EE C245 – ME C218
Introduction to MEMS Design
Fall 2007

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Lecture 12: Mechanics of Materials

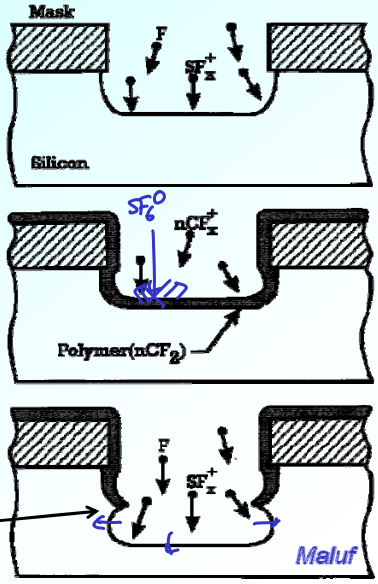
Lecture Outline

- Reading: Senturia Chpt. 3, 8, Jaeger Chpt. 11, Handouts: "Bulk Micromachining of Silicon", "Wafer-to-Wafer Bonding for Microstructure Formation"
- Lecture Topics:
  - Vapor Phase Etching of Silicon
  - Laser Assisted Silicon Etching
  - Wafer Bonding
  - Mechanics of Materials
    - Stress
    - Strain
    - Poisson Ratio
  - Material Properties

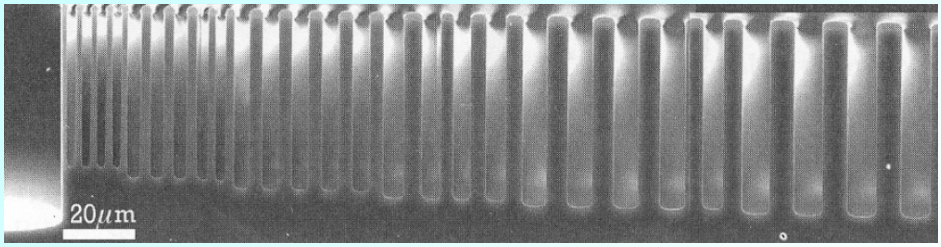
Deep Reactive-Ion Etching (DRIE)

The Bosch process:

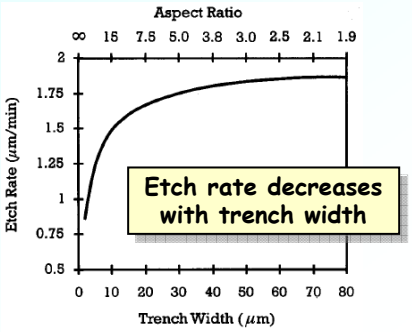
- Inductively-coupled plasma
- Etch Rate: 1.5-4 μm/min
- Two main cycles in the etch:
  - Etch cycle (5-15 s): SF_6 (SF_x^+) etches Si
  - Deposition cycle: (5-15 s): C_4F_8 deposits fluorocarbon protective polymer $(CF_2^-)_n$
- Etch mask selectivity:
  - SiO_2 ~ 200:1
  - Photoresist ~ 100:1
- Issue: finite sidewall roughness
  - scalloping < 50 nm
- Sidewall angle: 90° ± 2°



DRIE Issues: Etch Rate Variance



- Etch rate is diffusion-limited and drops for narrow trenches
  - Adjust mask layout to eliminate large disparities
  - Adjust process parameters (slow down the etch rate to that governed by the slowest feature)



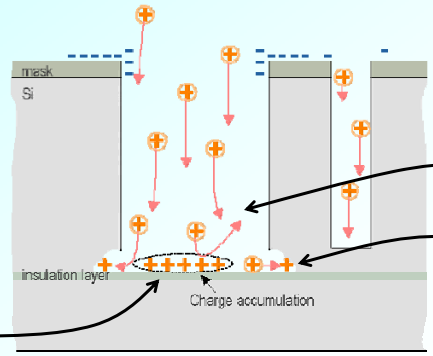
DRIE Issues: "Footing"

- Etch depth precision
  - Etch stop: buried layer of SiO_2
  - Due to 200:1 selectivity, the (vertical) etch practically just stops when it reaches SiO_2
- Problem: Lateral undercut at Si/SiO_2 interface → "footing"
  - Caused by charge accumulation at the insulator

Poor charge relaxation and lack of neutralization of e⁻'s at insulator

↓

Ion flux into substrate builds up (+) potential



Charging-induced potential perturbs the E-field

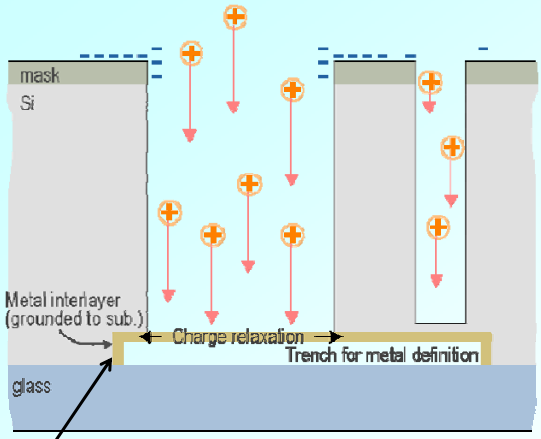
↓

Distorts the ion trajectory

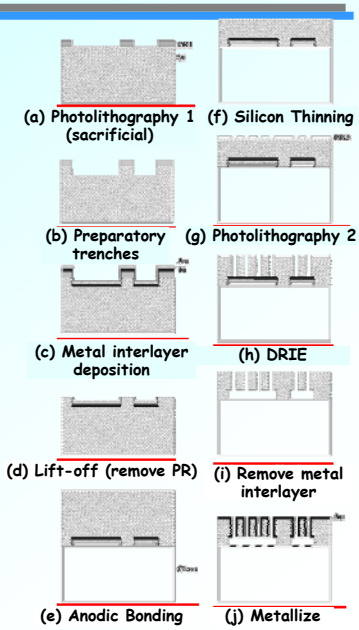
↓

Result: strong and localized damage to the structure at $Si-SiO_2$ interface → "footing"

Metal Interlayer to Prevent "Footing"



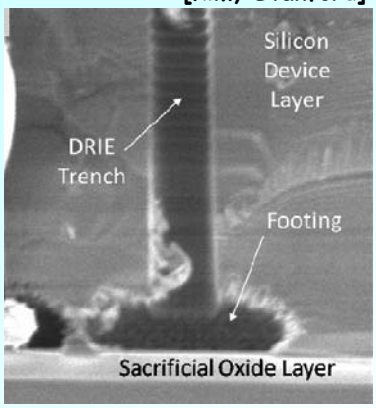
Pre-defined metal interlayer grounded to substrate supplies e's to neutralize (+) charge and prevent charge accumulation at the Si-insulator interface

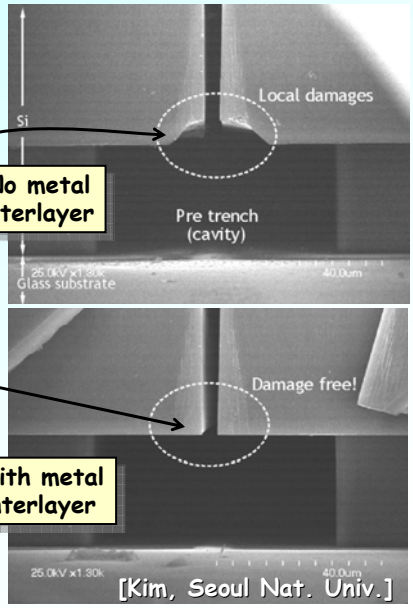


Footing Prevention (cont.)

- Below: DRIE footing over an oxide stop layer
- Right: efficacy of the metal interlayer footing prevention approach

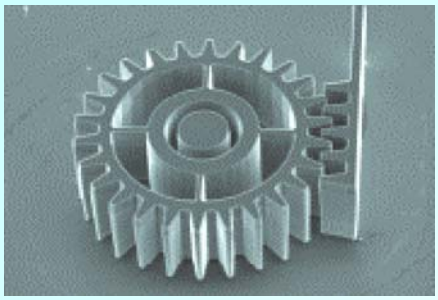
[Kim, Stanford]





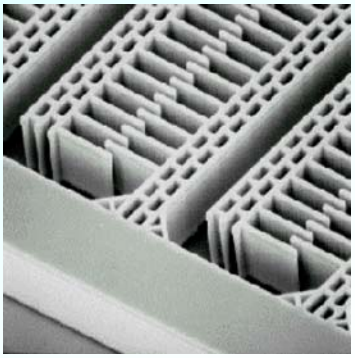
[Kim, Seoul Nat. Univ.]

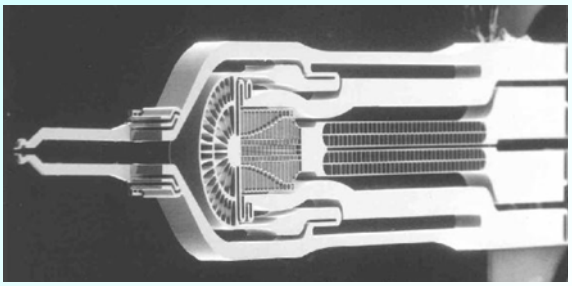
DRIE Examples



High aspect-ratio gear

Tunable Capacitor
[Yao, Rockwell]



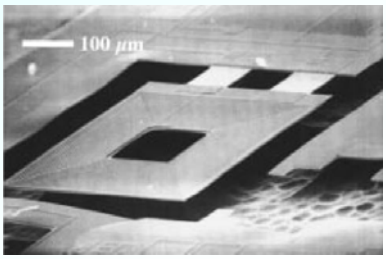


Microgripper
[Keller, MEMS
Precision Instruments]

Vapor Phase Etching of Silicon

- Vapor phase Xenon Difluoride (XeF_2)
  $2XeF_{2(g)} + Si_{(s)} \rightarrow 2Xe_{(g)} + SiF_{4(g)}$
- Set-up:
  - Xe sublimes at room T
  - Closed chamber, 1-4 Torr
  - Pulsed to control exothermic heat of reaction
- Etch rate: 1-3 μm/min, isotropic
- Etch masks: photoresist, SiO_2, Si_3N_4, Al, other metals
- Issues:
  - Etched surfaces have granular structure, 10 μm roughness
  - Hazard: XeF_2 reacts with H_2O in air to form Xe and HF

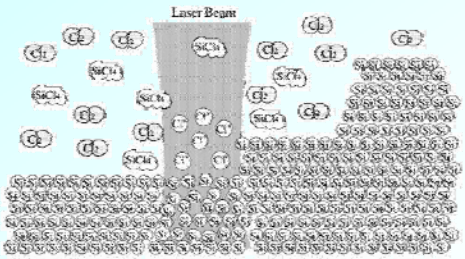
Xactix XeF_2 Etcher



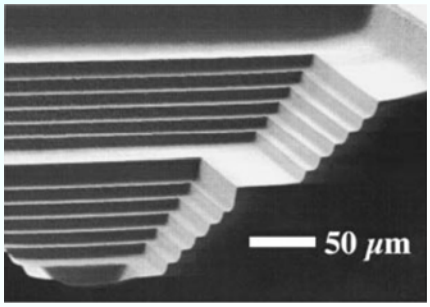
Inductor w/ no substrate [Pister]

Laser-Assisted Chemical Etching

- Laser creates Cl radicals from $Cl_2 \rightarrow$ reaction forms $SiCl_2$
- Etch rate: 100,000 $\mu m^3/s$
  - Takes 3 min. to etch 500×500×125 μm^3 trench
- Surface roughness: 30 nm rms
- Serial process: patterned directly from CAD file



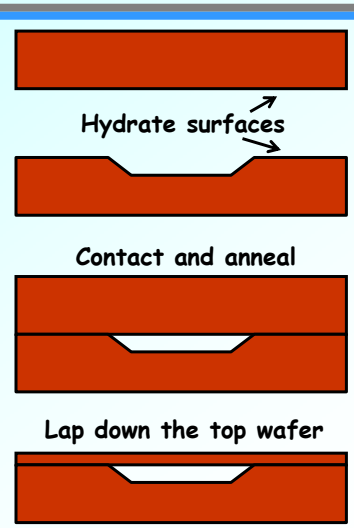
- At right:
  - Laser assisted etching of a 500x500 μm^2 terraced silicon well
  - Each step is 6 μm-deep



Wafer Bonding

Fusion Bonding

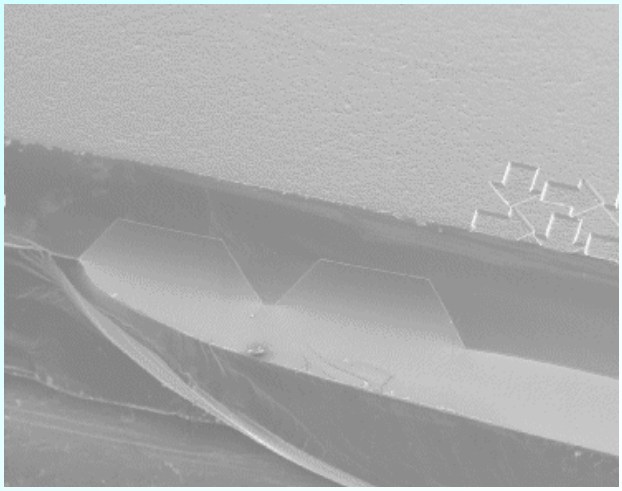
- Two ultra-smooth (<1 nm roughness) wafers are bonded without adhesives or applied external forces
- Procedure:
  - Prepare surfaces: must be smooth and particle-free
    - Clean & hydrate: O_2 plasma, hydration, or HF dip
  - When wafers are brought in contact at room temperature, get hydrogen bonding and/or van der Waals forces to hold them together
  - Anneal at 600-1200°C to bring the bond to full strength
- Result: a bond as strong as the silicon itself!



Works for Si-to-Si bonding and Si-to-SiO_2 bonding

Fusion Bonding Example

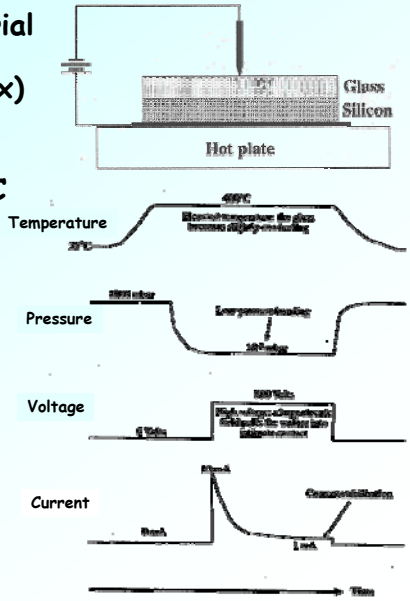
- Below: capacitive pressure sensor w/ fusion-bonded features



[Univ. of Southampton]

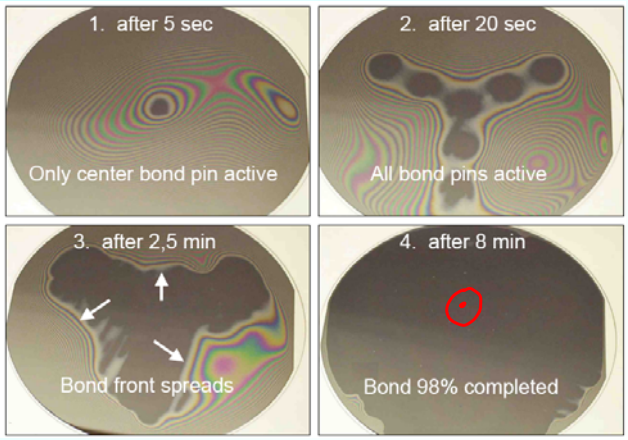
Anodic Bonding

- Bonds an electron conducting material (e.g., Si) to an ion conducting material (e.g., sodium glass = Pyrex)
- Procedure/Mechanism:
  - Press Si and glass together
  - Elevate temperature: 180-500°C
  - Apply (+) voltage to Si: 200-1500V
    - (+) voltage repels Na^+ ions from the glass surface
    - Get net (-) charge at glass surface
    - Attractive force between (+) Si and (-) glass → intimiate contact allows fusing at elevated temp.
  - Current drops to zero when bonding is complete



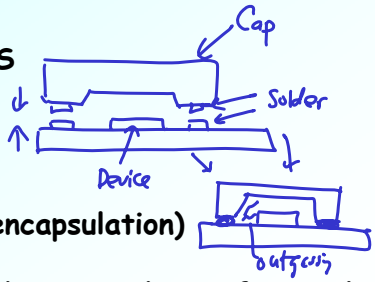
Anodic Bonding (cont.)

- Advantage: high pressure of electrostatic attraction smoothes out defects
- Below: 100 mm wafers, Pyrex glass 500 μm-thick, 430°C, 800V, N_2 @ 1000 mbar



Metal Layer Bonding

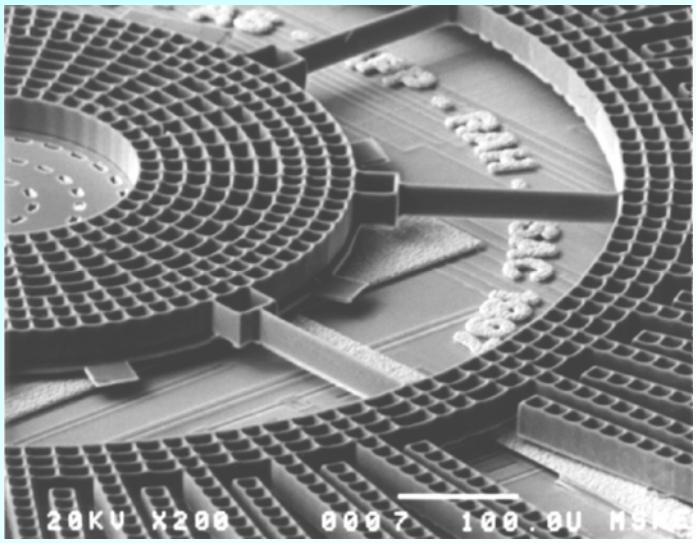
- Pattern seal rings and bond pads photolithographically
- Eutectic bonding
  - Uses eutectic point in metal-Si phase diagrams to form silicides
  - Au and Si have eutectic point at 363°C
  - Low temperature process
  - Can bond slightly rough surfaces
  - Issue: Au contamination of CMOS
- Solder bonding
  - PbSn (183°C), AuSn (280°C)
  - Lower-T process
  - Can bond very rough surfaces
  - Issue: outgassing (not good for encapsulation)



- Thermocompression
  - Commonly done with electroplated Au or other soft metals
  - Room temperature to 300°C
  - Lowest-T process
  - Can bond rough surfaces with topography

Thermocompression Bonding

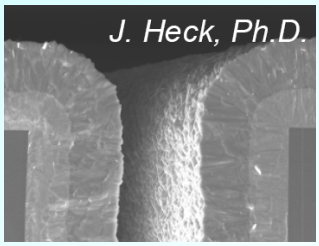
- Below: Transfer of hexsil actuator onto CMOS wafer

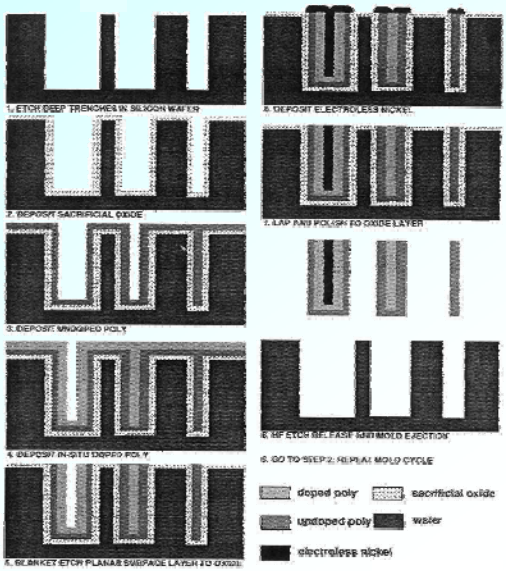


[Singh, et al, Transducers'97]

Hexsil MEMS

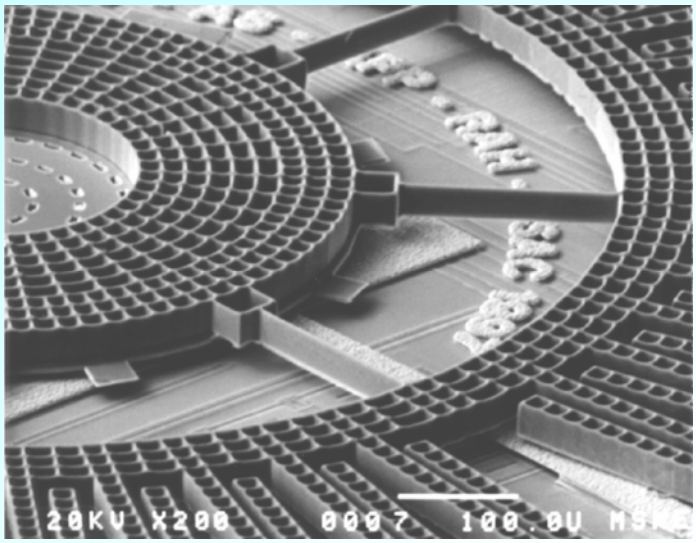
- Achieves high aspect ratio structures using conformal thin films in mold trenches
- Parts are demolded (and transferred to another wafer)
- Mold can be reused
- Design with honeycomb structure for strength





Hexsil MEMS Actuator

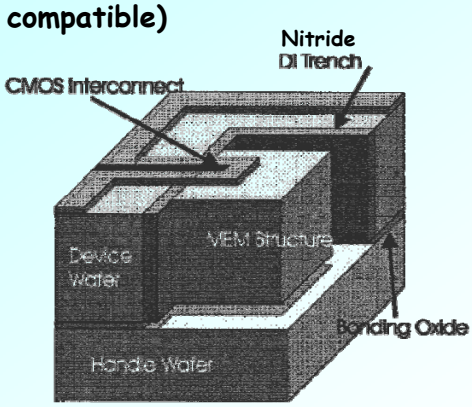
- **Below**: Transfer of hexsil actuator onto CMOS wafer

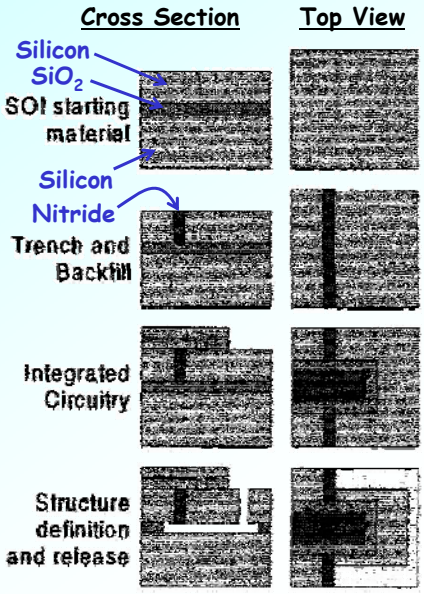


[Singh, et al, Transducers'97]

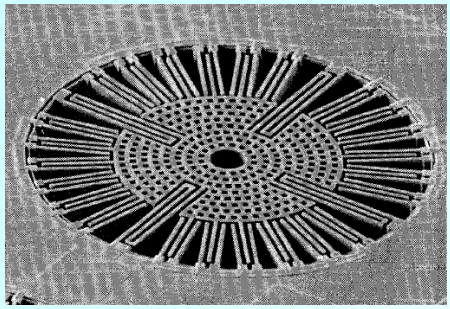
Silicon-on-Insulator (SOI) MEMS

- No bonding required
- Si mechanical structures anchored by oxide pedestals
- Rest of the silicon can be used for transistors (i.e., CMOS compatible)



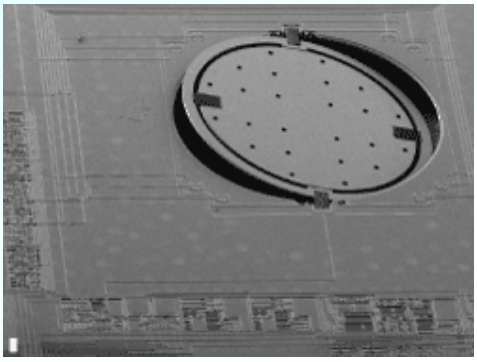


SOI MEMS Examples



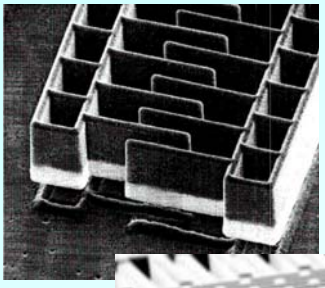
[Brosnihan]

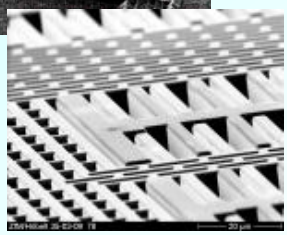
Micromirror
[Analog Devices]

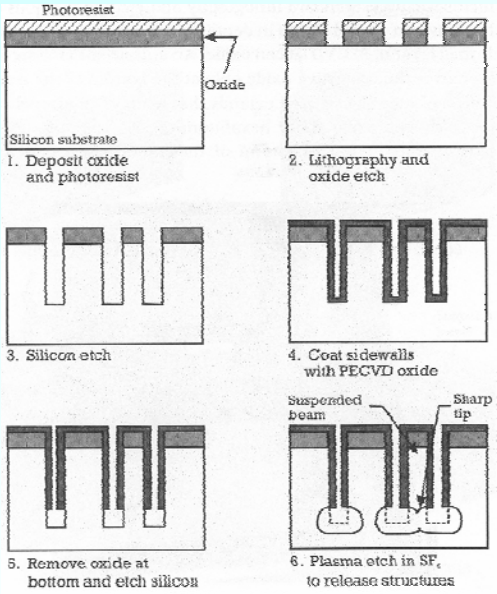


The SCREAM Process

- SCREAM: Single Crystal Reactive Etching and Metallization process

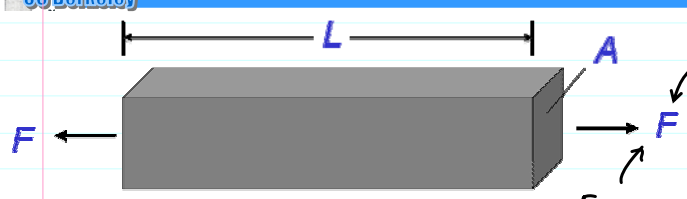






Elasticity

Normal Stress (1D)



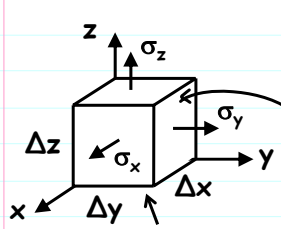
If the force acts normal to a surface, then the stress is called a **normal stress**

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

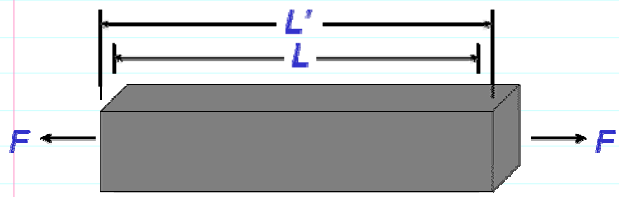
⇒ Microscopic Definition: force per unit area acting on the surface of a differential volume element of a solid body



Differential volume element

Note: force acts uniformly over each face

Strain (1D)



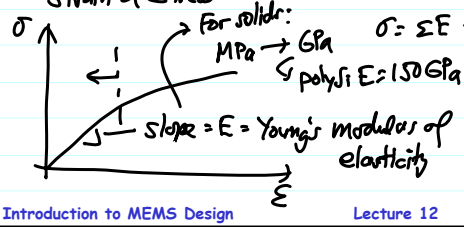
Sometimes a unit called "microstrain" is used, where $1\mu\varepsilon = \frac{\Delta L}{L}$ of 1 part in 10^6

$\frac{\Delta L}{L} = 10^{-6} = 1\mu\varepsilon$

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

In the elastic regime (i.e., for "small" stresses) & "low" temperatures

↳ strain ∝ stress



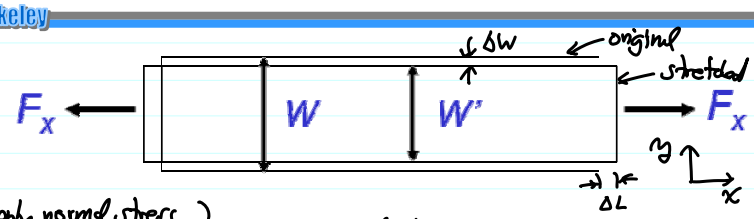
For solids: MPa → GPa

↳ polySi E = 150 GPa

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

∴ units of E same as σ → Pa

The Poisson Ratio



Apply normal stress to a free-standing object → uniaxial strain → ε_x

→ but also get contraction in directions transverse to the uniaxial strain

⇒ Contraction creates a (-) strain:

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

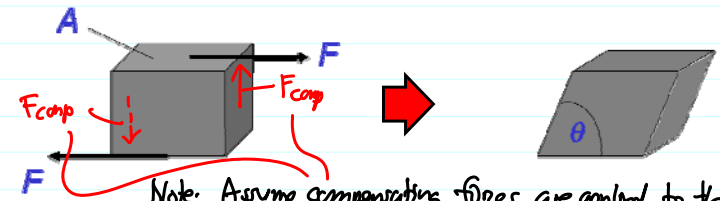
ν: Poisson ratio [unitless]

↳ typical values: 0 → 0.5

⇒ inorganic solids: 0.2 → 0.3

⇒ elastomers (e.g., rubber): ~0.5

Shear Stress & Strain (2D)



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

Shear Stress: $\left\{ \begin{array}{l} \text{Force per unit area} \\ \text{Parallel to the Surface} \end{array} \right\} = \tau = \frac{F}{A}$ [Pa]

Generates a shear strain:

$$\text{Shear Strain} = \theta = \frac{\tau}{G}$$

$G \Rightarrow$ shear modulus

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