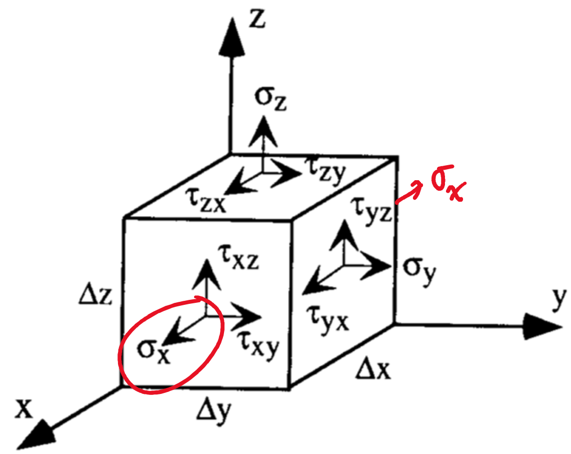
Lecture 10: Bulk Micromachining II & Mechanics of Materials I

- *Announcements*:
- HW#3 online soon
- Module 7 on "Mechanics of Materials" online
- -------------------------------------
- Today:
- 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)
- 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
- -------------------------------------
- Last Time:
- Going through Module 6 on "Bulk Micromachining"
- Now, continue with this …

1

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?

Before Stress		After Stress
Δx	⟶	$\Delta x(1+\epsilon_x)$
Δy	⟶	$\Delta y(1-\nu\epsilon_x)$
Δz	⟶	$\Delta z(1-\nu\epsilon_x)$

Assuming isotropic material ↓ same ν along y & z

The resulting change in volume:

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

2

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

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

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

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

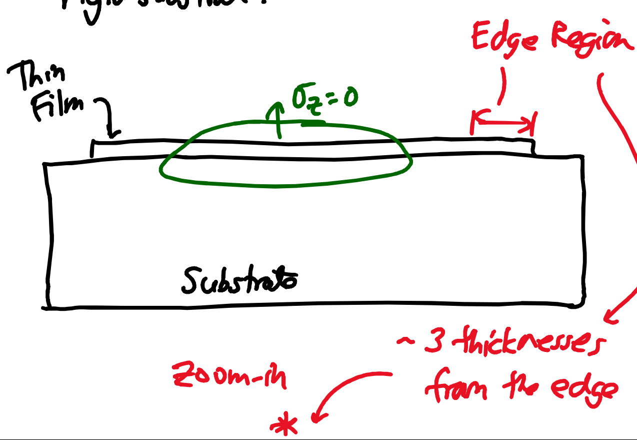
For $\nu = 0.5$ (rubber) $\rightarrow$ no ΔV!

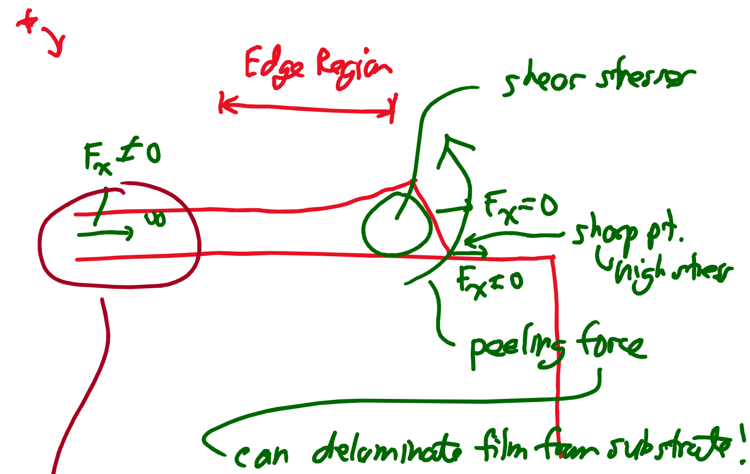
$\nu < 0.5 \rightarrow$ finite ΔV

For more general isotropic formulation, see Module 7, pg. 13

Important Case: Plane Stress

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





Take a closer look @ this (simpler) 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) $\downarrow$

$\epsilon_x = \epsilon_y = \epsilon$

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

where $E' \triangleq$ Biaxial Modulus $= \dfrac{E}{1-\nu}$

Linear Thermal Expansion

temperature ↑ → solids expand in volume

Definition. Linear Thermal Expansion Coefficient

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

Remarks.

① α_T values tend to be in the 10^{-6} to 10^{-7} range.

② $10^{-6}K^{-1}$ = 1 μstrain/K

③ In 3D, get a volume thermal expansion coefficient

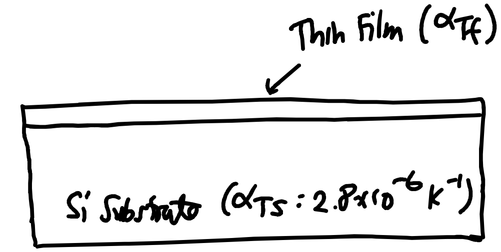
$$\frac{\Delta V}{V} = 3\alpha_T \Delta T$$

④ For moderate ΔT's → $\alpha_T \cong$ constant

→ For larger ΔT, then $\alpha_T = f(T)$

5

Ex. Thin-Film Thermal Stress



Assume:

① Substrate is much thicker than the film.

② Film deposits stress free @ T_d ← deposition temperature

③ 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!

→ thickness substrate >> thickness of film

→ ∴ the substrate wins! *

6

* Therefore, 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 a biaxial strain (assuming the film deposits isotropically onto the substrate)

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

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

$E' = 4$ GPa

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

7

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

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

$$\sigma_{f,mismatch} = (4\underset{10^9}{G})(1.5\times10^{-2}) = 60.5\text{ MPa}$$

stress is (+) → tensile

[(-) would be compressive]

SiO_2

8