Lecture 10 - 12

MEMS Materials Properties

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Outline

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Lecture 10

Young’s Modulus & Poisson’s ratio

MEMS Material Science

- Elastic modulus measures the resistance of the material to elasticor "springy"deformation.
- Low modulus materials are floppy, and stretch a lot when they are pulled (squash down a lot when pushed).
- High modulus materials are the oppositethey stretch very little when pulled (squash down very little when pushed).
- Youngs modulus and Poisons ratio are basic elastic properties that govern the mechanical behavior.
- Young's modulus, also known as the elastic modulus, is a measure of the stiffness of a solid material.
- It is a mechanical property which defines the relationship between stress (force per unit area) and strain (proportional deformation) in a material.

Hookes Law

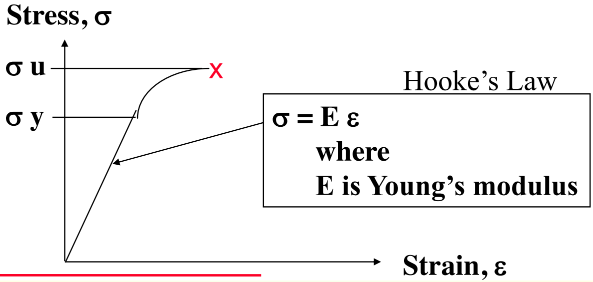
Stress is the applied force per crossectional area, $\sigma = F/A$

Strain is the elongation per unit length, $\varepsilon = \delta L/L$

σ_y = yield strength

σ_u = ultimate or maximum strength

σ_b = rupture strength (for brittle material $\sigma_u = \sigma_b$)



Young's Modulus

- Young's modulus (elastic modulus), is a measure of the stiffness of a solid material.
- Young's modulus is the ratio of stress (force per unit area) to strain (proportional deformation) in a material (SI unit =Pascal (*Pa*))
- A solid material will deform when a load is applied to it and if it returns to its original shape after the load is removed, this is called elastic deformation.
- In the range where the ratio between load and deformation remains constant, the stress-strain curve is linear.
- Young's modulus represents the factor of proportionality in Hooke's law, which relates the stress and the strain. However, Hooke's law is only valid under the assumption of an elastic and linear response.

Young's Modulus

- Young's modulus E, can be calculated by dividing the tensile stress, $\sigma(\epsilon)$ by the extensional strain ϵ in the elastic (initial, linear) portion of the physical stressstrain curve:

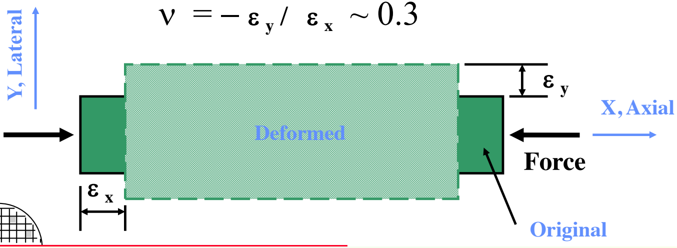
$$E = \frac{\sigma(\epsilon)}{\epsilon} = \frac{F/Ao}{\Delta L/L_0} = \frac{FL_o}{A_0 \Delta L} \quad (1)$$

E is the Young's modulus (modulus of elasticity)
F is the force exerted on an object under tension;
A_0 is the actual cross-sectional area through which the force is applied;
ΔL is the amount by which the length of the object changes;
L_0 is the original length of the object

Poisson's Ratio

Poisson's ratio (ν) gives the relationship between lateral strain and axial strain. In all engineering materials the elongation produced by an axial tensile force in the direction of the force is accompanied by a contraction in any transverse direction.

$$\nu = -\varepsilon_y / \varepsilon_x \sim 0.3$$



Poisson's Ratio

- **consider a bar under longitudinal tension or compression**
  - **under tension**
    - **length increases: Young's modulus**
    - **ALSO: cross sectional area decreases**
    - **this constitutes a transverse strain $\delta W/W$**
  - **Poisson's ratio ν = transverse strain / longitudinal strain**
    - **dimensionless (since both strains are dimensionless)**

$$\nu = \left(\frac{\delta W}{W}\right) \Big/ \left(\frac{\delta L}{L}\right)$$

$$\frac{\delta W}{W} = \frac{\nu}{E} \cdot (\text{longitudinal stress})$$

Lecture 11
Piezoresistive coefficients & Density

Piezoresistive coefficients

- Piezoresistance is the fractional change in bulk resistivity induced by small mechanical stresses applied to a material.
- Most the resistance change in metals is due to dimensional changes: under stress, the resistor gets longer, narrower, and thinner
- Piezoresistivity arises from the deformation of the energy bands as a result of an applied stress. In turn, the deformed bands affect the effective mass and the mobility of electrons and holes, hence modifying resistivity.
- Tthe fractional change in resistivity, $\frac{\Delta R}{R}$, is to a first order linearly dependent on $\sigma_{\parallel}$ and $\sigma_{\perp}$, the two stress components parallel and orthogonal to the direction of the resistor, respectively.

Piezoresistive coefficients of Si

- The direction of the resistor is here defined as that of the current flow and the relationship can be expressed as

$$\Delta R/R = \pi_{\shortparallel}\sigma_{\shortparallel} + \pi_{\perp}\sigma_{\perp} \quad (2)$$

- The proportionality constants, $\pi_{\shortparallel}$ and $\pi_{\perp}$ are called the parallel and perpendicular piezoresistive coefficients. $\sigma_{\shortparallel}$ is stress component parallel to the direction of the current (longitudinal stress component) and $\sigma_{\perp}$ the stress component perpendicular to the direction of the current (transverse stress component)
- These are related to the gauge factor by the Youngs modulus of the material.
- The piezoresistive coefficients depend on crystal orientation and change significantly from one direction to the other
- They also depend on dopant type (n-type versus p-type) and concentration.
- C. S. Smith's discovery in 1954 that the piezoresistive effect in silicon and germanium was much greater (by roughly two orders of magnitude) than in metals spurred significant interest.

Piezoresistive coefficients of Si

Table 18.1. Typical room-temperature piezoresistance coefficients for n- and p-type silicon [98].

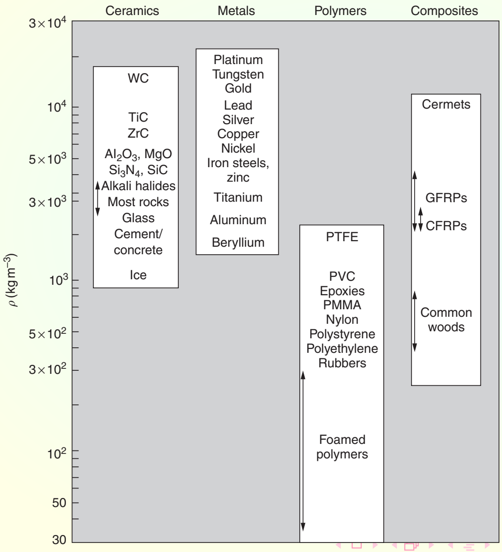
Type	Resistivity	π_{11}	π_{12}	π_{44}
Units	Ω-cm	10^{-11} Pa^{-1}	10^{-11} Pa^{-1}	10^{-11} Pa^{-1}
n-type	11.7	-102.2	53.4	-13.6
p-type	7.8	6.6	-1.1	138.1

- At higher doping, the temperature dependence of the piezoresistive coefficients becomes small.
- Therefore, if it is desired to operate a piezoresistive sensor over a wide temperature range, there may be a design advantage in sacrificing piezoresistive sensitivity in exchange for small temperature dependences by using heavily doped piezoresistors.

Density of Solids

- Density reflect the mass and diameter of the atoms that make them up and the efficiency with which they are packed to fill space.
- Metals, most of them, have high densities because the atoms are heavy and closely packed.
- Polymers are much less dense because the atoms of which they are made (C, H, O) are light, and the structures are not close packed.
- Ceramics-even the ones in which atoms are packed closely-are, on average, a little less dense than metals because most of them contain light atoms such as O, N, and C.
- Composites have densities that are an average of the materials from which they are made.

Bar chart of data for density, ρ



Lecture 12

TCR and Thermal Conductivity

Temperature Coefficient of Resistance (TCR)

- Resistance changes with temperature (TCR)
- Thermal resistor is an electrical resistor with significant temperature sensitivity
- All resistors vary with temperature (except those carefully designed for zero TCR over a restricted temperature range). For moderate temperature excursions, we can use a linear variation of resistance with temperature:

$$R = R_0(1 + \alpha_R(T_R - T_0)) \tag{3}$$

$$\Delta R = \frac{R - R_0}{R_0} = \alpha_R \Delta T \tag{4}$$

- R_0 is the resistance at reference temperature T_0 and R is the resistance at temperature T_R , α_R is the temperature coefficient of resistivity

Temperature Coefficient of Resistance (TCR)

- The temperature coefficient of resistance α_R is typically positive for metallic resistors, but can be either positive or negative for semi- conductors, depending on the region of operation and the specific design of the resistor.
- Typical values for metals are in the range of 10^{-4} per Kelvin
- Values in semiconductors can be larger.
- In specially designed thermistor materials, the resistance-temperature function can be an exponential, with incremental negative TCR values on the order of 10^{-2} per Kelvin or greater.

Temperature Coefficient of Resistance (TCR)

- For pure metal the TCR is positive $\Rightarrow$ the resistance increases with increase in temperature and decreases with increase in temperature
- For alloys the TCR is zero ie the resistance hardly changes at all with variation in temperature.
- One advantage of poly Si over Cryst. Si is its reduced TCR
- The deposition process and type of dopant can alter the sign of TCR
- Resistance with positive TCR are used in compensating the negative temp dependence of piezoresistance sensor.

Thermal Conductivity

- In physics, thermal conductivity, k is the property of a material's ability to conduct heat. It appears primarily in Fourier's Law for heat conduction.
- Thermal conductivity is measured in watts per kelvin-meter
- In general, good conductors of electricity (metals like copper, aluminum, gold, and silver) are also good heat conductors, whereas insulators of electricity (wood, plastic, and rubber) are poor heat conductors.
- There are four factors $(k, A, \Delta T, d)$ that affect the rate at which heat is conducted through a material.

$$\frac{Q}{t} = \frac{kA\Delta T}{d} \tag{5}$$

  - Q represents the amount of heat transferred in a time t
  - k is the thermal conductivity constant for the material
  - A is the cross sectional area of the material transferring heat
  - ΔT is the difference in temperature between one side of the material and the other
  - d is the thickness of the material

Thermal conductivity data for polycrystalline silicon