficients of p-type silicon piezoresistors in various directions

Crystal Planes	Orientation <x>	Orientation <y>	π_L	π_T
(100)	<111>	<111>	$+0.66\pi_{44}$	$-0.33\pi_{44}$
(100)	<110>	<100>	$+0.5\pi_{44}$	~ 0
(100)	<110>	<110>	$+0.5\pi_{44}$	$-0.5\pi_{44}$
(100)	<100>	<100>	$+0.02\pi_{44}$	$+0.02\pi_{44}$

Example 7.3

Estimate the change of resistance in silicon piezoresistors attached to the diaphragm of a pressure sensor in Example 4.4.

From Example 4.4, the corresponding maximum stress at the mid-span of each of the 4 edges is:

$\sigma_{\max} = 186.81 \text{ MPa}$ with an applied pressure at 70 MPa.

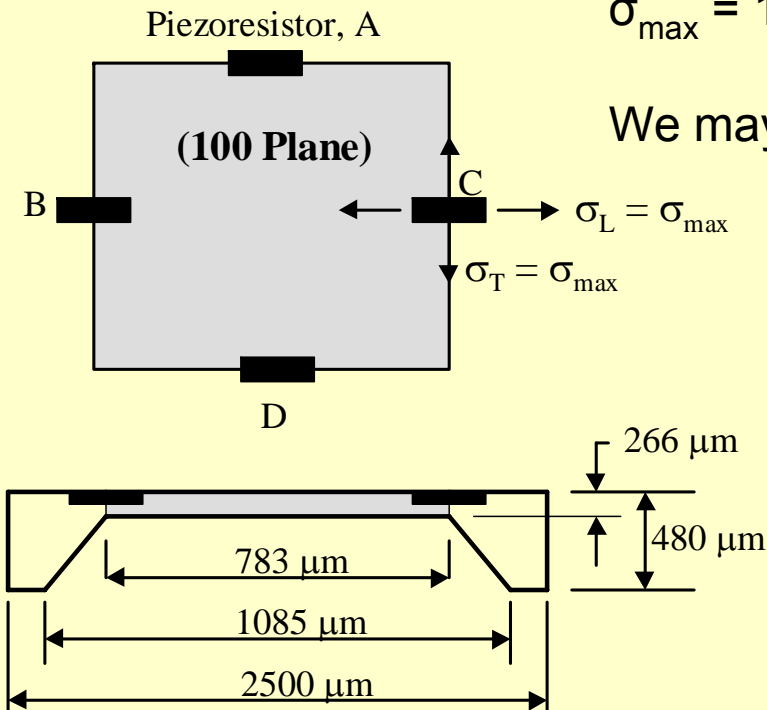
We may thus let: $\sigma_L = \sigma_T = \sigma_{\max} = 186.8 \text{ MPa}$, or
 $= 186.8 \times 10^6 \text{ Pa (N/m}^2\text{)}$

Since the diaphragm is on (100) face, the two piezoresistive coefficients are:

$$\pi_L = \pi_T = 0.02 \pi_{44}$$

But $\pi_{44} = 138.1 \times 10^{-11} \text{ Pa}^{-1}$ from the Table, we thus have:

$$\frac{\Delta R}{R} = \pi_L \sigma_L + \pi_T \sigma_T = 2 \pi_{44} \sigma_{\max} = 2 \times 0.02 (138.1 \times 10^{-11}) (186.8 \times 10^6) = 0.01032 \quad \Omega/\Omega$$



Temperature sensitivity of silicon piezoresistors

A major deficiency of silicon piezoresistors is its sensitivity of temperature as indicated in the table:

Doping concentration ($10^{18}/\text{cm}^3$)	p-Type TCR (% per °C)	p-Type TCP (% per °C)	n-Type TCR (% per °C)	n-Type TCP (% per °C)
5	0.0	-0.27	0.01	-0.28
10	0.01	-0.27	0.05	-0.27
30	0.06	-0.18	0.09	-0.18
100	0.17	-0.16	0.19	-0.12

TCR = temperature coefficient of resistance;

TCP = temperature coefficient of piezoresistivity.

Example: a p-type silicon piezoresistor with a doping of 10^{19} atoms/cm³, The loss of piezoresistivity is **0.27%/°C**. In an operating temperature of 120°C, It would lose $(120-20) \times 0.27\% = 27\%$ of the value of the piezoresistivity coefficient.

Gallium Arsenide (GaAs)

- **GaAs** is a compound semiconductor with equal number of Ga and As atoms.
- Because it is a compound, it is **more difficult to process**.
- It is excellent material for monolithic **integration of electronic and photonic** devices on a single substrate.
- The reason for being excellent material for photoelectronics is its **high electron mobility** (7 times more mobile than silicon):

Materials	Electron Mobility, m ² /V-sec
Aluminum	0.00435
Copper	0.00136
Silicon	0.145
<i>Gallium Arsenide, GaAs</i>	0.850
Silicon oxide	≅ 0
Silicon nitride	≅ 0

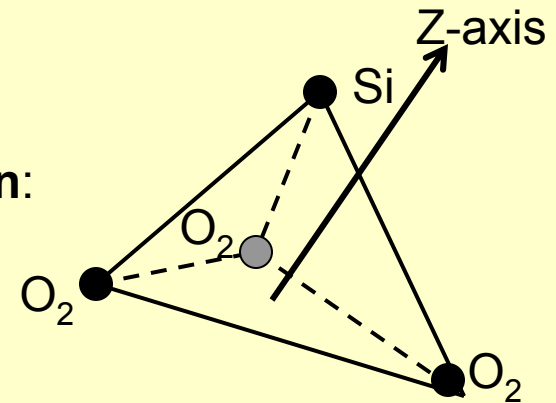
Gallium Arsenide (GaAs)-Cont'd

- GaAs is also a good **thermal insulator**.
- **Low yield strength** (only 1/3 of that of silicon) – “bad”.
- A comparison of GaAs and silicon as substrate materials in micromachining:

Properties	GaAs	Silicon
Opto-electronics	Very good	Not good
Piezoelectric effect	Yes	No
Piezoelectric coefficient (pN/°C)	2.6	Nil
Thermal conductivity	Relatively low	Relatively high
Cost	High	Low
Bonding to other substrates	Difficult	Relatively easy
Fracture	Brittle, fragile	Brittle, strong
Operating temperature	High	Low
Optimum operating temp. (°C)	460	300
Physical stability	Fair	Very good
Hardness (GPa)	7	10
Fracture strength (GPa)	2.7	6

Quartz

- Quartz is a **compound of SiO_2** .
- The single-unit cell is in shape of tetrahedron:
- Quartz crystal is made of up to 6 rings with 6 silicon atoms.



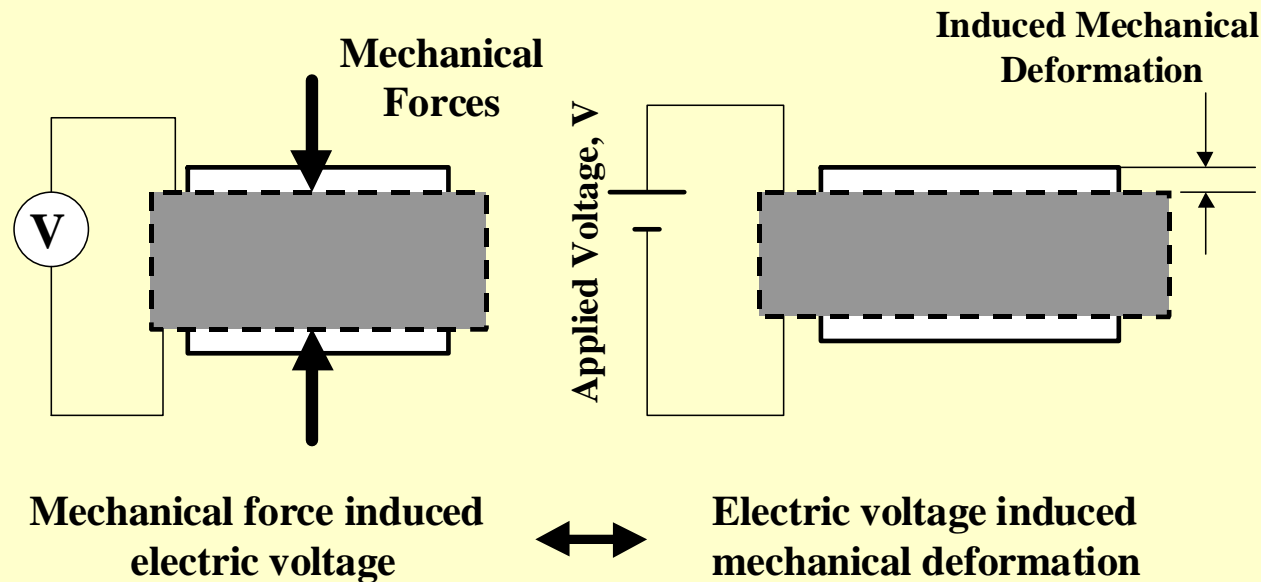
Properties	Value Z	Value \perp Z	Temperature Dependency
Thermal conductivity (Cal/cm/sec/ $^{\circ}\text{C}$)	29×10^{-3}	16×10^{-3}	\downarrow with T
Relative permittivity	4.6	4.5	\downarrow with T
Density (Kg/m^3)	2.66×10^3	2.66×10^3	
Coefficient of thermal expansion ($\text{ppm}/^{\circ}\text{C}$)	7.1	13.2	\uparrow with T
Electrical resistivity (Ω/cm)	0.1×10^{15}	20×10^{15}	\downarrow with T
Fracture strength (GPa)	1.7	1.7	\downarrow with T
Hardness (GPa)	12	12	

Quartz-Cont'd

- Quartz is ideal material for sensors because of its **extreme dimensional stability**.
- It is used as **piezoelectric** material in many devices.
- It is also excellent material for microfluidics systems used in biomedical applications.
- It offers excellent **electric insulation** in microsystems.
- A major disadvantage is its **hard in machining**. It is usually etched in HF/NH₄F into desired shapes.
- Quartz wafers up to **75 mm diameter by 100 μm thick** are available commercially.

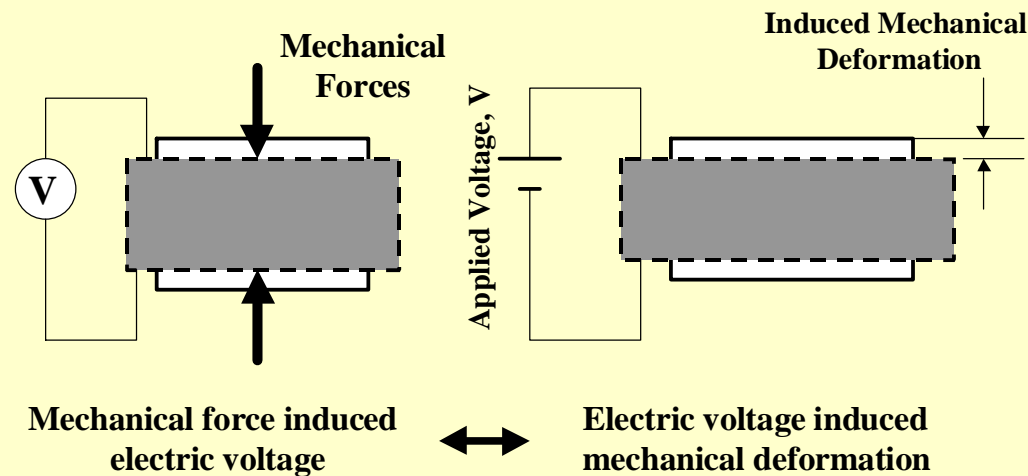
Piezoelectric Crystals

- Piezoelectric crystals are solid ceramic compounds that produce **piezoelectric effects**:



- Natural piezoelectric crystals are: quartz, tourmaline and sodium potassium tartrate.
- Synthesized crystals are: Rochelle salt, barium titanate and lead zirconate.

Piezoelectric Crystals – Cont'd



Mechanical strain by electric field:

$$\epsilon = d V$$

where ϵ = induced strain
 d = piezoelectric coefficient
 V = applied voltage, V/m

Electric field by stress:

$$V = f \sigma$$

where V = generated voltage in volts/m
 σ = applied stress in Pa

$$\frac{1}{fd} = E$$

Piezoelectric Crystals – Cont'd

Piezoelectric coefficients:

Piezoelectric Crystals	Coefficient, d (10^{-12} m/volt)	Electromechanical conversion factor, K^{**}
Quartz (crystal SiO_2)	2.3	0.1
Barium titanate (BaTiO_3)	100-190	0.49
Lead zirconate titanate, PZT ($\text{PbTi}_{1-x}\text{Zr}_x\text{O}_3$)	480	0.72
PbZrTiO_6	250	
PbNb_2O_6	80	
Rochelle salt ($\text{NaKC}_4\text{H}_4\text{O}_6 \cdot 4\text{H}_2\text{O}$)	350	0.78
Polyvinylidene fluorid, PVDF	18	

$$K^2 = \frac{\text{Output of mechanical energy}}{\text{Input of electrical energy}}$$

or

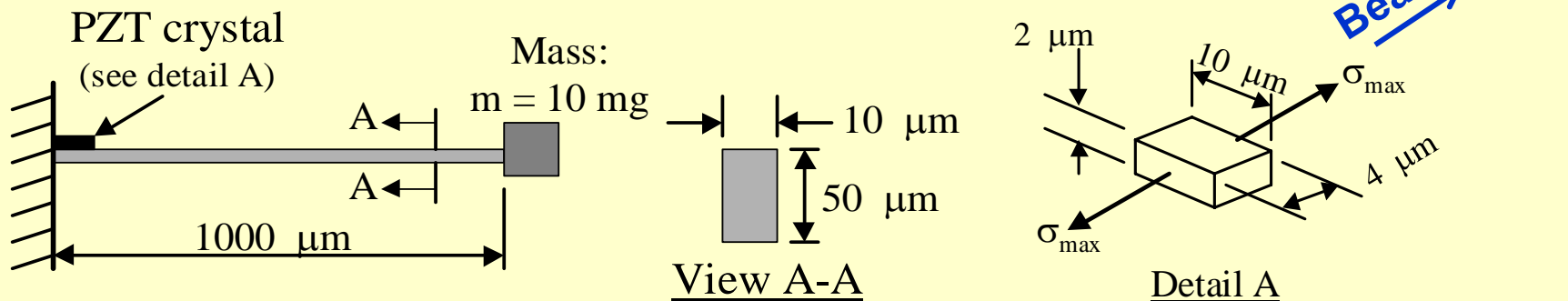
$$K^2 = \frac{\text{Output of electrical energy}}{\text{Input of mechanical energy}}$$

Example 7.4

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 is design for **maximum acceleration/deceleration of 10 g**.

The PZT transducer is located at the support of the cantilever beam where the maximum strain exists (near the support) during the bending of the beam as illustrated below.

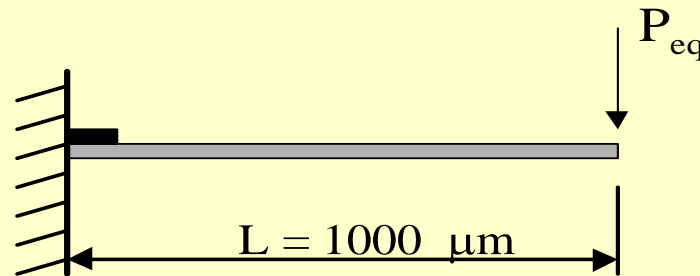
Determine the electrical voltage output from the PZT film at a maximum acceleration/deceleration of 10 g.



Example 7.4 – Cont'd

Solution:

Use Newton's 2nd law to find the **equivalent dynamic force** with an acceleration of 10 g: $P_{eq} = ma = (10 \times 10^{-6}) \times (10 \times 9.81) = 981 \times 10^{-6} \text{ N}$



The **maximum bending moment** is:

$M_{max} = P_{eq}L = (981 \times 10^{-6})(1000 \times 10^{-6}) = 0.981 \times 10^{-6} \text{ N-m}$ and it occurs at the built-in end

The corresponding **maximum stress** is:

$$\sigma_{max} = \frac{M_{max} C}{I} = \frac{(0.981 \times 10^{-6})(25 \times 10^{-6})}{(0.1042 \times 10^{-18})} = 235.36 \times 10^6 \text{ Pa}$$

and the **maximum strain** is: $\epsilon_{max} = \frac{\sigma_{max}}{E} = \frac{235.36 \times 10^6}{1.9 \times 10^{11}} = 123.87 \times 10^{-5} \text{ m/m}$

The **voltage** generated in the PZT piezoelectric crystal is:

$$V = \frac{\epsilon}{d} = \frac{\epsilon_{max}}{d} = \frac{123.87 \times 10^{-5}}{480 \times 10^{-12}} = 0.258 \times 10^7 \text{ Volts/m}$$

or

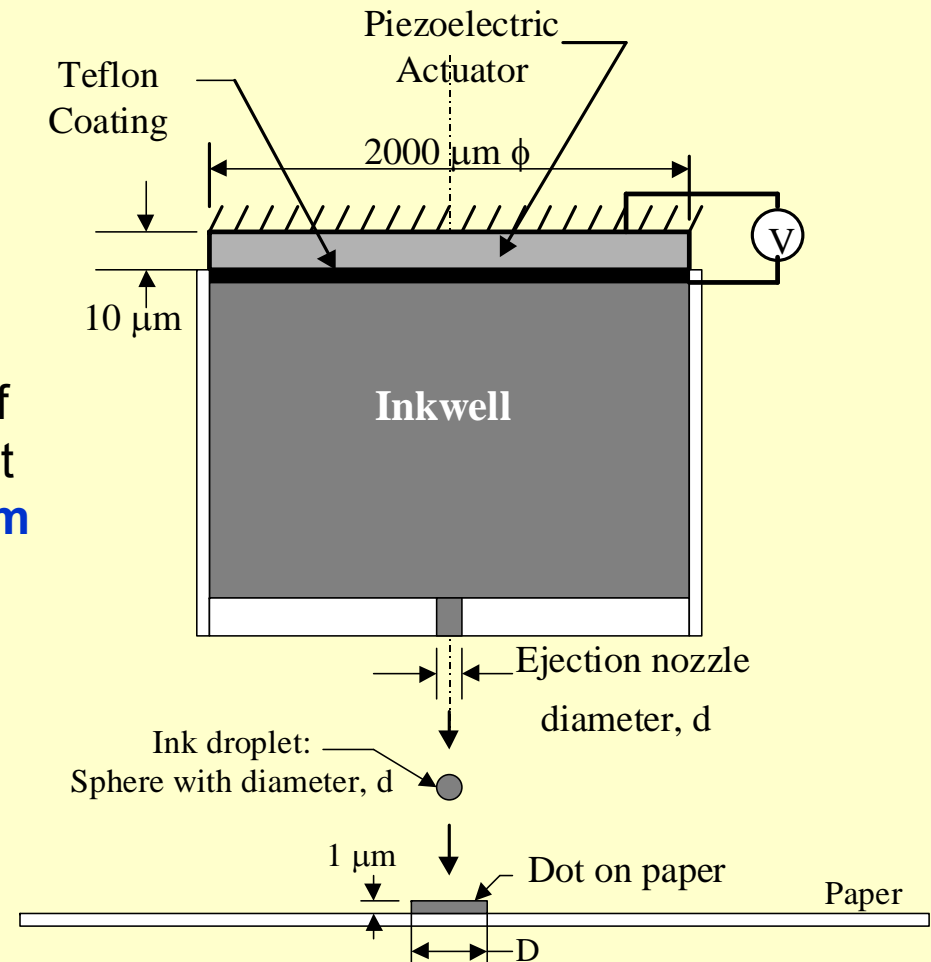
$$v = V\ell = (0.258 \times 10^7)(4 \times 10^{-6}) = 10.32 \text{ volts}$$

Example 7.5

Determine the **required electric voltage** for ejecting a droplet of ink from an inkjet printer head using **PZT** piezoelectric crystal as a pumping mechanism.

The ejected ink will have a resolution of **300 dpi** (dots per inch). The ink droplet is assumed to produce **a dot with a film thickness of $1\ \mu\text{m}$** on the paper.

The geometry and dimension of the printer head is illustrated below. Assume that the **ink droplet takes a shape of a sphere** and the inkwell is always re-filled after ejection.



Example 7.5 – Cont'd

Solution:

- Determine the ejection nozzle diameter, d :

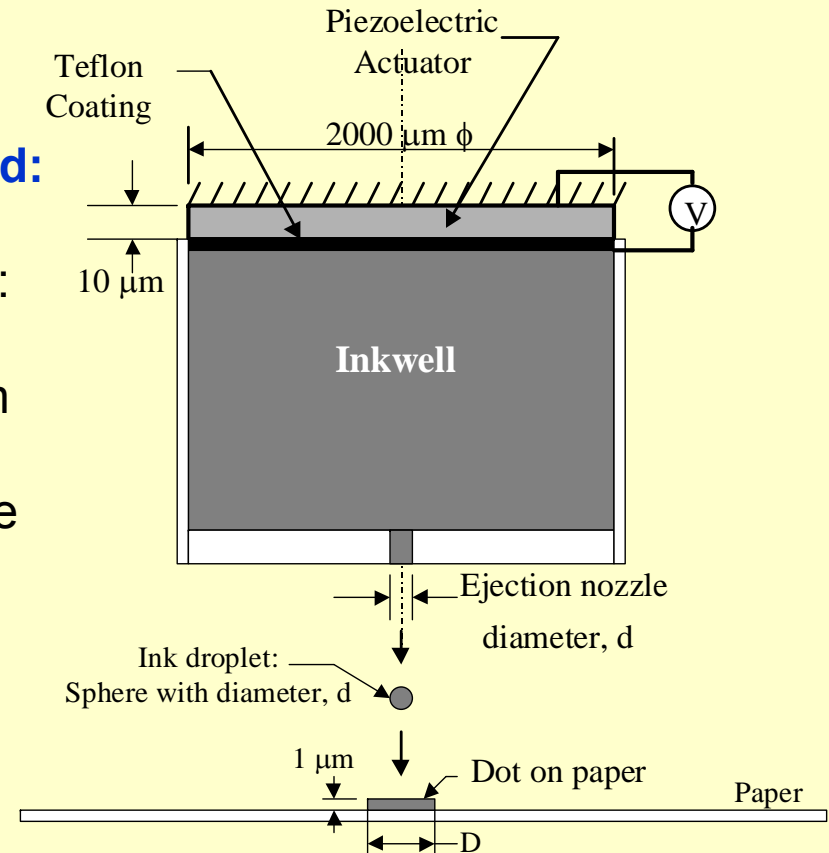
The diameter of the dot film on the paper is:

$$D = 1/300 \text{ inch} = 0.084666 \text{ mm} = 84.67 \mu\text{m}$$

By **equating the volumes** of the dot sphere the flat dot on the paper, we have:

$$\frac{4}{3} \pi r^3 = \left(\frac{\pi}{4} D^2 \right) (t)$$

from which, we get the radius of the dot, $r = 11.04 \times 10^{-6} \text{ m}$, with $D = 84.7 \mu\text{m}$ and $t = 1 \mu\text{m}$



Example 7.5 – Cont'd

- We assume that:

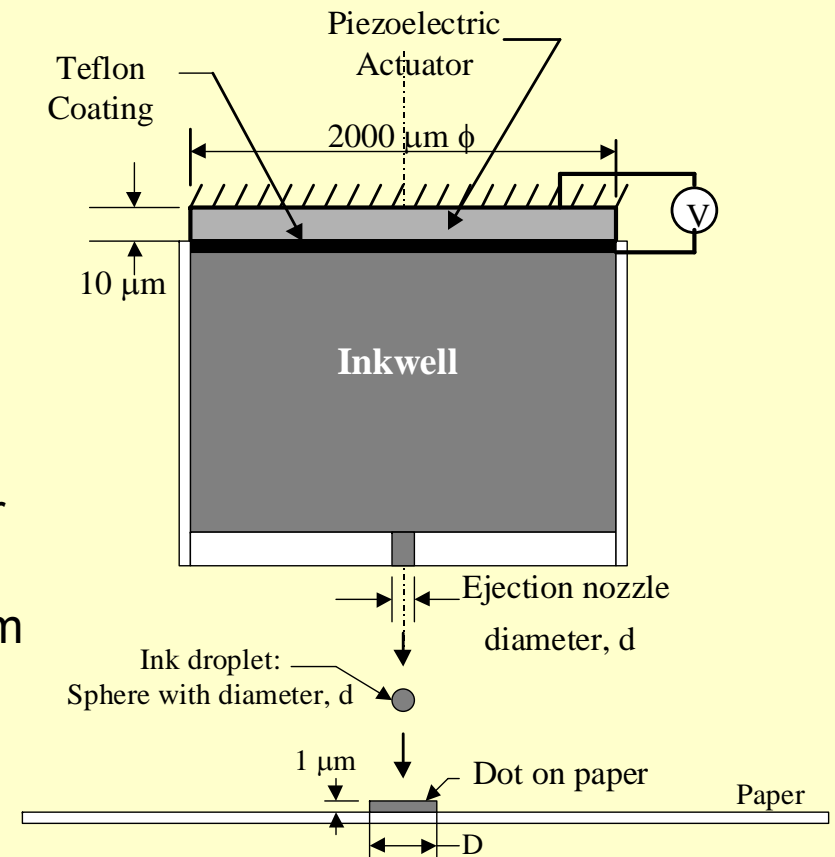
**Volume of an ink droplet
leaving the ink well**

**= Volume created by vertical
expansion of the PZT cover**

Let W = vertical expansion of the PZT cover
induced by the applied voltage, V
 Δ = diameter of the PZT cover = $2000 \mu\text{m}$

We will have:

$$W = \frac{4V_{dot}}{\pi \Delta^2} = \frac{4 \times 5629.21 \times 10^{-18}}{3.1416(2000 \times 10^{-6})^2} = 1791.83 \times 10^{-12} \text{ m}$$



Example 7.5 – Cont'd

- The corresponding strain in the PZT piezoelectric cover is:

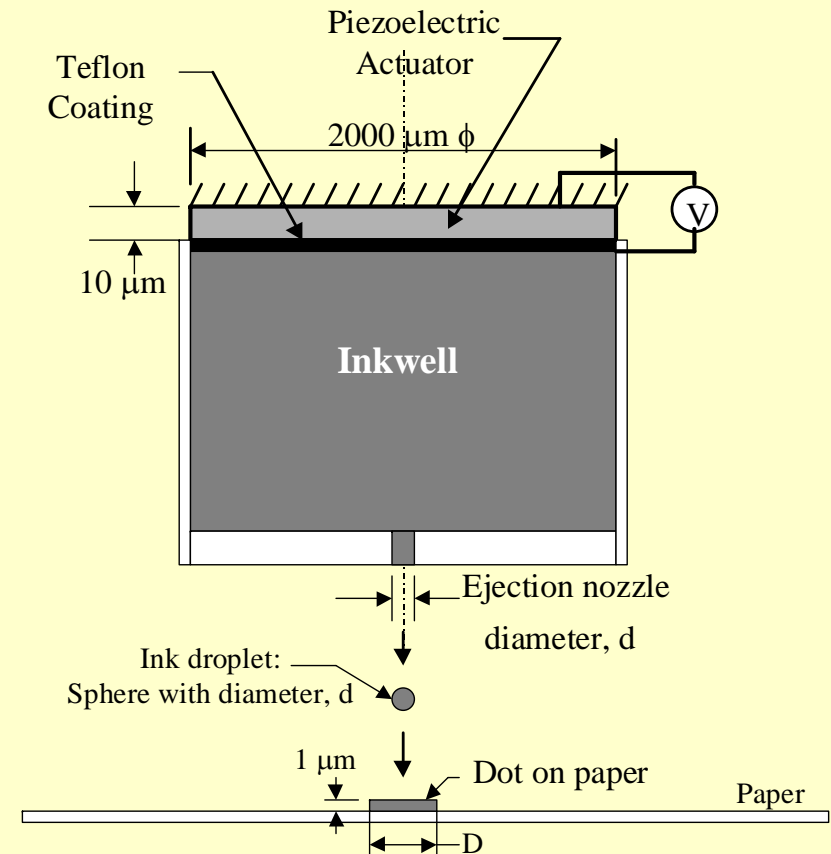
$$\varepsilon = \frac{W}{L} = \frac{1791.83 \times 10^{-12}}{10 \times 10^{-6}} = 179.183 \times 10^{-6} \text{ m/m}$$

The piezoelectric coefficient of the PZT crystal is $d = 480 \times 10^{-12} \text{ m/v}$, leading to the **required voltage** to be:

$$V = \frac{\varepsilon}{d} = \frac{179.183 \times 10^{-6}}{480 \times 10^{-12}} = 0.3733 \times 10^6 \text{ volts/m}$$

or

$$v = LV = (10 \times 10^{-6}) (0.3733 \times 10^6) = 3.733 \text{ volts}$$



Polymers

What is polymer?

Polymers include: Plastics, adhesives, Plexiglass and Lucite.

Principal applications of polymers in MEMS:

- Currently in biomedical applications and adhesive bonding.
- New applications involve using polymers as substrates with electric conductivity made possible by doping.

Molecular structure of polymers:

- It is made up of long chains of organic (hydrocarbon) molecules.
- The molecules can be as long as a few hundred nm.

Characteristics of polymers:

- Low melting point; Poor electric conductivity
- Thermoplastics and thermosets are common industrial products
- Thermoplastics are easier to form into shapes.
- Thermosets have higher mechanical strength even at temperature up to 350°C.

Polymers as industrial materials

Polymers are popular materials used for many industrial products for the following advantages:

- **Light weight**
- **Ease in processing**
- **Low cost of raw materials and processes for producing polymers**
- **High corrosion resistance**
- **High electrical resistance**
- **High flexibility in structures**
- **High dimensional stability**

Polymers for MEMS and microsystems

- (1) Photo-resist polymers are used to produce masks for creating desired patterns on substrates by **photolithography** technique.
- (2) The same photoresist polymers are used to produce the prime mold with desirable geometry of the MEMS components in a **LIGA process** in micro manufacturing.
- (3) **Conductive polymers** are used as “organic” substrates for MEMS and microsystems.
- (4) The **ferroelectric polymers** that behave like piezoelectric crystals can be used as the source of actuation in micro devices such as in micro pumping.
- (5) The thin **Langmuir-Blodgett (LB) films** can be used to produce multilayer microstructures.
- (6) Polymers with unique characteristics are used as **coating substance** to capillary tubes to facilitate effective **electro-osmotic flow** in microfluidics.
- (7) Thin polymer films are used as **electric insulators** in micro devices, and as **dielectric substance** in micro capacitors.
- (8) They are widely used for electromagnetic interference (**EMI**) and radio frequency interference (**RFI**) shielding in microsystems.
- (9) Polymers are ideal materials for **encapsulation** of micro sensors and the packaging of other microsystems.

Conductive Polymers

- Polymers are poor electric conducting materials by nature.
- A comparison of electric conductivity of selected materials are:

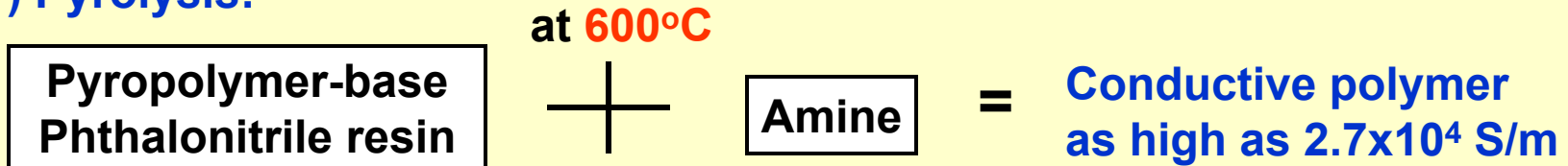
Materials	Electric Conductivity, S/m*
<u>Conductors:</u> Copper, Cu Carbon	10^6 - 10^8 10^4
<u>Semiconductors:</u> Germanium, Ge Silicon	10^0 10^{-4} - 10^{-2}
<u>Insulators:</u> Glass Nylon SiO ₂ Polyethylene	10^{-10} - 10^{-8} 10^{-14}-10^{-12} 10^{-16} - 10^{-14} 10^{-16}-10^{-14}

* S/m = siemens per meter = Ω^{-1} = $A^2 \cdot s^3 / Kg \cdot m^2$

Conductive Polymers – Cont'd

Some polymers can be made electrically conductive by the following 3 methods:

(1) Pyrolysis:



(2) Doping:

Introducing metal atoms into molecular matrices of polymers
→ Conductive polymers

Polymers groups	Dopants
Polyacetylenes (PA)	Br ₂ , I ₂ , AsF ₅ , HClO ₄ and H ₂ SO ₄ for p-type Sodium naphthalide in tetrahydrofuran for n-type
Polyparaphenylenes (PPP)	AsF ₅ for p-type; alkali metals for n-type
Polyphenylene sulfide (PPS)	AsF ₅

(3) Insertion of conductive fibers:

Fibers made of Au, Ag, stainless steel, aluminum fibers and flakes.

Langmuir-Blodgett (LB) films

- The process was first introduced by Langmuir in 1917 and was later refined by Blodgett. That was why it is called Langmuir-Blodgett process, or **LB films**.
- The process involves the **spreading volatile solvent** over the surface-active substrate materials.
- The LB process can produce more than one single monolayer by depositing films of various compositions onto a substrate to produce a multilayer structure.
- LB films are good candidate materials for exhibiting **ferro (iron)-** , **pyro (heat)-** and **piezoelectric** properties. LB films may also be produced with controlled optical properties such as refractive index and anti reflections.

They are thus ideal materials for **micro sensors** and **optoelectronic devices**.

Langmuir-Blodgett (LB) films – Cont'd

- Following are a few examples of LB film applications in microsystems:

(1) Ferroelectric (magnetic) polymer thin films:

- The one in particular is the Poly-vinylidene fluoride (PVDF).
- Applications of this type of films include:
 - Sound transducers in air and water,
 - Tactile sensors,
 - Biomedical applications such as tissue compatibility, cardio-pulmonary sensors and implantable transducers and sensors for prosthetics and rehabilitation devices.
- As a **piezoelectric source**. The piezoelectric coefficient of PVDF is given in Table 7-14.

(2) Coating materials with controllable optical properties:

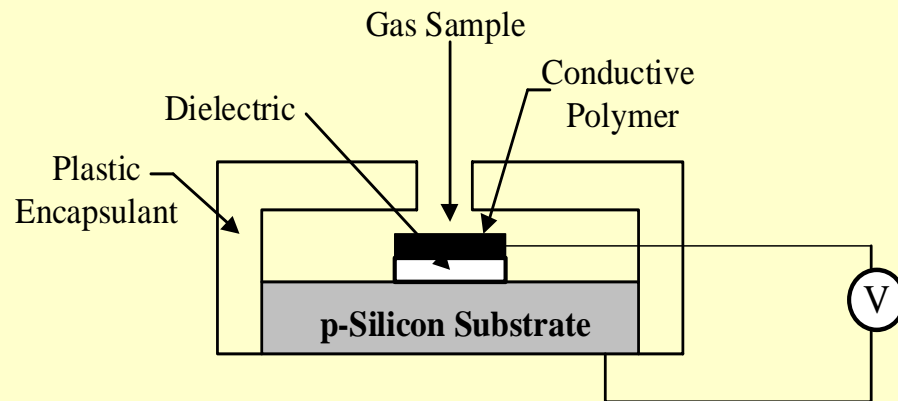
- Broadband optical fibers that transmit light at various wavelengths.

Langmuir-Blodgett (LB) films – Cont'd

(3) Microsensors:

Many electrically conducting polymeric materials are sensitive to the exposed gas and other environmental conditions. So they are suitable materials for micro sensors.

Its ability of detecting specific substances relies on the reversible and specific absorption of species of interest on the surface of the polymer layer and the subsequent measurable change of conductivity of the polymer.

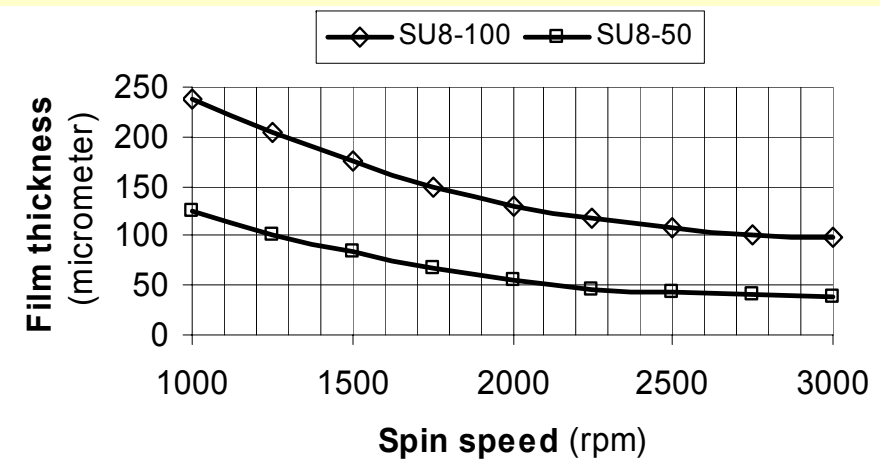
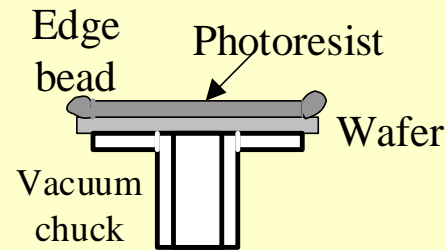
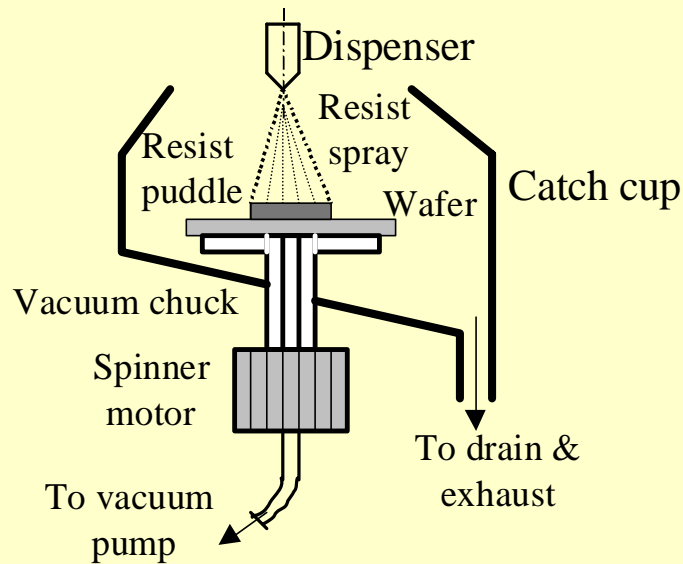


A gas sensor:

Electrical conductivity changes with absorption of the exposed gas.

SU-8 Photoresists

- It is a negative epoxy-based polymer sensitive to UV light ($\lambda = 350\text{-}400\text{ nm}$)
- It is used for thin-film production with thickness from $1\text{ }\mu\text{m}$ to 2 mm
- Reasons for it being popular in MEMS:
 - Can be built to thick films for 3-D MEMS structures (aspect ratio to 50)
 - Much lower production costs than thick films by silicon
- It is commercially available in liquid form
- SU-8 films can be produced by a spin-process:



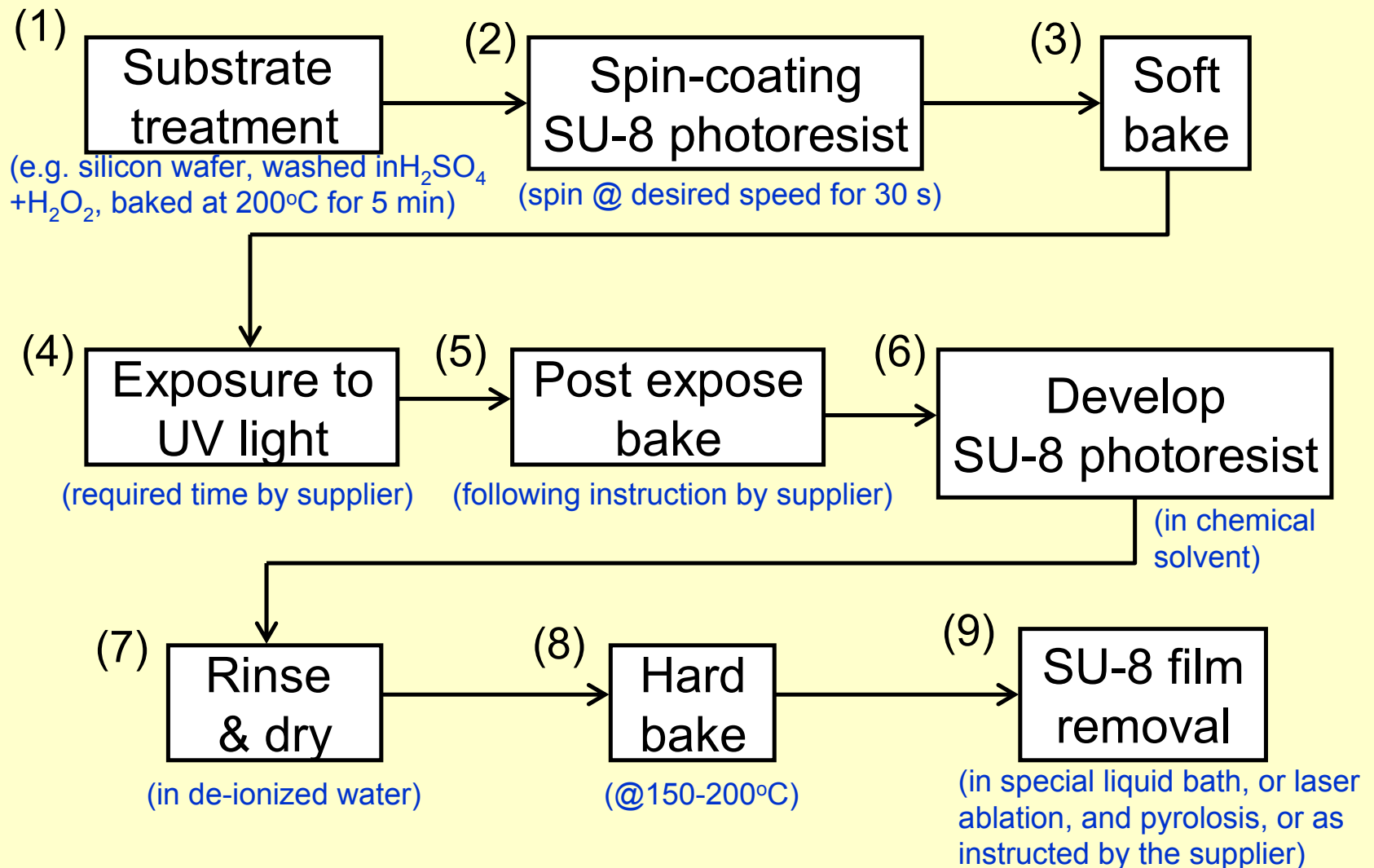
Mechanical Properties of SU-8 Polymer

Young's modulus	4400 MPa
Poisson's ratio	0.22
Viscosity	0.06 Pa-s (40% SU-8 – 60% solvent) 1.50 Pa-s (60% SU-8 – 40% solvent) 15.0 Pa-s (70% SU-8 – 30% solvent)
Coefficient of thermal expansion*	0.183 ppm /°C
Thermal conductivity	0.073 W/cm-°C
Glass transition temperature	200°C
Reflective index	1.8 at 100 GHz 1.7 at 1.6 THz
Absorption coefficient	2/cm at 100 GHz 40/cm a 1.6 THz
Relative dielectric constant	3 at 10 MHz

Source: Guerin 2005.

* in comparison to 2.33 ppm/°C for silicon

Typical Process Flow for Constructing SU-8 Films



Packaging Materials

Unlike IC packaging in which plastic or ceramic are extensively used as encapsulate materials for the delicate IC circuits, MEMS packaging involve **a great variety of materials-varying from plastic and polymers to stainless steel**, as can be seen in a specially packaged micro pressure sensor:

