EE C247B – ME C218
Introduction to MEMS Design
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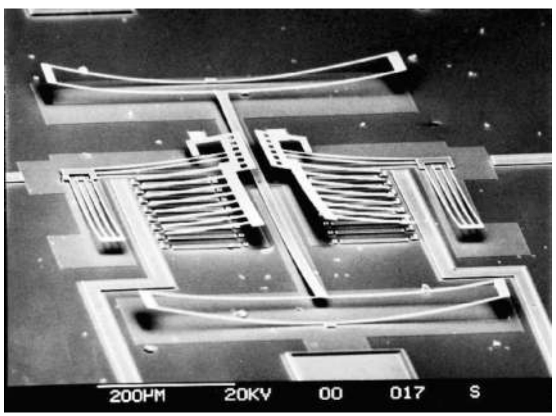
Lecture Module 7: Mechanics of Materials

Outline

- Reading: Senturia, Chpt. 8
- Lecture Topics:
  - Stress, strain, etc., for isotropic materials
  - Thin films: thermal stress, residual stress, and stress gradients
  - Internal dissipation
  - MEMS material properties and performance metrics

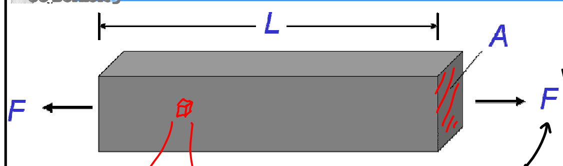
Vertical Stress Gradients

- Variation of residual stress in the direction of film growth
- Can warp released structures in z-direction



Elasticity

Normal Stress (1D)

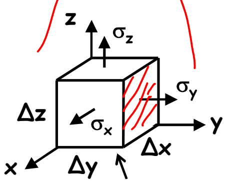


If the force acts normal to a surface, then the stress is called a **normal stress**

Force assumed uniform over the whole area A

$$\text{Stress} = \left\{\begin{matrix}\text{Force per}\\ \text{unit area}\end{matrix}\right\} = \sigma = \frac{F}{A} \quad [N/m^2 = Pa]$$

standard mks unit

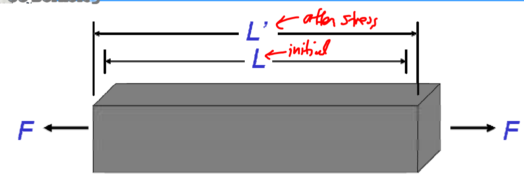


Differential volume element

⇒ Microscopic Definition: force per unit area acting on the surface of a differential volume element of a solid body

⇒ Note: assume stress acts uniformly across the entire surface of the element, not at just a point

Strain (1D)

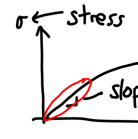


Sometimes a unit called the "microstrain" is used, where

$1\mu\varepsilon = \frac{\Delta L}{L}$ of 1 part in 10^6

$$\text{Strain} = \left\{\begin{matrix}\text{Fractional Change}\\ \text{in Length}\end{matrix}\right\} = \varepsilon = \frac{L'-L}{L} = \frac{\Delta L}{L} \quad [\text{unitless}]$$

In the elastic regime (i.e., for "small" stresses at "low" temperatures), strain is found to be proportional to stress



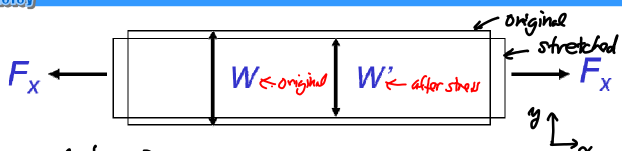
slope = E = Young's modulus of elasticity

For solids: MPa → GPa

$\sigma = \varepsilon E \rightarrow \boxed{\varepsilon = \frac{\sigma}{E} \quad [\text{unitless}]}$

Thus, the units of E are the same as σ → Pa

The Poisson Ratio



Apply normal stress to a free-standing object → uniaxial strain → but also get contraction in directions transverse to the uniaxial strain

⇒ contraction creates a (-) strain:

$$\varepsilon_y = \frac{W'-W}{W} = \frac{\Delta W}{W} = -\nu\varepsilon_x$$

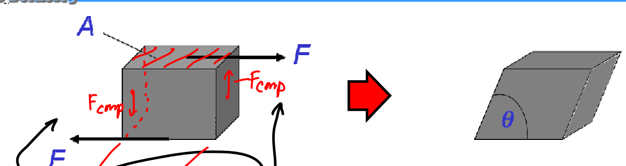
ν = Poisson ratio [unitless]

typical values: 0 → 0.5

⇒ inorganic solids: 0.2 → 0.3

⇒ elastomers (e.g., rubber): ~0.5

Shear Stress & Strain (1D)



Note: Assume compensating forces are applied to the vertical faces to avoid a net torque. (This by convention.)

$$\text{Shear Stress} = \left\{\begin{matrix}\text{Force Per Unit Area}\\ \text{Parallel to the Surfaces}\end{matrix}\right\} = \tau = \frac{F}{A} \quad [Pa]$$

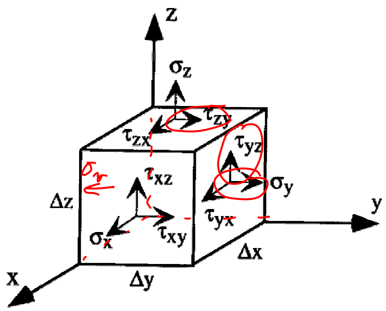
Generates a shear strain:

$\text{Shear Strain} = \theta = \frac{\tau}{G} \leftarrow G \triangleq \text{shear modulus}$

$$G = \frac{E}{2(1+\nu)}$$

2D and 3D Considerations

- Important assumption: the differential volume element is in static equilibrium → no net forces or torques (i.e., rotational movements)
  - Every σ must have an equal σ in the opposite direction on the other side of the element
  - For no net torque, the shear forces on different faces must also be matched as follows:

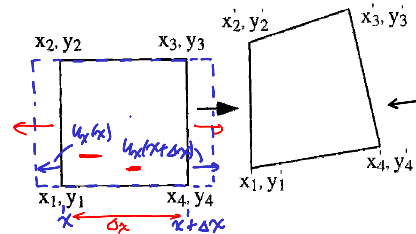


Stresses acting on a differential volume element

$\tau_{xy} = \tau_{yx}$ $\tau_{xz} = \tau_{zx}$ $\tau_{yz} = \tau_{zy}$

2D Strain

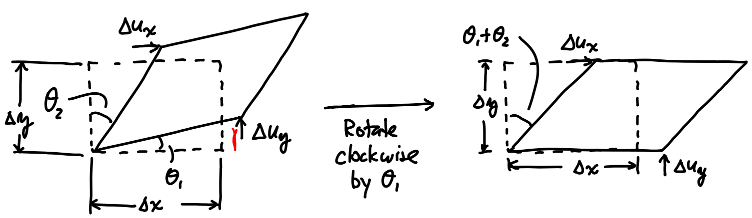
- In general, motion consists of
  - rigid-body displacement (motion of the center of mass)
  - rigid-body rotation (rotation about the center of mass)
  - Deformation relative to displacement and rotation



Area element experiences both displacement and deformation

- Must work with displacement vectors
- Differential definition of axial strain: → $\varepsilon_x = \dfrac{u_x(x+\Delta x) - u_x(x)}{\Delta x} = \dfrac{\partial u_x}{\partial x}$

2D Shear Strain



⇒ For shear strains, must remove any rigid body rotation that accompanies the deformation

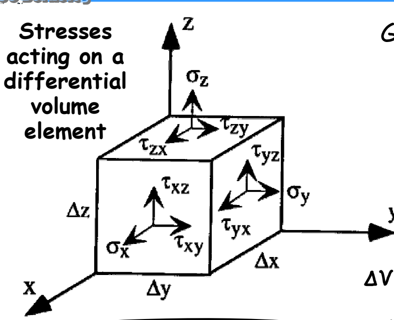
↳ use a symmetric definition of shear strain:

$$\gamma_{xy} = \theta_2 + \theta_1 \approx \left(\frac{\Delta u_x}{\Delta y} + \frac{\Delta u_y}{\Delta x}\right) = \left(\frac{\partial u_x}{\partial y} + \frac{\partial u_y}{\partial x}\right)$$

↑ For small amplitude deformations.

Volume Change for a Uniaxial Stress

Stresses acting on a differential volume element



Given an x-directed uniaxial stress, σ_x:

$\Delta x \to \Delta x(1+\epsilon_x)$

$\Delta y \to \Delta y(1-\nu\epsilon_x)$

$\Delta z \to \Delta z(1-\nu\epsilon_x)$

↓ The resulting change in volume ΔV

$$\Delta V = \Delta x \Delta y \Delta z (1+\epsilon_x)(1-\nu\epsilon_x)^2 - \Delta x \Delta y \Delta z = \Delta x \Delta y \Delta z\left[(1+\epsilon_x)(1-\nu\epsilon_x)^2 - 1\right]$$

{Assume small strains} ⇒ $\Delta V = \Delta x \Delta y \Delta z\left[(1+\epsilon_x)(1-2\nu\epsilon_x) - 1\right]$

$[(1+mx)^n \approx 1+nmx]$ ⇒ $\approx \Delta x \Delta y \Delta z\left[\cancel{1} + \epsilon_x - 2\nu\epsilon_x - \cancel{2\nu\epsilon_x^2} - \cancel{1}\right]$ negl.

$$\boxed{\Delta V \approx \Delta x \Delta y \Delta z (1-2\nu)\epsilon_x}$$

For $\nu = 0.5$ (rubber) → no ΔV!

$\nu < 0.5$ → finite ΔV

Isotropic Elasticity in 3D

- Isotropic = same in all directions
- The complete stress-strain relations for an isotropic elastic solid in 3D: (i.e., a generalized Hooke's Law)

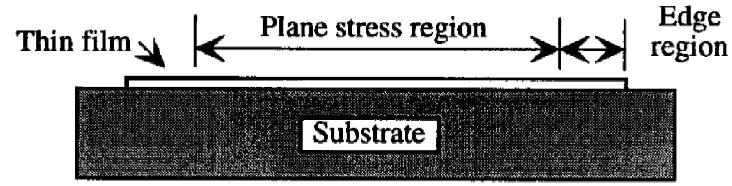
$$\varepsilon_x = \frac{1}{E}\left[\sigma_x - \nu\left(\sigma_y + \sigma_z\right)\right] \qquad \gamma_{xy} = \frac{1}{G}\tau_{xy}$$

$$\varepsilon_y = \frac{1}{E}\left[\sigma_y - \nu\left(\sigma_z + \sigma_x\right)\right] \qquad \gamma_{yz} = \frac{1}{G}\tau_{yz}$$

$$\varepsilon_z = \frac{1}{E}\left[\sigma_z - \underbrace{\nu\left(\sigma_x + \sigma_y\right)}_{\text{Basically, add in off-axis strains from normal stresses in other directions}}\right] \qquad \gamma_{zx} = \frac{1}{G}\tau_{zx}$$

Important Case: Plane Stress

- Common case: very thin film coating a thin, relatively rigid substrate (e.g., a silicon wafer)



- At regions more than 3 thicknesses from edges, the top surface is stress-free → $\sigma_z = 0$
- Get two components of in-plane stress:

$$\varepsilon_x = (1/E)[\sigma_x - \nu(\sigma_y + 0)]$$

$$\varepsilon_y = (1/E)[\sigma_y - \nu(\sigma_x + 0)]$$

Important Case: Plane Stress (cont.)

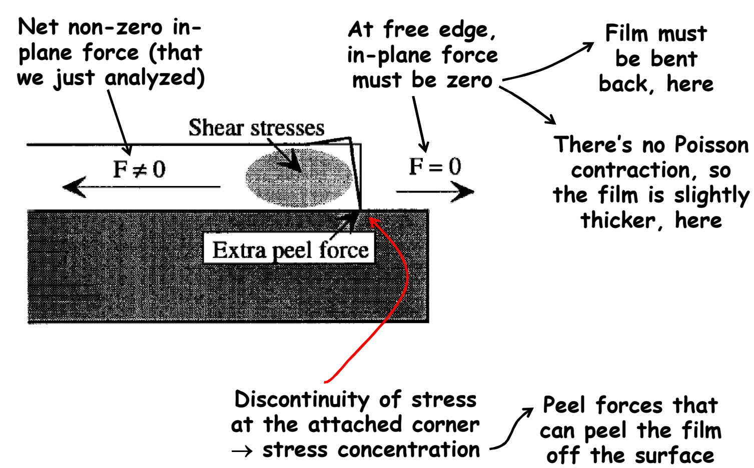
- Symmetry in the xy-plane → $\sigma_x = \sigma_y = \sigma$
- Thus, the in-plane strain components are: $\varepsilon_x = \varepsilon_y = \varepsilon$ where

$$\varepsilon_x = (1/E)[\sigma - \nu\sigma] = \frac{\sigma}{[E/(1-\nu)]} = \frac{\sigma}{E'}$$

and where

$$\text{Biaxial Modulus} \triangleq E' = \frac{E}{1-\nu}$$

Edge Region of a Tensile (σ>0) Film



Linear Thermal Expansion

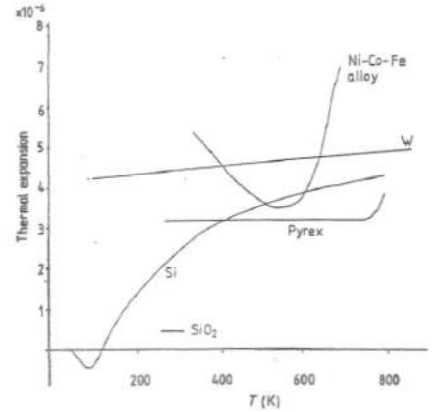
- As temperature increases, most solids expand in volume
- Definition: linear thermal expansion coefficient

$$\left.\begin{array}{c}\text{Linear thermal}\\ \text{expansion coefficient}\end{array}\right\} \triangleq \alpha_T = \frac{d\varepsilon_x}{dT} \qquad [\text{Kelvin}^{-1}]$$

Remarks:

- α_T values tend to be in the 10^{-6} to 10^{-7} range
- Can capture the 10^{-6} by using dimensions of μstrain/K, where 10^{-6} K^{-1} = 1 μstrain/K
- In 3D, get volume thermal expansion coefficient $\longrightarrow$ $\frac{\Delta V}{V} = 3\alpha_T \Delta T$
- For moderate temperature excursions, α_T can be treated as a constant of the material, but in actuality, it is a function of temperature

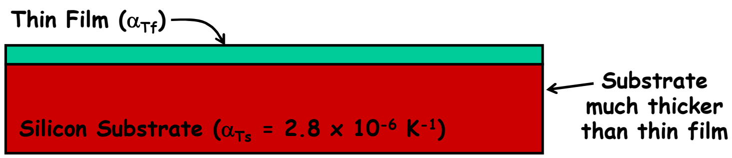
α_T As a Function of Temperature



[Madou, Fundamentals of Microfabrication, CRC Press, 1998]

- Cubic symmetry implies that α is independent of direction

Thin-Film Thermal Stress



- Assume film is deposited stress-free at a temperature T_r, then the whole thing is cooled to room temperature T_r
- Substrate much thicker than thin film → substrate dictates the amount of contraction for both it and the thin film

Thermal strain of the substrate: (in one in-plane dimension)

$$\epsilon_s = -\alpha_{Ts}\Delta T \quad , \text{ where } \Delta T = T_d - T_r$$

If the film were not attached to the substrate: $\epsilon_{f,free} = -\alpha_{Tf}\Delta T$

over

Linear Thermal Expansion

But the film is attached to the substrate, so the actual strain in the film is the same as that in the substrate:

$$\epsilon_{f,attached} = -\alpha_{Ts}\Delta T$$

Thus:

$$\boxed{\text{Thermal Mismatch Strain} = \epsilon_{f,mismatch} = (\alpha_{Tf} - \alpha_{Ts})\Delta T}$$

Note that this is biaxial strain

it can only be developed by an in-plane biaxial stress:

$$\sigma_{f,mismatch} = \left(\frac{E}{1-\nu}\right)\epsilon_{f,mismatch}$$

Ex. Thin-film is polyimide → $\alpha_{Tf} = 70\times10^{-6}\ K^{-1}$, $E' = 4GPa$ e.g., SiO_2

deposited @ 250°C, then cooled to RT = 25°C → $\Delta T = 225K$

$$\epsilon_{f,mismatch} = (70-2.8)\mu(225) = 1.5\times10^{-2}$$

$\sigma_{f,mismatch} = (4G)(1.5\times10^{-2}) = 60.5MPa$ ← stress is (+), ∴ tensile [(-) would be compressive]