Lectures 05-09

MEMS Materials

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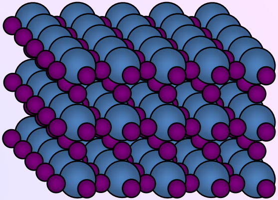
Outline

Lecture 05

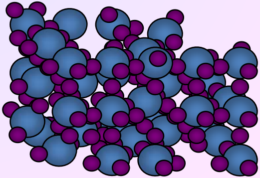
Basics of MEMS materials

Materials Definitions

- Types of solid matter
  - Crystalline – periodic throughout
  - Polycrystalline – periodic grains
  - Amorphous - disordered
- Crystal Structures are periodic arrangements of matter in 3 dimensions.
- Observation of crystallographic orientation is most commonly performed using X-ray diffraction.
- Destructive methods such as fracture tests, and chemical etching can also indicate crystal structure.
- Orientation is described using Miller Indices: A set of three integers that describe crystallographic planes, as determined from the reciprocals of fractional axial intercepts

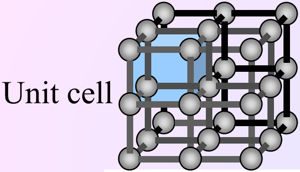


Single Crystal: Periodic Ordering of Solid Matter

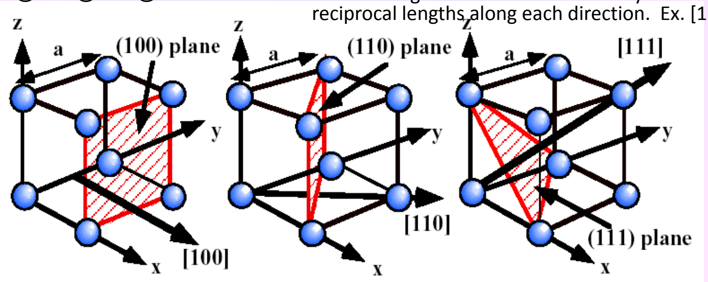


Amorphous Solid: Disordered Solid Matter

Crystal Basics



- Unit cell is the smallest repeated unit in a crystal.
- Within a unit cell there are 1-2 fundamental units (atoms).
- Surfaces between these atoms define the crystallographic planes of the unit cell.
- Directions normal to those planes are defined by Miller Indices.
  - Principle axis (x, y, and z) are defined as [100],[010], and [001]
  - Planes along two axis are described by the ratio of reciprocal lengths along each direction. Ex. [110]

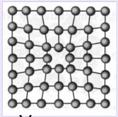


Defects in crystals

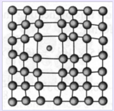
- All crystals have defects (yes even diamonds and silicon ☺)
- Three generic types of defects
  - **Point Defects:** Thermodynamic point defects due to atomic mobility in solids. Lead to changes in electronic properties of materials due to symmetry errors in the electronic band structure

$$n_v = n e^{\left(\frac{-Q}{RT}\right)}$$

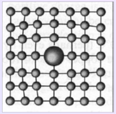
~10^{-5} n_v/n at 1000K
For undoped material



Vacancy



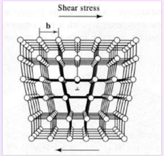
Interstitial



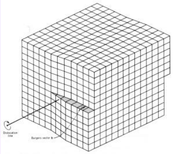
Substitutional

  - **Dislocation:** line defects that bear a definite crystallographic relationship to the lattice. Two basic types: edge and screw. Defects caused by linear or rotational forces acting on the lattice. Effect electronic properties and reduce local shear strength of the material allowing for crack propagation.
  - **Grain boundaries:** area defects that constitute interfaces between two single crystal grains of different orientation. Morphology, orientation and size of grains (and therefore boundaries) are directly linked to the mechanical, optical, electrical, and thermal properties of the material.

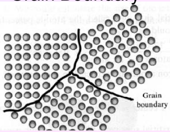
Edge Dislocation



Screw Dislocation



Grain Boundary



Substrates and Wafers

- Substrate in microelectronics means a flat macroscopic object on which microfabrication processes take place
- In microsystems, a substrate serves an additional purpose: it acts as signal transducer besides supporting other transducers that convert mechanical actions to electrical outputs or vice versa.
- In semiconductors, the substrate is a single crystal cut in slices from a larger piece called a wafer.
- Two types of substrate materials used in microsystems: (1) active substrate materials and (2) passive substrate materials

Table 7.1 | Typical electrical resistivity of insulators, semiconductors, and conductors

Materials	Approximate electrical resistivity ρ, Ω-cm	Classification
Silver (Ag)	10^{-6}	Conductors
Copper (Cu)	$10^{-5.8}$	
Aluminum (Al)	$10^{-5.5}$	
Platinum (Pt)	10^{-5}	
Germanium (GE)	10^{-3}–$10^{1.5}$	Semiconductors
Silicon (Si)	10^{-3}–$10^{4.5}$	
Gallium arsenide (GaAs)	10^{-3}–10^{8}	
Gallium phosphide (GaP)	10^{-2}–$10^{6.5}$	
Oxide	10^{9}	Insulators
Glass	$10^{10.5}$	
Nickel (pure)	10^{13}	
Diamond	10^{14}	
Quartz (fused)	10^{18}	

Active substrate materials

- Active substrate materials are primarily used for sensors and actuators in Microsystems
- Typical materials: Si, GaAs, Ge, and quartz. (All except quartz are classified as semiconductors)
- Have a cubic crystal lattice with tetrahedral atomic bond.
- These materials are selected as active substrates primarily for their dimensional stability, which is relatively insensitive to environmental conditions. Dimensional stability is a critical requirement for sensors and actuators with high precision.
- Each atom carries 4 electrons in the outer orbit, and shares these 4 electrons with its 4 neighbors.

Substrates

- Silicon (Crystalline)
  - IC standard processing
  - Readily available in pure form
  - Material properties are extremely well defined
- GaAs (Crystalline)
  - Excellent for GHz and THz devices, solid state lasers
  - Low voltage breakdown of Oxide
  - Oxide is slightly soluble in water
- Ceramics (Polycrystalline)
  - Used in Packaging and MEMS for vias and hermetic seals
  - Machinable, handles high temperatures
  - Low tensile strength, but very high compressive strength
- Kapton (amorphous plastic)
  - Polymer with only 10% shrinkage at 400oC
  - Used for flex circuits: Heaters, RF Electronics
- Quartz or Sapphire (Crystalline)
  - Optics, Microfluidcs
  - Stable at high temperatures
- Pyrex Glass (amorphous)
  - Can be fused hermetically to silicon by anodic bonding
  - Biocompatible, Optically transparent
  - Softening temperatures around 400oC
- Polymer substrates (amorphous)
  - Used for MEMS
  - Sometimes biocompatible
  - Not hermetic
  - Have glass transition temperatures (soften) around 100-150oC
- Metals (polycrystalline)
  - High tensile strength
  - Often amenable to high temperatures
  - Provide RF or magnetic shielding
  - Require electronic isolation in the process sequence

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 (~ 2×10^5 MPa), but is as light as aluminum with a density of about 2.3 g/cm^3.

Silicon - an ideal substrate material for MEMS

(4) It has a melting point at 1400^{o}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.

Silicon as a Substrate Material

- Is the primary substrate for integrated circuits
  - Easily controlled carrier densities
  - Stable oxides and nitrides
  - Allows for high temperature processing
  - large carrier densities, high mobility, and low scattering losses
- For the rest of the microfabricated world
  - Most of the fabrication equipment used today was designed to operate with silicon wafers
    - Silicon wafers are slabs of single crystal silicon produced by industries largest crystal growth processes to yield large rods of Si that are then cut into slabs and polished atomically smooth
    - Note: glass wafers are amorphous materials floated from liquid melts. They are often not polished and have 100nm or less surface finish.
  - The IC industry has characterized and developed processes for single crystal growth of silicon so well that that it is .....
    - Available in a wide variety of sizes, shapes and resistivities
    - Smooth, flat, mechanically strong, and CHEAP!!!

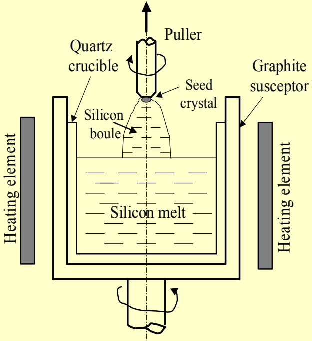
Lecture 06

Single-Crystal Silicon and Wafers

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.

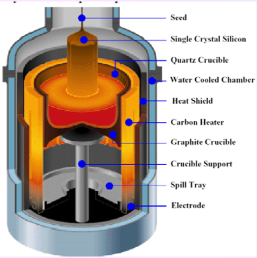
(3) The "puller" slowly pulls the molten Si up to form pure Si "boule" after the solidification.

(4) The diameters of the "bologna-like" boules vary from 100 mm (4") to 300 mm (12") in diameters.

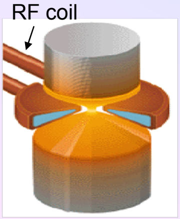
Chemical reaction for the process: $SiC + SiO_2 \rightarrow Si + CO + SiO$

Creating Silicon Substrate

- Silicon is grown using the Czochralski crystal growth method at 1450ºC to sizes of 3”, 100, 125, 150,200, and 300 mm dia.
- Reanealing and modifying dopant concentrations in bulk silicon is achieved by float zone growth



CZ growth

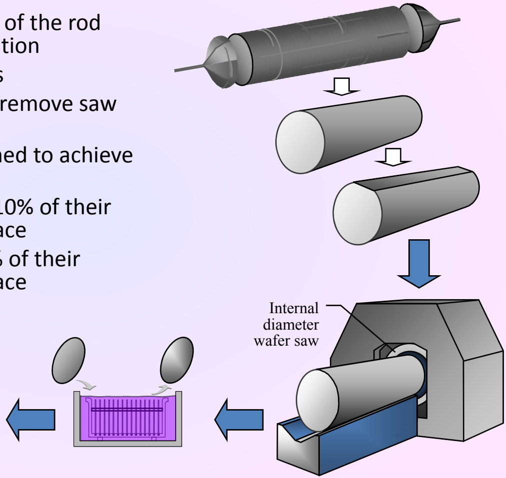


FZ growth

Characteristic	CZ	FZ
Growth Speed (mm/min)	1 to 2	3 to 5
Dislocation-Free?	Yes	Yes
Crucible?	Yes	No
Consumable Material Cost	High	Low
Heat-Up/Cool-Down Times	Long	Short
Axial Resistivity Uniformity	Poor	Good
Oxygen Content (atoms/cm^3)	$>1\times10^{18}$	$<1\times10^{16}$
Carbon Content (atoms/cm^3)	$>1\times10^{17}$	$<1\times10^{16}$
Metallic Impurity Content	Higher	Lower
Bulk Minority Charge Carrier Lifetime (μs)	5-100	1,000-20,000
Mechanical Strengthening	10^{17} Oxygen	10^{15} Nitrogen
Production Diameter (mm)	150-200	100-150
Operator Skill	Less	More
Polycrystalline Si Feed Form	Any	Crack-free rod

Creating Silicon Substrate

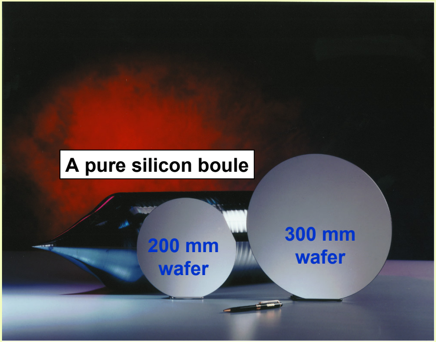
- Flats are cut down the long axis of the rod (ignot) indicating crystal orientation
- Ignots are then sawed into discs
- Silicon discs are then etched to remove saw damage
- Mechanical polishing is performed to achieve 0.1nm surface finish
- Inexpensive wafers vary about 10% of their thickness across the entire surface
- Expensive wafers vary about 5% of their thickness across the entire surface



Pure Silicon Wafers

Pure silicon wafers

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



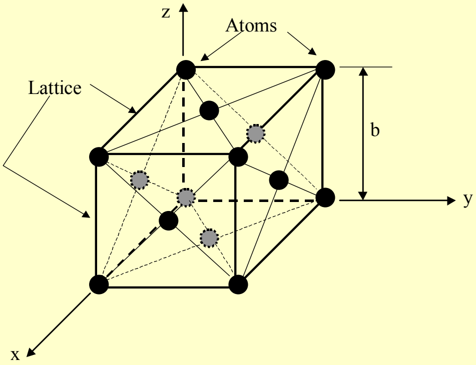
These boules are sliced into thin disks (wafers) using diamond saws.

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

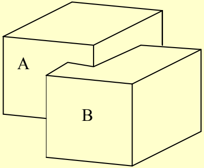
- **Single silicon crystals are basically of "face-cubic-center" (FCC) structure.**
- **The crystal structure of a typical FCC crystal is shown below:**



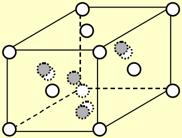
Note: Total number of atoms: 8 at corners and 6 at faces = **14 atoms**

Single Silicon Crystal Structure

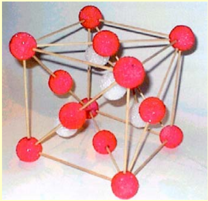
- **Single crystal silicon, however has 4 extra atoms in the interior.**
- **The situation is like to merge two FCC crystals together as shown below:**



(a) Merger of two FCC



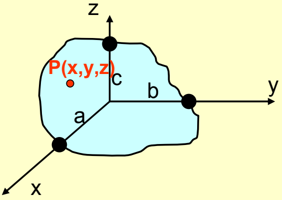
(b) Merged crystal structure



- **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:

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

Express Eq. (7.1) in a different form:

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

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

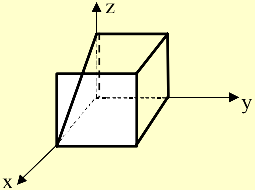
- Miller indices involve:

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

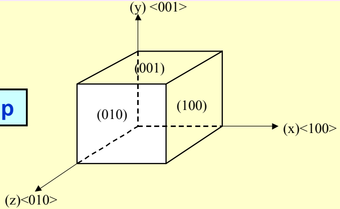
<hkm> = designation of a **direction** that is perpendicular to the (hkm) plane.

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

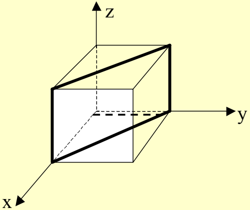
The 3 Principal Planes of a Silicon Crystal



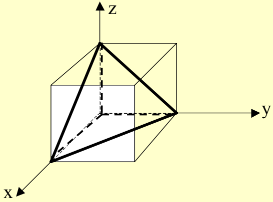
The (100) group



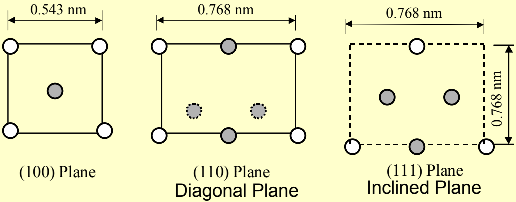
The (110) group



The (111) group



The 3 Principal Planes of a Silicon Crystal



- **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.

Lecture 07

Silicon Compounds

Mechanical and Thermophysical Properties of MEMS Material

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-^{o}C)	k (W/cm-^{o}C)	α (10^{-6}/^{o}C)	T_M (^{o}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_3N_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

Silicon dioxide (S_iO_2)

There are **3** principal silicon compounds used in MEMS and microsystems: Silicon dioxide (**SiO_2**), Silicon carbide (**SiC**) and silicon nitride (**Si_3N_4**) – each Has distinct characteristic and unique applications.

Silicon dioxide (SiO_2)

- **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: $Si + O_2 \longrightarrow SiO_2$

- or by oxide silicon in wet steam: $Si + 2H_2O \longrightarrow SiO_2 + 2H_2$

S_iO_2 and SiC

Silicon dioxide (SiO_2) – cont'd

Properties	Values
Density (g/cm^3)	2.27
Resistivity (Ω-cm)	$\geq 10^{16}$
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 (Si_3N_4)

- **Produced by chemical reaction:**

$$3SiCl_2H_2 + 4NH_3 \longrightarrow Si_3N_4 + 6HCL + 6H_2$$

- **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 Si_3N_4 films are as follows:**

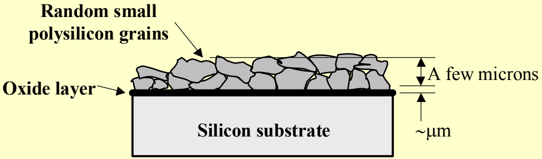
Properties	LPCVD*	PECVD**
Deposition temperature (°C)	700-800	250-350
Density (g/cm^3)	2.9-3.2	2.4-2.8
Film quality	Excellent	Poor
Dielectric constant	6-7	6-9
Resistivity (Ω-cm)	10^{16}	10^6-10^{15}
Refractive index	2.01	1.8-2.5
Atom % H	4-8	20-25
Etch rate in concentrated HF	200 A/min	
Etch rate in boillng HF	5-10A/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

Comparison of Mechanical Properties of Polysilicon with Other Materials

Materials	Young's modulus (GPa)	Poisson's ratio	Coefficient of thermal expansion (ppm/°C)
As substrates:			
Silicon	190	0.23	2.6
Alumina	415		8.7
Silica	73	0.17	0.4
As thin films:			
Polysilicon	***160***	***0.23***	***2.8***
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

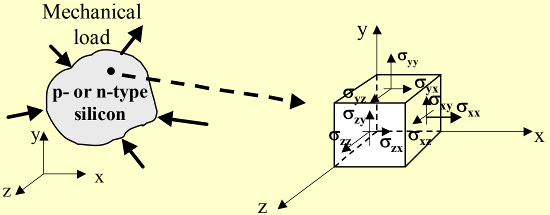
Piezoresistance = **a change in electrical resistance of solids when subjected to stress fields. Doped silicon are piezoresistors (p-type or n-type).**

Relationship between change of resistance {ΔR} and stresses {σ}:

$$\{\Delta R\} = [\pi]\,\{\sigma\} \tag{7-6}$$

where **{ΔR}** = $\{\Delta R_{xx}\ \ \Delta R_{yy}\ \ \Delta R_{zz}\ \ \Delta R_{xy}\ \ \Delta R_{xz}\ \ \Delta R_{yz}\}^T$ represents the change of resistances in an infinitesimally small cubic piezoresistive crystal element with corresponding stress components:
{σ} = $\{\sigma_{xx}\ \ \sigma_{yy}\ \ \sigma_{zz}\ \ \sigma_{xy}\ \ \sigma_{xz}\ \ \sigma_{yz}\}^T$ and **[π] = piezoresistive coefficient matrix**.

A silicon piezoresistance subjected to a stress field:



Silicon Piezoresistors

- 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:

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

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

$$\Delta R_{xx} = \pi_{11}\sigma_{xx} + \pi_{12}\left(\sigma_{yy} + \sigma_{zz}\right) \qquad \Delta R_{xy} = \pi_{44}\sigma_{xy}$$

$$\Delta R_{yy} = \pi_{11}\sigma_{yy} + \pi_{12}\left(\sigma_{xx} + \sigma_{zz}\right) \qquad \Delta R_{xz} = \pi_{44}\sigma_{xz}$$

$$\Delta R_{zz} = \pi_{11}\sigma_{11} + \pi_{12}\left(\sigma_{xx} + \sigma_{yy}\right) \qquad \Delta R_{yz} = \pi_{44}\sigma_{yz}$$

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

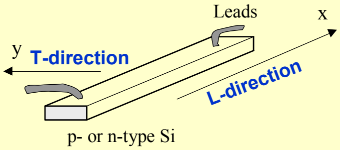
Silicon Piezoresistors

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



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

Lecture 08

GaAs and Quartz

Gallium Arsenide (GaAs)

- **GaAs is a compound simiconductor 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
Gallium Arsenide, GaAs	***0.850***
Silicon oxide	$\cong 0$
Silicon nitride	$\cong 0$

Gallium Arsenide (GaAs)

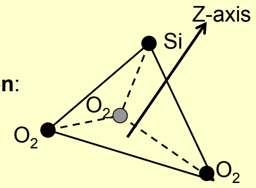
- **GaAs is also a good thermal insulator.**
- **Low yield strength (only 1/3 of that of silicon) – "bad".**
- **A comparison of GaAs and silicon as substrate materials in micromachining:**

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

- **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.**



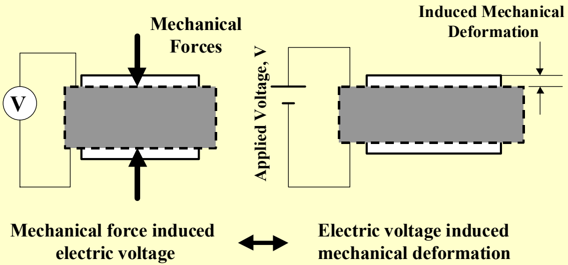
Properties	Value ∥ Z	Value ⊥ Z	Temperature Dependency
Thermal conductivity (Cal/cm/sec/°C)	29×10^{-3}	16×10^{-3}	↓with T
Relative permittivity	4.6	4.5	↓with T
Density (Kg/m^3)	2.66×10^{3}	2.66×10^{3}	
Coefficient of thermal expansion (ppm/°C)	7.1	13.2	↑with T
Electrical resistivity (Ω/cm)	0.1×10^{15}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

Quartz

- **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 microfluics 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

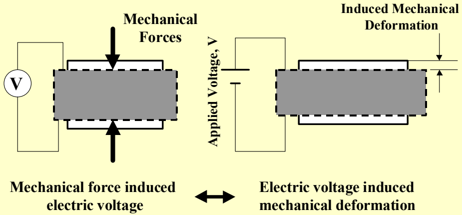
- **Piezoelectric crystals are solid ceramic compounds that produce piezoelectric effects:**



- **Natural piezoelectric crystals are: quartz, tourmaline and sodium potassium tartrate.**

- **Synthesized crystals are: Rochelle salt, barium titanate and lead zirconate.**

Piezoelectric Crystals



Mechanical strain by electric field:

$$\varepsilon = d\,V$$

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

Piezoelectric coefficients:

Piezoelectric Crystals	**Coefficient, d** (10^{-12} m/volt)	**Electromechanical conversion factor**, K**
Quartz (crystal SiO_2)	2.3	0.1
Barium titnate ($BaTiO_3$)	100-190	0.49
Lead zirconate titanate, PZT ($PbTi_{1-x}Zr_xO_3$)	480	0.72
$PbZrTiO_6$	250	
$PbNb_2O_6$	80	
Rochelle salt ($NaKC_4H_4O_6$-$4H_2O$)	350	0.78
Polyvinylidene fluorid, PVDF	18	

** $K^2 = \dfrac{Output \quad of \quad mechanical \quad energy}{Input \quad of \quad electrical \quad energy}$ or $K^2 = \dfrac{Output \quad of \quad electrical \quad energy}{Input \quad of \quad mechanical \quad energy}$

Lecture 09

Polymers

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^{o}C.**

Polymer applications

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

Polymer applications

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***
Conductors:	
Copper, Cu	10^{6}-10^{8}
Carbon	10^{4}
Semiconductors:	
Germanium, Ge	10^{0}
Silicon	10^{-4}-10^{-2}
Insulators:	
Glass	10^{-10}-10^{-8}
Nylon	$\mathbf{10^{-14}}$-$\mathbf{10^{-12}}$
SiO_2	10^{-16}-10^{-14}
Polyethlene	$\mathbf{10^{-16}}$-$\mathbf{10^{-14}}$

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

Conductive Polymers

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

(1) Pyrolysis:

Pyropolymer-base Phthalonitrile resin + (at **600°C**) **Amine** = **Conductive polymer as high as 2.7×10^4 S/m**

(2) Doping:

Introducing metal atoms into molecular matrices of polymers

$\longrightarrow$ Conductive polymers

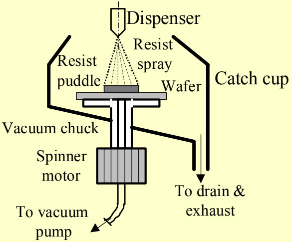
Polymers groups	Dopants
Polyacetylenes (PA)	Br_2, I_2, AsF_5, $HClO_4$ and H_2SO_4 for p-type Sodium naphthalide in tetrahydrofuran for n-type
Polyparaphenylenes (PPP)	AsF_5 for p-type; alkali metals for n-type
Polyphenylene sulfide (PPS)	AsF_5

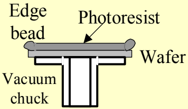
(3) Insertion of conductive fibers:

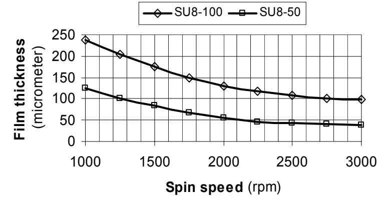
Fibers made of Au, Ag, stainless steel, aluminum fibers and flakes.

SU-8 Photoresists

- It is a negative epoxy-based polymer sensitive to UV light (λ = 350-400 nm)
- It is used for thin-film production with thickness from 1 μm 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:





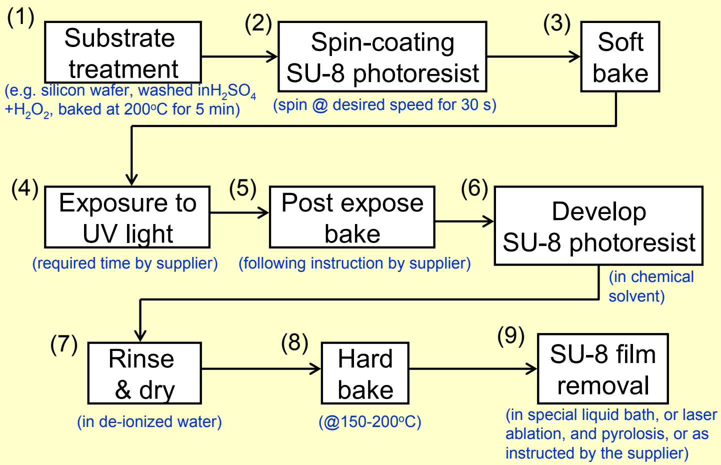


Mechanical Properties of SU-8 Polymer

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 /^{o}C
Thermal conductivity	0.073 W/cm-^{o}C
Glass transition temperature	200^{o}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/^{o}C for silicon

Typical Process Flow for Constructing SU-8 Films



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