- Announcements:
- Lecture schedule for the next 4 weeks:

Monday	Tuesday	Wednesday	Thursday	Friday
Oct. 5 Lecture 5-6:30 241 Cory	6 Lecture 3:30-5 Moffitt	7	8 Discuss 3:30-5 Moffitt	9
12 Lecture 5-6:30 241 Cory	13	14	15 Discuss 3:30-5 Moffitt	16
19 Lecture 5-6:30 241 Cory	20 Lecture 3:30-5 Moffitt	21	22 Lecture 3:30-5 Moffitt	23
26 Discuss 3:30-5 Moffitt	27	28	29 Lecture 3:30-5 Moffitt	30
Nov. 2 Lecture 5-6:30 241 Cory	3 Midterm 3:30-5 Moffitt	4	5 Lecture 3:30-5 Moffitt	6

- Midterm Exam:
  - Tu, Nov. 3, during regular lecture
  - 1.5 hours, but might go longer
- ----------

- 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)
  - Wafer Bonding
- ----------
- Finish up bulk micromachining Module 6
- Start through material of Module 7: Mechanics of Materials, but lectures themselves will be mostly handwritten
- 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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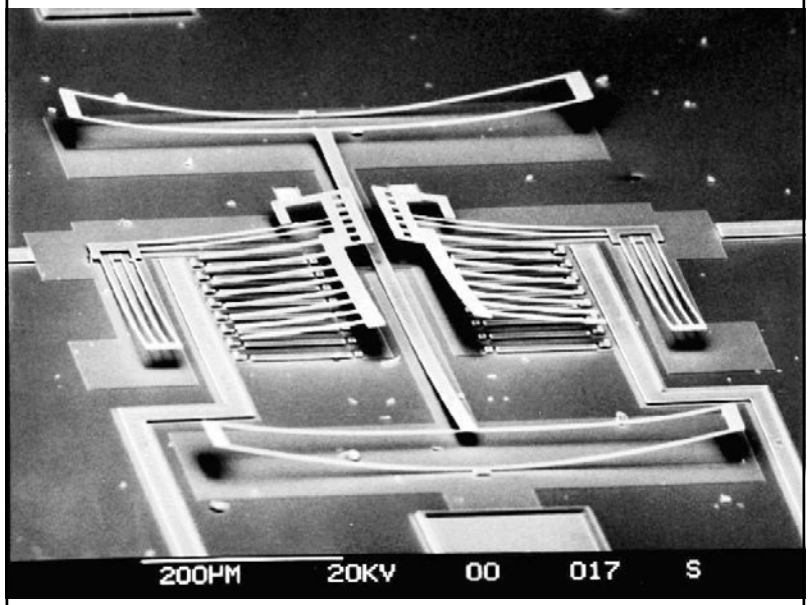
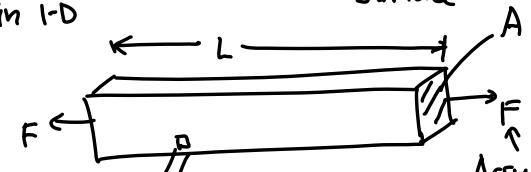
- We need to be able to model and understand this:



Stress

⇒ in 1-D

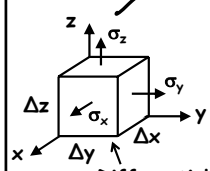
If F is normal to the surface → "normal stress"



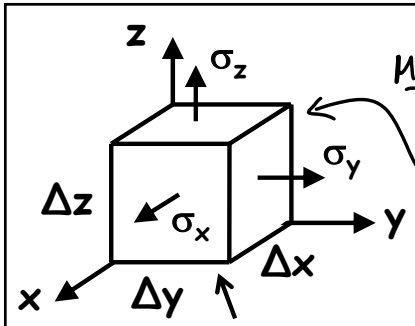
Assume uniform over area A.

Stress: $\left\{\begin{matrix}\text{Force per}\\ \text{unit area}\end{matrix}\right\} = \sigma = \frac{F}{A}$ [N/m² "Pa"]

↑ standard mks unit



Differential volume element



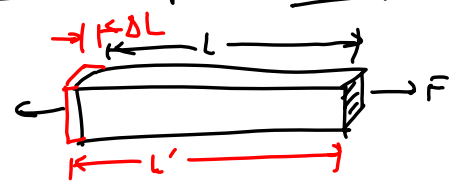
Differential volume element

Microscopic Definition: applied to a differential volume element

↓

w/ this easily assume that the stress is uniform on each face (not @ just one point)

Strain (other part of elasticity)



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

Sometimes use "microstrain" where

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

↑ just $\times 10^{-6}$

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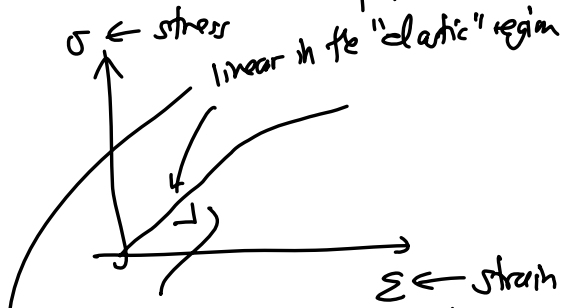
In the elastic regime
"small" stresses at "low" temperatures
→ strain is found to be proportional to stress:

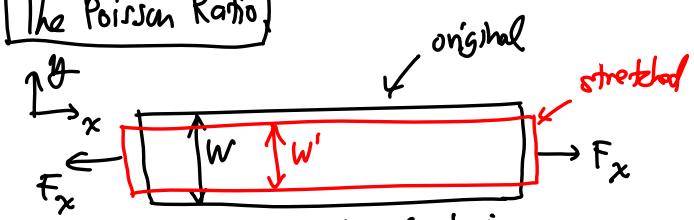


Slope = E = Young's modulus of elasticity
↳ For solids: MPa → GPa

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

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

The Poisson Ratio



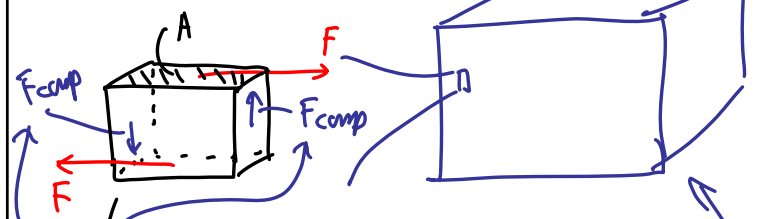
Apply normal stress } → uniaxial strain
→ but also contraction in directions transverse to the uniaxial strain

⇒ 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



Note: Assume compensating forces applied to prevent a net torque (i.e., to prevent rotation – which doesn't happen when this element is embedded in

shear strain

Shear Stress = { Force per unit area parallel to the surfaces }
$= \tau = \frac{F}{A}$ [Pa]

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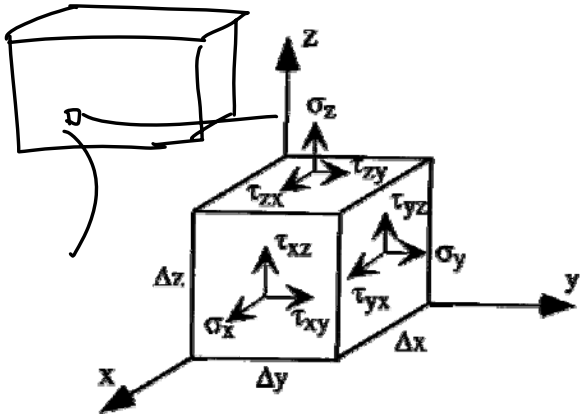
↳ generates a Shear Strain:

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

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

2D & 3D Considerations

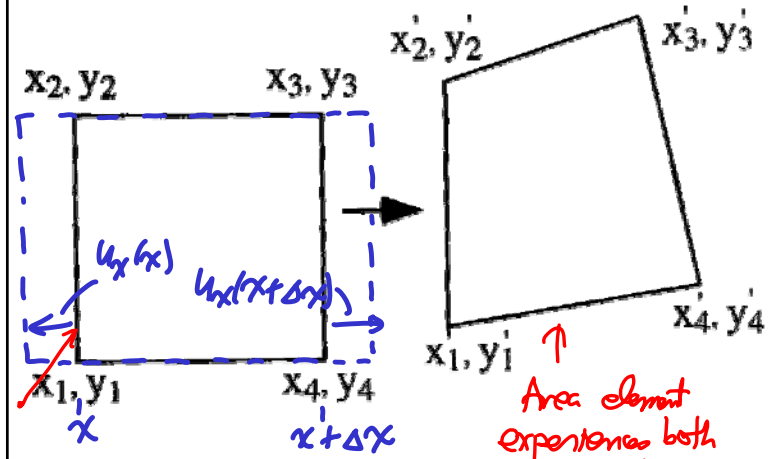


⇒ Every σ must have an equal σ in the opposite direction on the other side of the element

⇒ No net torque:

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

2D Strain



Area element experiences both displacement & deformation.

In general, motion consists of:

① Rigid body displacement (motion of the center of mass)

② Rigid body rotation (rotation about the center of mass)

③ Deformation relative to displacement & rotation.

⇒ handle by using displacement vectors:

For axial strain in the x-direction:

$$\varepsilon_x = \frac{u_x(x+\Delta x) - u_x(x)}{\Delta x} = \frac{\partial u_x}{\partial x}$$

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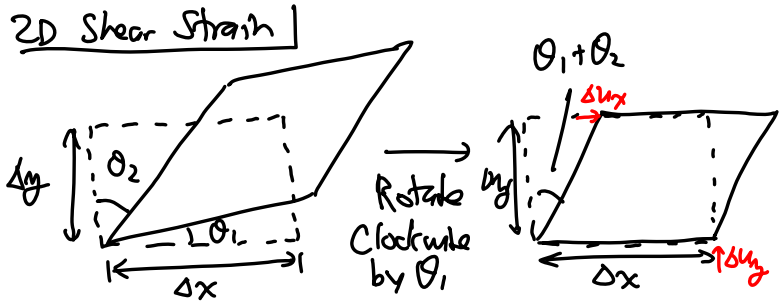
2D Shear Strain



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

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

For small amplitude deformations

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