Lecture 9: Mechanics of Materials I

- Announcements:
- Module 6 on Bulk Micromachining online
- Module 7 on Mechanics of Materials online
- HW#2 due this coming Friday morning
- Wednesday Office Hours will change to 2:30-3:30 p.m. starting this week
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- Reading: Senturia Chpt. 3, Jaeger Chpt. 11, Handouts: "Bulk Micromachining of Silicon"
- Lecture Topics:
  - Bulk Micromachining
  - Anisotropic Etching of Silicon
  - Boron-Doped Etch Stop
  - Electrochemical Etch Stop
  - Isotropic Etching of Silicon
  - Deep Reactive Ion Etching (DRIE)
  - Wafer Bonding
- --------------------------------
- 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
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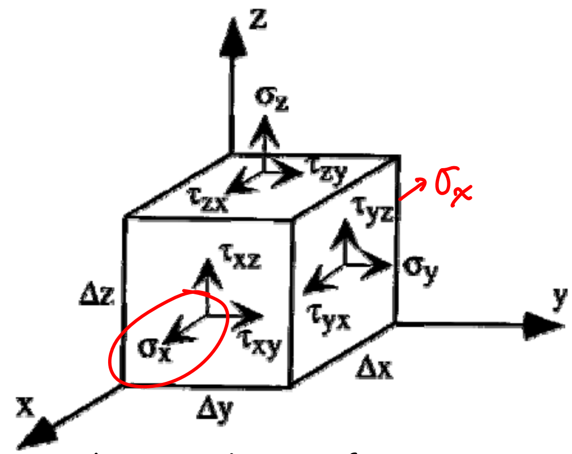
- Last Time: Going thru Module 6 … finish this
- Move on to Module 7

Example. Exercise the "terms"

⇒ determine the volume change ΔV for a uniaxial stress (along the x-direction)



Upon application of σ_x, what is ΔV?

$$\left.\begin{aligned} \Delta x &\to \Delta x(1+\epsilon_x) \\ \Delta y &\to \Delta y(1-\nu\epsilon_x) \\ \Delta z &\to \Delta z(1-\nu\epsilon_x) \end{aligned}\right\}$$

assuming isotropic material
↓
same ν along y & z

The resulting change in volume, ΔV

$$\Delta V = \underbrace{\Delta x \Delta y \Delta z (1+\epsilon_x)(1-\nu\epsilon_x)^2}_{\text{volume after application of } \sigma_x} - \Delta x \Delta y \Delta z$$

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

[Assume small strains] $\Rightarrow (1+mx)^n \approx 1 + nmx$

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

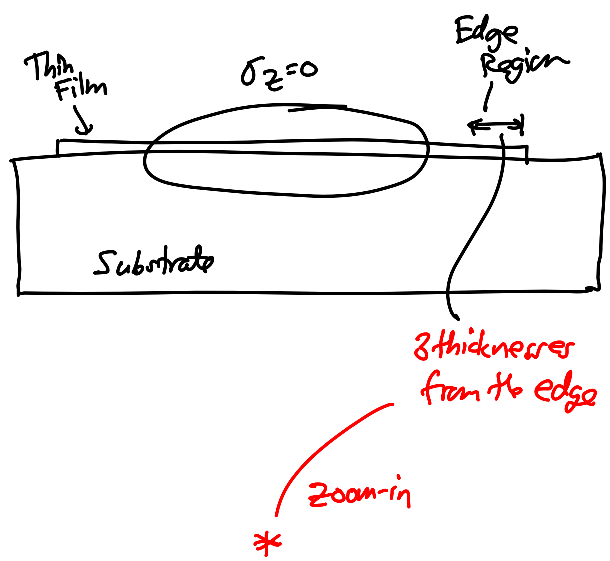
$$\boxed{\Delta V = \Delta x \Delta y \Delta z\,(1-2\nu)\epsilon_x}$$

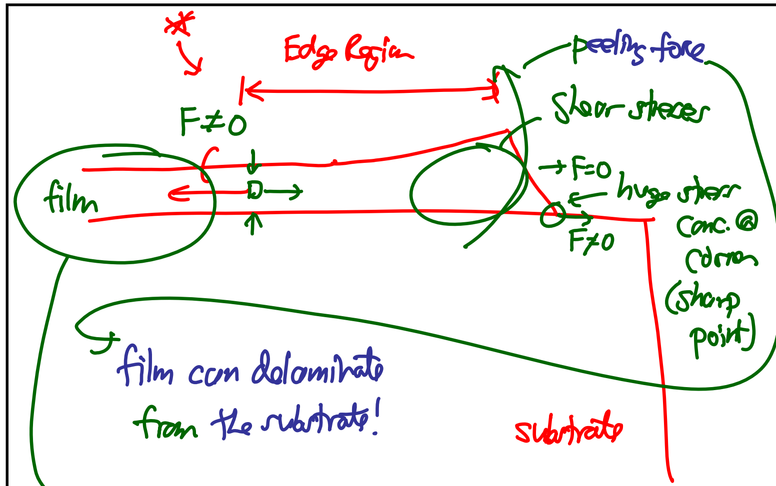
For $\nu = 0.5$ (rubber) $\rightarrow$ no ΔV!

$\nu < 0.5 \rightarrow$ finite ΔV

Important Case: Plane Stress

$\Rightarrow$ common case for a thin-film coating on a rigid substrate:





Take a closer look @ this region: $\sigma_z = 0$

Get two components of stress:

$$\epsilon_x = \frac{1}{E}\left[\sigma_x - \nu(\sigma_y + 0)\right]$$

$$\epsilon_y = \frac{1}{E}\left[\sigma_y - \nu(\sigma_x + 0)\right]$$

Assume: Plane Stress $\rightarrow$ isotropic $\rightarrow \sigma_x = \sigma_y = \sigma$
(symmetry in the xy-plane)

$$\epsilon_x = \epsilon_y = \epsilon$$

$$\epsilon_x = \frac{1}{E}\left[\sigma - \nu\sigma\right]$$

$$= \frac{\sigma}{\left(\frac{E}{1-\nu}\right)} \Rightarrow \epsilon_x = \frac{\sigma}{E'}$$

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

Linear Thermal Expansion

temperature $T \uparrow \rightarrow$ solids (generally) expand in volume

Definition: Linear Thermal Expansion Coefficient

$$\left.\begin{array}{l}\text{Linear Thermal}\\ \text{Exp. Coefficient}\end{array}\right\} \triangleq \alpha_T = \frac{d\epsilon_x}{dT} \quad [\text{kelvin}^{-1}]$$

Remarks:

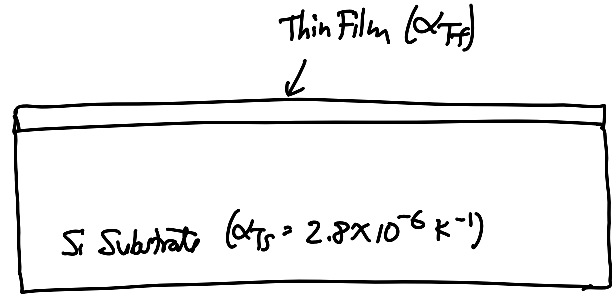
1. α_T values tend to be in the 10^{-6} to 10^{-7} range.
2. $10^{-6} K^{-1} = 1 \mu\text{strain}/K$
3. In 3D, get a volume thermal exp. coefficient

$$\frac{\Delta V}{V} = 3\alpha_T \Delta T$$

4. For moderate ΔT's $\rightarrow$ $\alpha_T \approx$ constant

for larger ΔT, then $\alpha_T = f(T)$

Ex. Thin-Film Thermal Stress



Assume:

1. Substrate is much thicker than the film.
2. Film is deposited stress free @ T_d ← deposition temperature
3. Then the whole thing is cooled to room temperature, T_r.

Thermal Strain of the Substrate: (in one plane dimension)

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

If the film were not attached to the substrate:

$$\epsilon_{f,free} = -\alpha_{Tf} \Delta T$$

But the film is attached to the substrate

$\Rightarrow$ thickness sub >> thickness film

$\therefore$ substrate wins!

*

* → Thus, the actual strain experienced by the film is that of 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 this is biaxial strain (assuming the film is deposited isotropically onto the substrate)

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

Ex. Thin film is polyimide → $\alpha_{Tf} = 70\times10^{-6}\,K^{-1}$

$E' = 4GPa$

deposited @ 250°C, then cooled to RT = 25°C

$$\underbrace{\text{deposited @ 250°C, then cooled to RT = 25°C}}_{\Delta T = 225K}$$

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

$[\mu = 10^{-6},\ m = 10^{-3},\ k = 10^{3},\ G = 10^{9}]$

$$\sigma_{f,mismatch} = (4G)(1.5\times10^{-2}) = 60.5MPa$$

SiO_2 → stress is (+) → tensile

[(-) would be compressive]