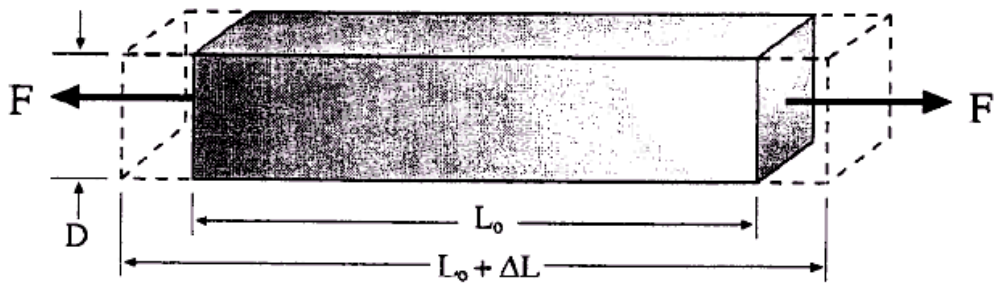
Micro-Electro-Mechanical Systems (MEMS) Fabrication

- **Fabrication Considerations**
  - Stress-Strain, Thin-film Stress, Stiction
- **Special Process Modules for MEMS**
  - Bonding, Cavity Sealing, Deep RIE, Spatial forming (Molding), Layer Transfer
- **Principle of Sensing and Actuation**
  - Beam and Thin-Plate Deflections
- **Micromachining Process Flows**
  - MEMS-IC Integration
  - BioMEMS, PhotoMEMS

Axial Stress and Strain

Stress σ: force per unit area acting on a material
[unit: Newtons/m^2 (pascal)]

$\sigma = F/A$, A = area
$\sigma > 0$ tensile
$\sigma < 0$ compressive



Strain ε: displacement per unit length (dimensionless)
$\varepsilon = \Delta L / L_o$

* Figure assumes there is no change in lateral dimensions

Young's Modulus of a material

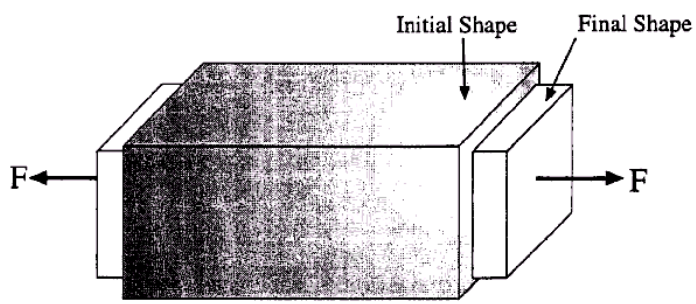
$$E = \sigma / \varepsilon \quad [\text{ in } N/m^2 \text{ (Pascal) }]$$

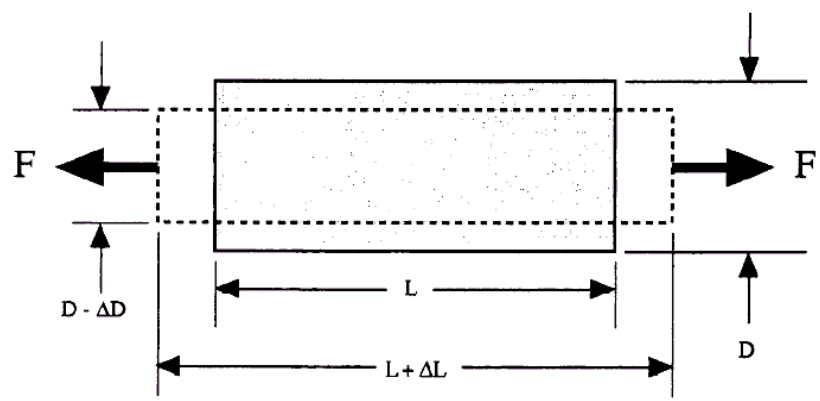
	E in GPa (1E9 N/m2)
Si	190
SiO2	73
Diamond	1035

Poisson's Ratio ν

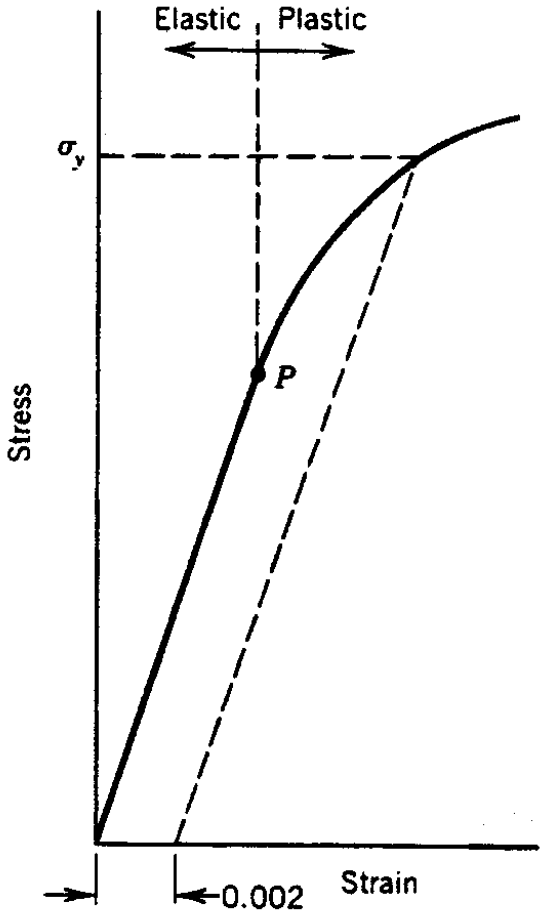
$$\nu = \frac{\text{transverse strain}}{\text{longitudinal strain}} = -\frac{\varepsilon_t}{\varepsilon_a} = -\frac{\frac{\Delta D}{D_o}}{\frac{\Delta L}{L_o}}$$

$\nu = 0.5 \Rightarrow$ volume conserved





Stress-Strain Characteristic



For low stress:

- material responds in elastic fashion
- (Hooke's Law) stress/strain = constant

σ_y = yield stress

Material	Yield Strength (MPa)
Al	170
Steel	2,100
W	4,000
Si	7,000
Quartz (SiO_2)	8,400
Diamond	53,000

Ultimate stress - material will break;
For Si (brittle) ultimate stress ~ yield stress

Mechanical Properties of Microelectronic Materials

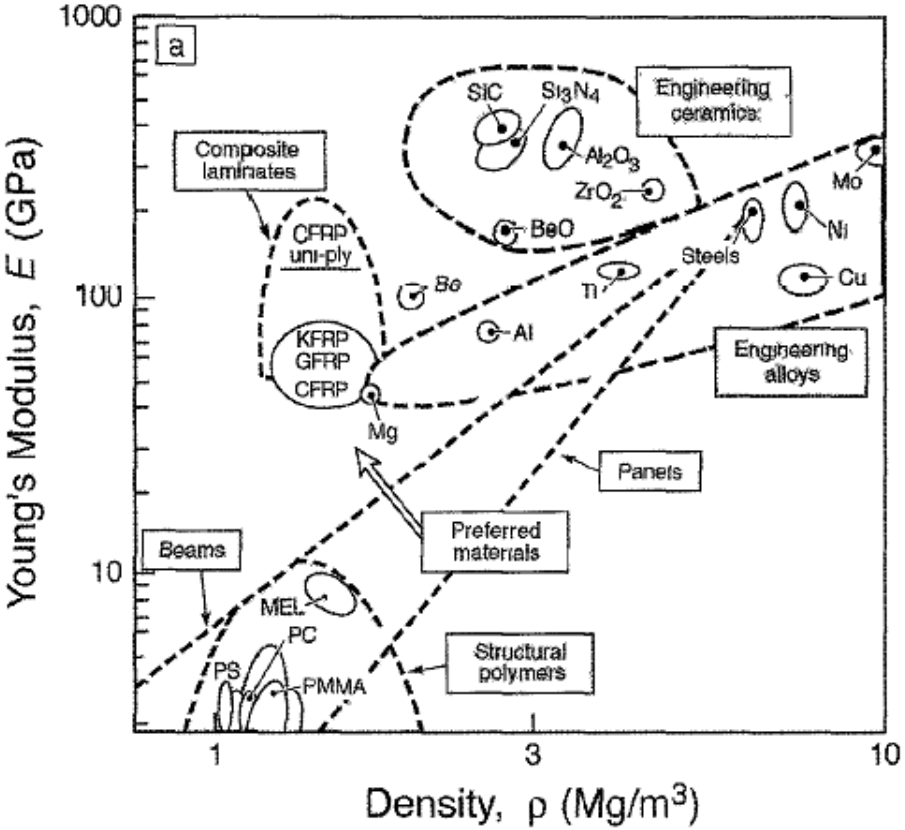
	E(GPa)	ν	α(1/°C)	σ_0
Substrates				
Silicon	190	0.23	2.6×10^{-6}	—
Alumina	~415	—	8.7×10^{-6}	—
Silica	73	0.17	0.4×10^{-6}	—
Films				
Polysilicon	160	0.23	2.8×10^{-6}	Varies
Thermal SiO_2	70	0.20	0.35×10^{-6}	Compressive, e.g., 350 MPa
PECVD SiO_2	—	—	2.3×10^{-6}	—
LPCVD Si_3N_4	270	0.27	1.6×10^{-6}	Tensile
Aluminum	70	0.35	25×10^{-6} (high!)	Varies
Tungsten (W)	410 (stiff!)	0.28	4.3×10^{-6}	Varies
Polyimide	3.2	0.42	$20–70 \times 10^{-6}$ (very high)	Tensile

Note: E = Young's modulus, ν = Poisson ratio, α = coefficient of thermal expansion, σ_0 = residual stress.

Source: Based on lecture notes from Senturia, S.D. and R.T. Howe.

Material Choices

(a) Stiffness



(b) Strength

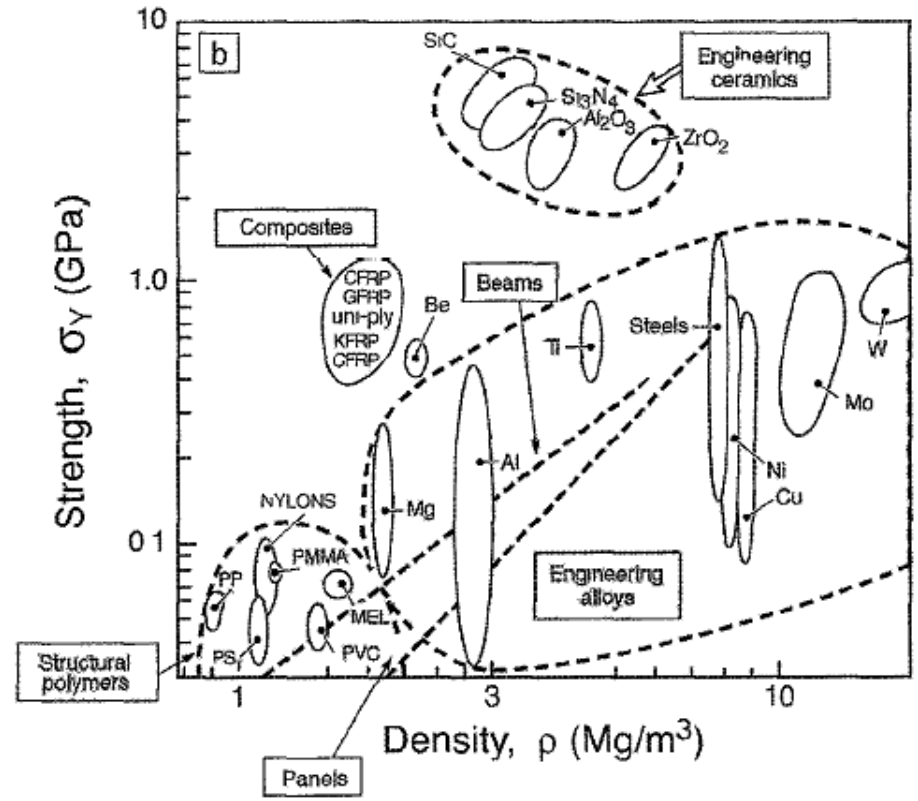
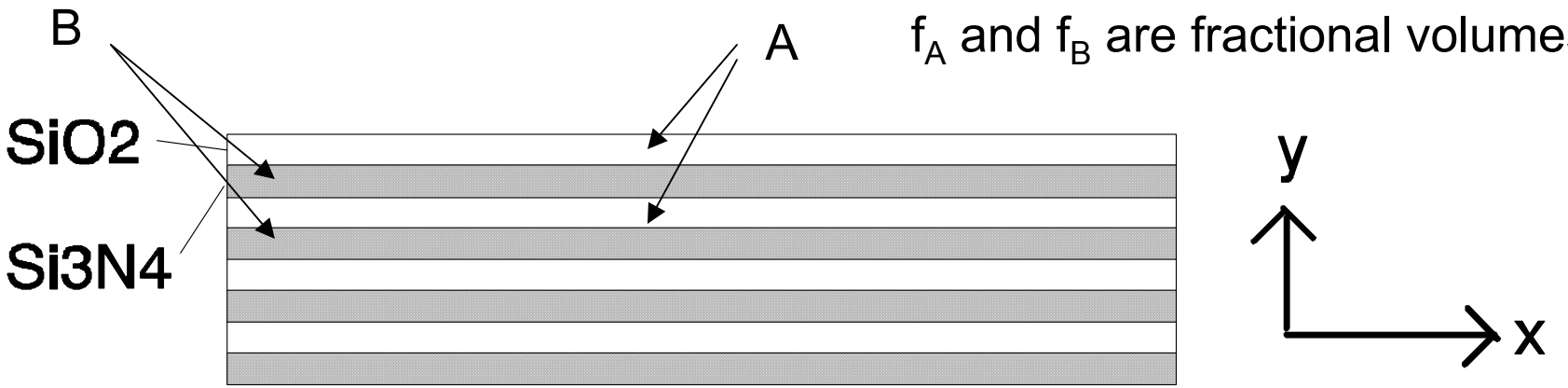


Figure 1 Property diagrams used for materials selection (a) stiffness and (b) strength. The diagonal dotted lines indicate equivalent performance for lightweight beams and panels subjected to bending, using mild steel as the reference material. Materials that reside farthest away from these lines, in a vector toward the top left of the diagrams, are preferred The ceramics are discounted because of their brittle-failure susceptibility. CFRP is carbon-fiber reinforced polymer, GFRP is graphite-fiber reinforced polymer, and KFRP is Kevlar-fiber reinforced polymer PP is poly(propylene), PS is polystyrene, PVC is poly(vinyl chloride), PMMA is poly(methyl methacrylate), and MEL is melamine

Effective Young's Modulus of Composite Layers



f_A and f_B are fractional volumes

Stressing along the x-direction, all layers take the same strain

$$E_x = f_A E_A + f_B E_B$$

* Material with larger E takes the larger stress

Stressing along the y-direction, all layers take the same stress

$$E_y = 1 / [f_A / E_A + f_B / E_B]$$

* Material with smaller E takes the larger strain

Poly-Si as a Structural Material in MEMS

- Stronger than steel?

  (Not quite, but close: poly ~ 1.6E11Pa, steel 1.6E11 to2E11Pa)

- Does not readily fatigue

- Directly compatible with modern IC fabrication processes

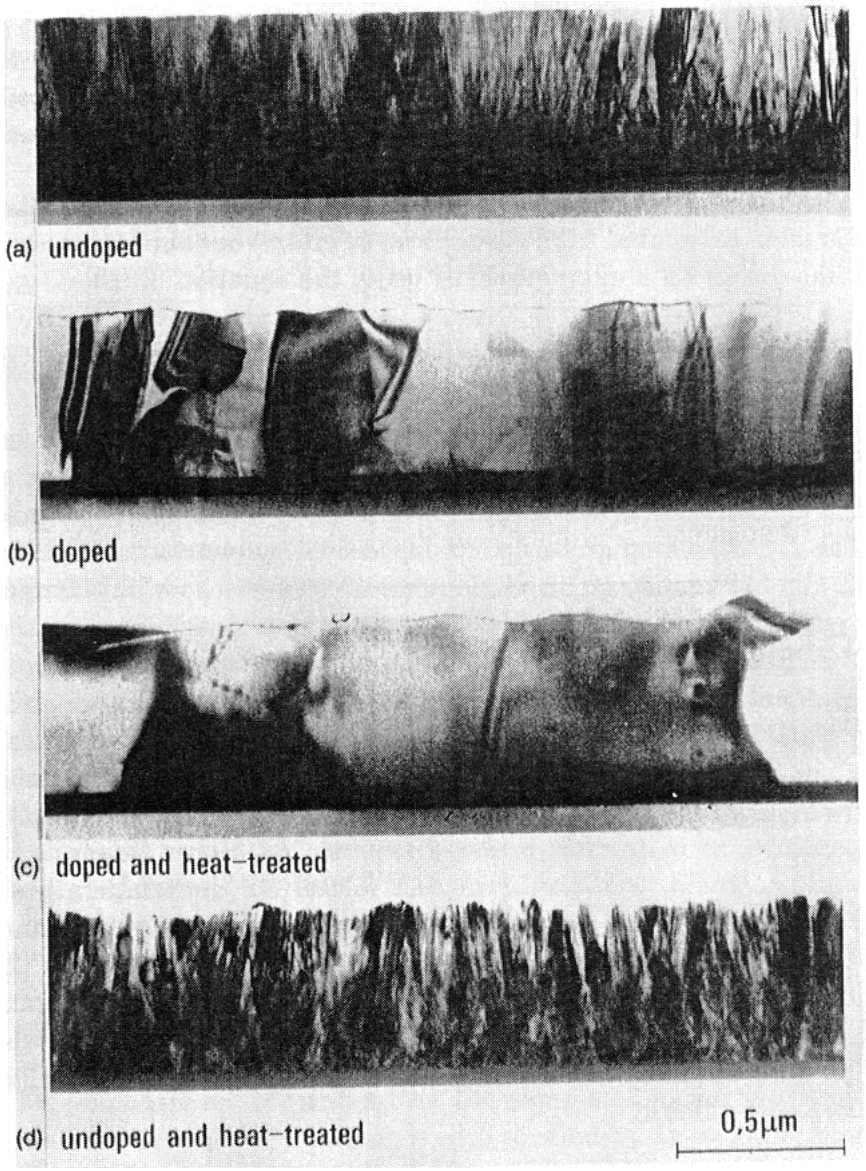
  => batch fabrication in foundry

  --> high-volume production at low unit cost

- Mechanical properties depend on film microstructure

  – microstructure determined by fabrication process (deposition and annealing conditions)

Poly-Si Structure



- Effect of substrate:

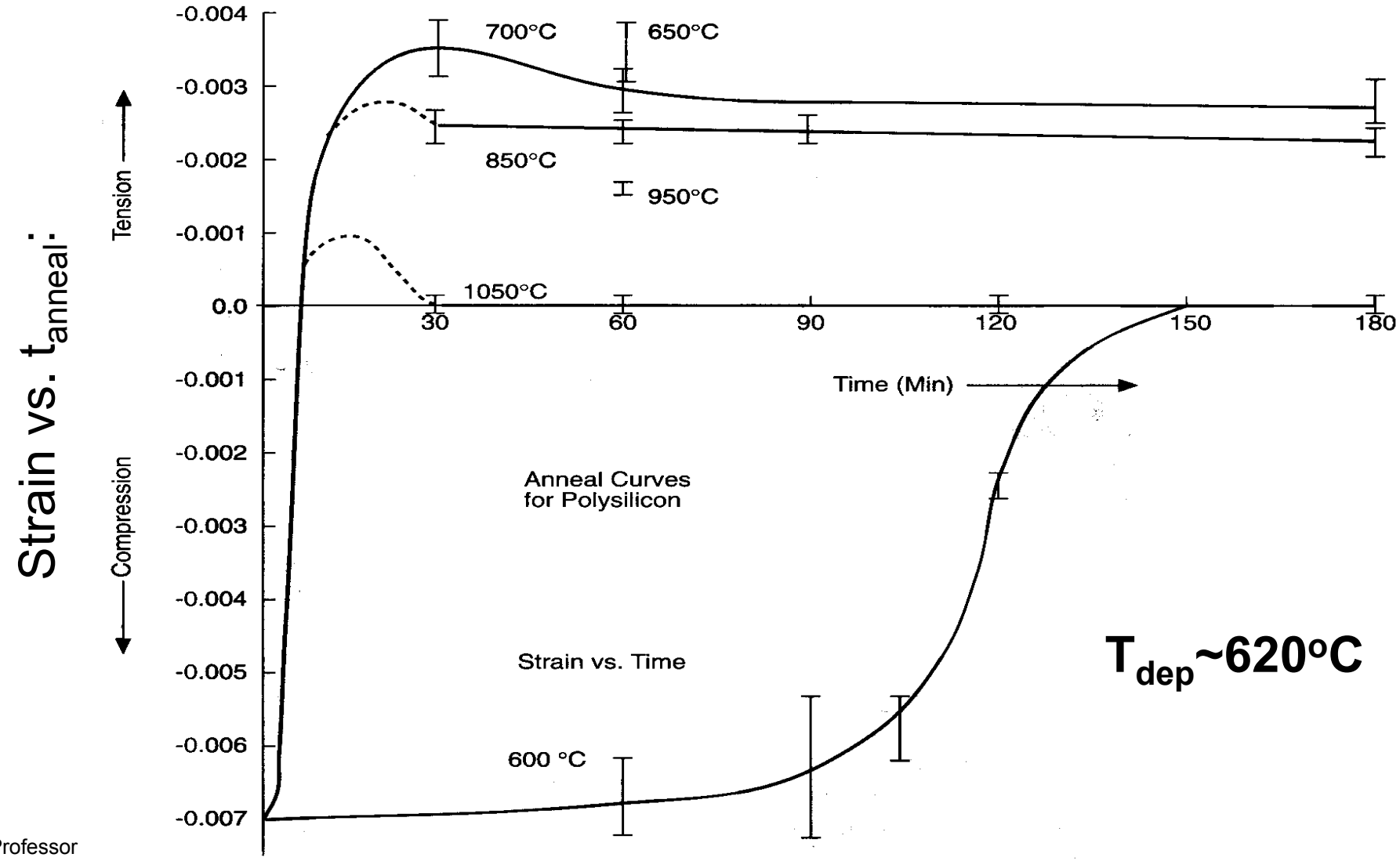
  single-crystal substrate (clean surface)
  ⇒ epitaxial layer

  amorphous substrate
  ⇒ polycrystalline film

- Average grain size depends on deposition & annealing conditions

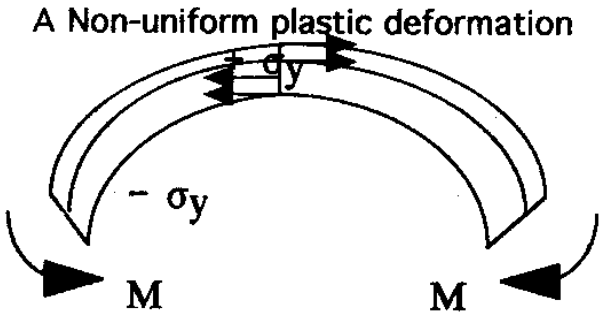
Stress in LPCVD Poly-Si Films

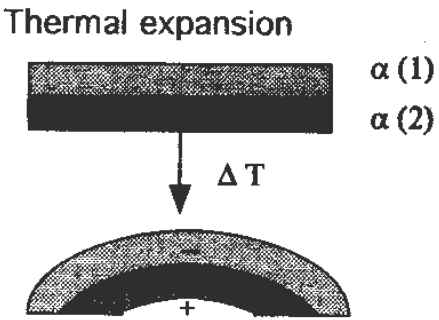
- Stress varies significantly with process conditions
  - strong correlation between microstructure and stress



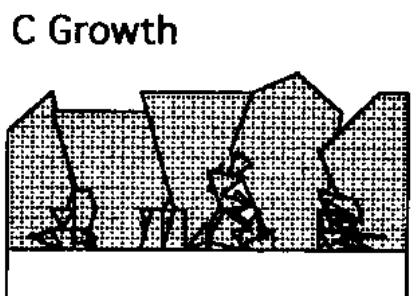
Origins of Thin-film Stress

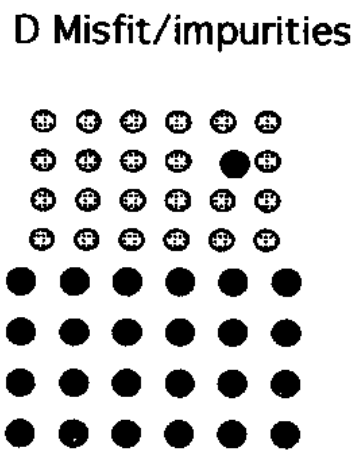
- **Extrinsic**
  - Applied stress
  - Thermal expansion
  - Plastic deformation

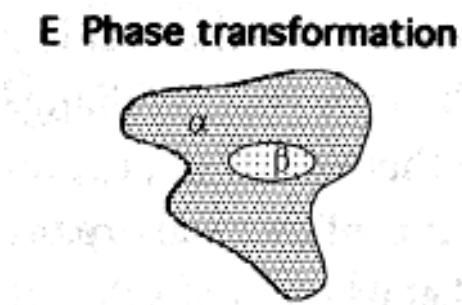




- **Intrinsic**
  - Growth morphology
  - Lattice misfit
  - Phase transformation

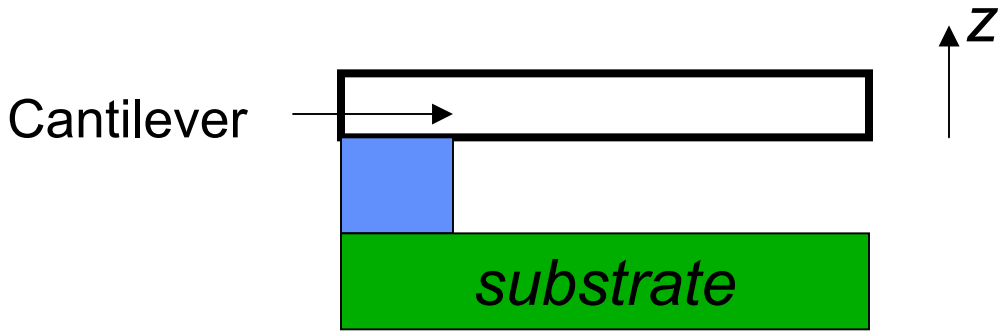




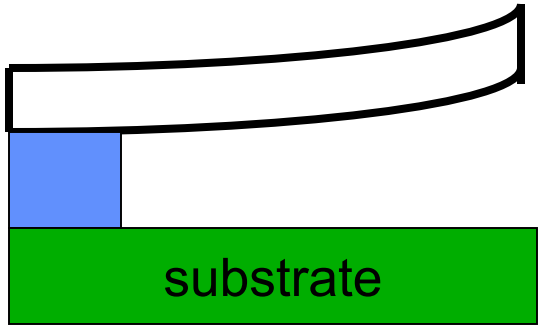


$$\sigma_{tot} = \sigma_{th} + \sigma_{int} + \sigma_{ext}$$

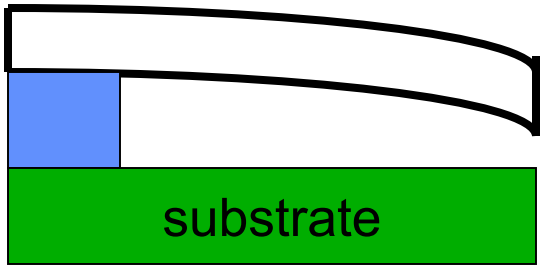
Effect of Thin-film Stress Gradient on Cantilever Deflection



(1) No stress gradient along z-direction



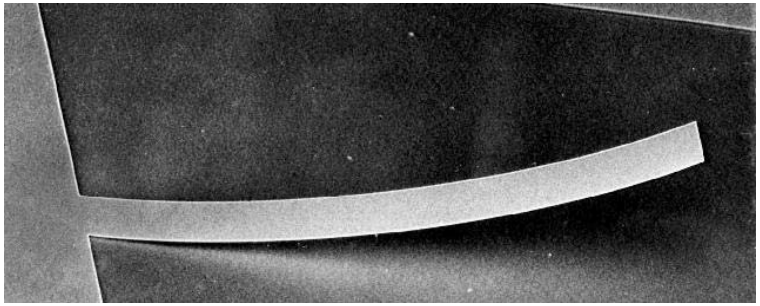
(2) Higher tensile stress near top surface of cantilever before release from substarte



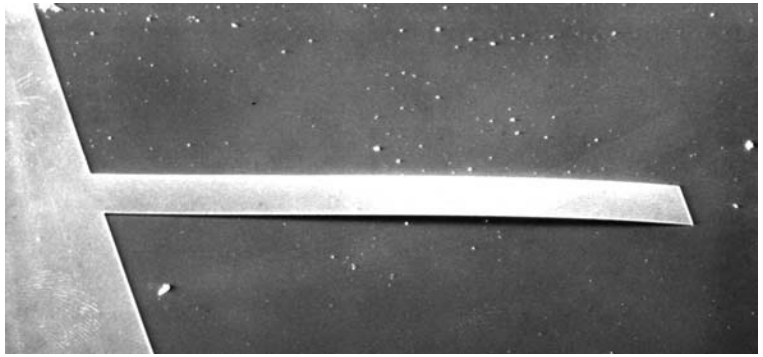
(3) Higher compressive stress near top surface of cantilever before release from substrate

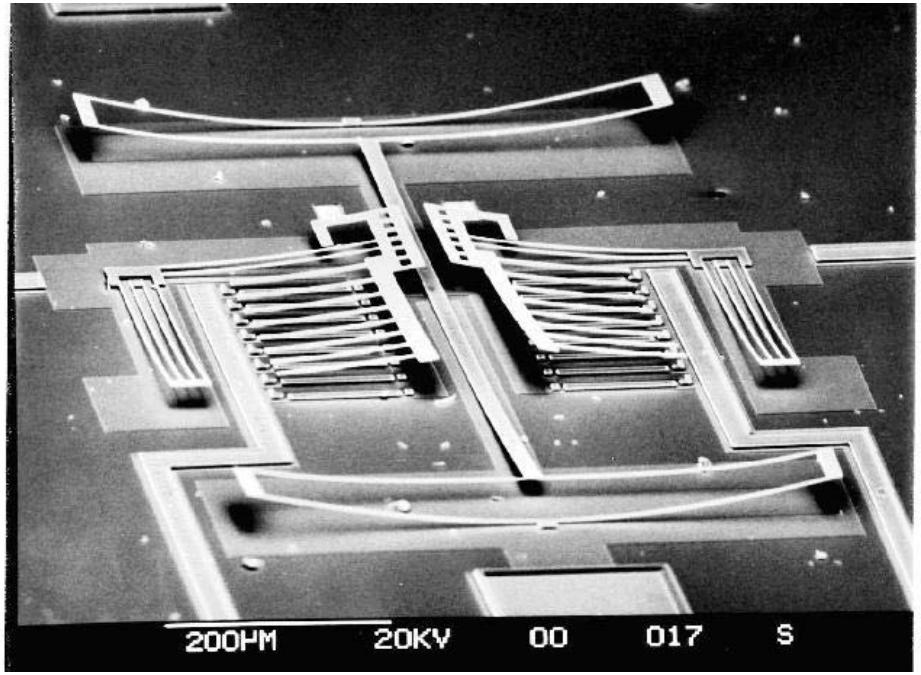
Thin-films Stress Gradient Effects on MEMS Structures

Top of beam more tensile



Top of beam more compressive





Use of Stressed Composite layer to reduce bending

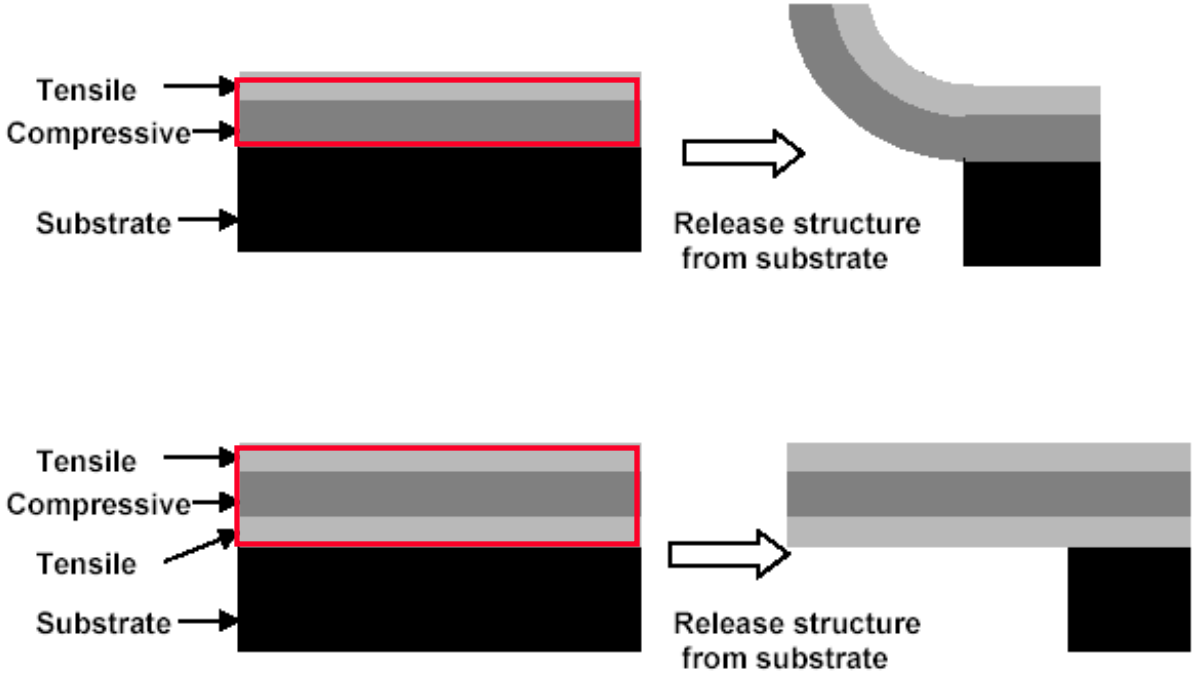
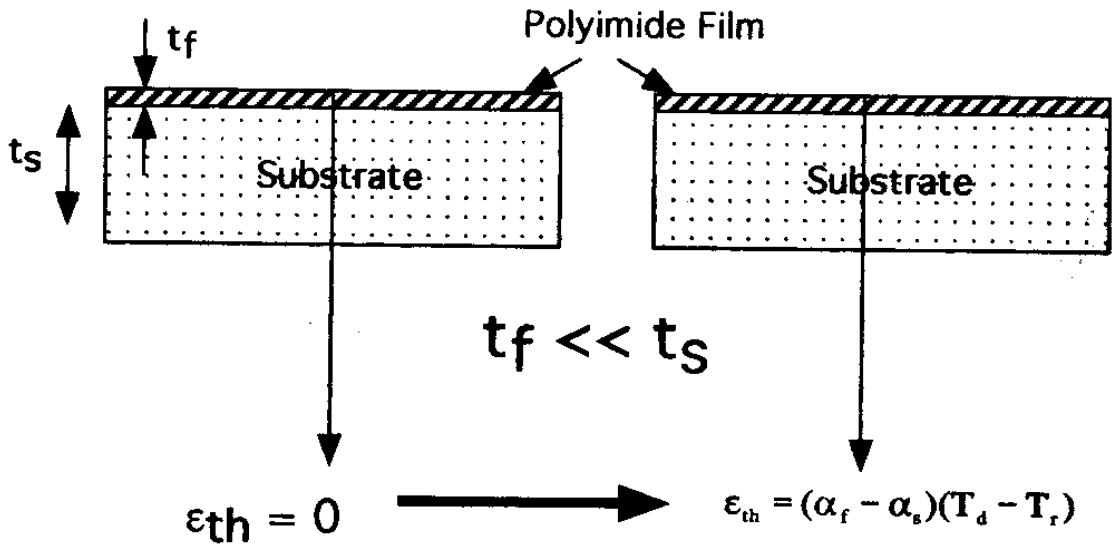


Figure 16: Top, a bi-layer of tensile and compressive layers, showing undesirable curvature upon release from substrate. Bottom, a stress match structure showing little stress induced bending.

Thermal Strain

$$\varepsilon_{th} = \int(\alpha_f(T) - \alpha_s(T))dT = (\alpha_f - \alpha_s)(T_{Dep} - T_{Room})$$

(deposition temperature) $T = T_d$ → (room temperature) $T = T_r$



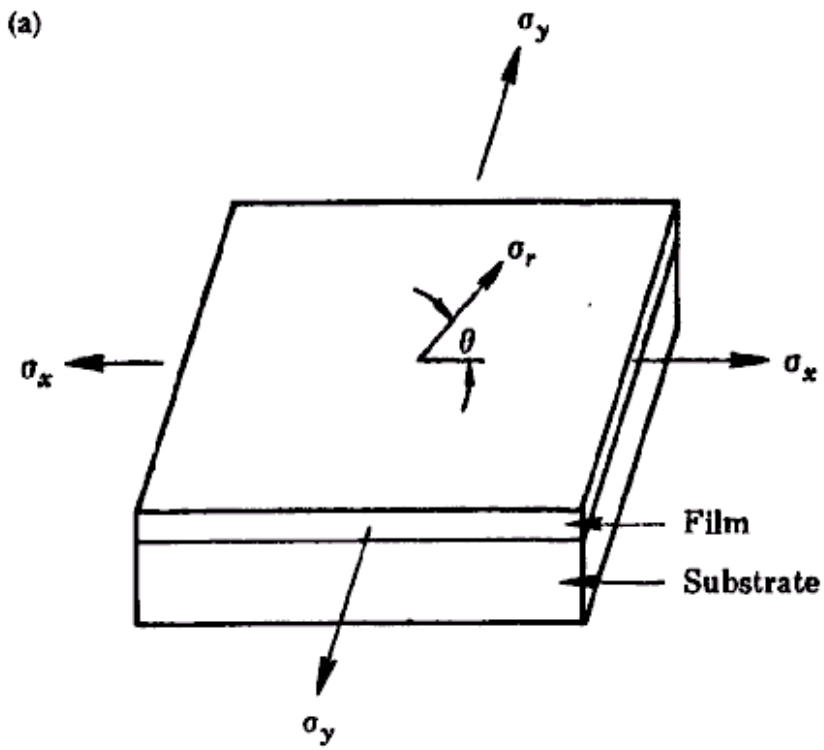
$\alpha_f > \alpha_s$: tension (polyimide on Si)

$\alpha_f < \alpha_s$: compression (SiO_2 on Si)

Biaxial Stress in Thin Film on Thick Substrate

No stress occurs in direction normal to substrate (σ_z=0)

Assume isotropic film ($\varepsilon_x=\varepsilon_y=\varepsilon$ so that $\sigma_x=\sigma_y=\sigma$)



$$\sigma = \frac{E}{1-\nu}\varepsilon$$

* See derivation in EE143 handout
(Tu et al, Electronic Thin Film Science)

Substrate Warpage

Radius of Curvature of warpage

$$r = \frac{E_s \times t_s^2}{(1-\nu)_s \times 6 \times \sigma_f \times t_f}$$

"Stoney Equation"

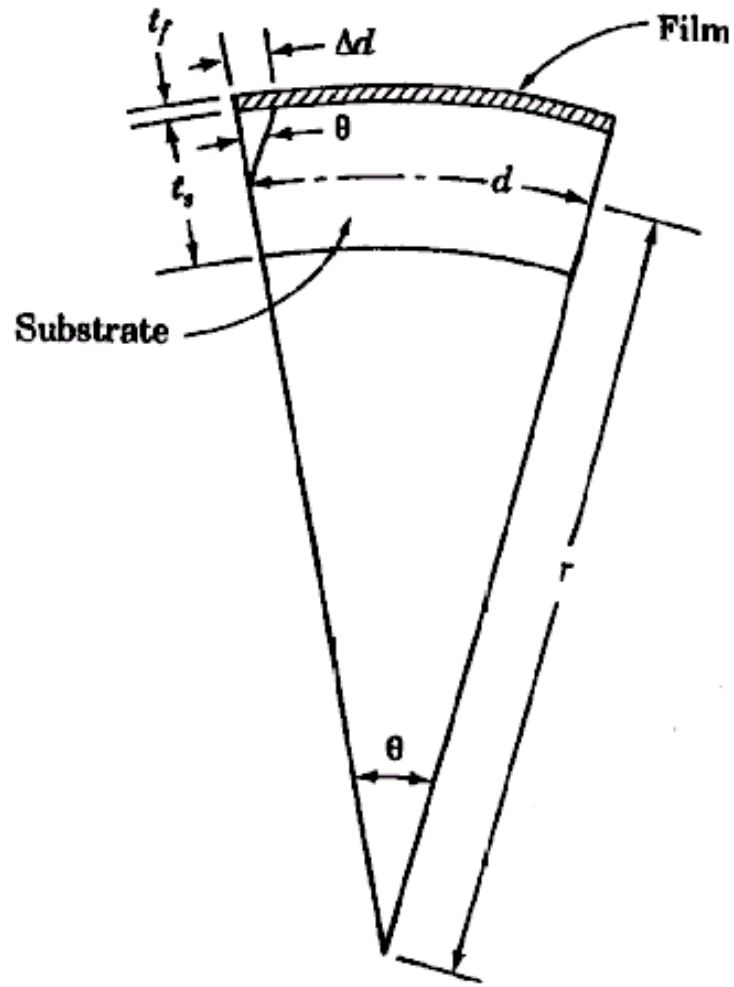
t_s = substrate thickness

t_f = film thickness

E = Young's modulus of substrate

n = Poisson's ratio of substrate

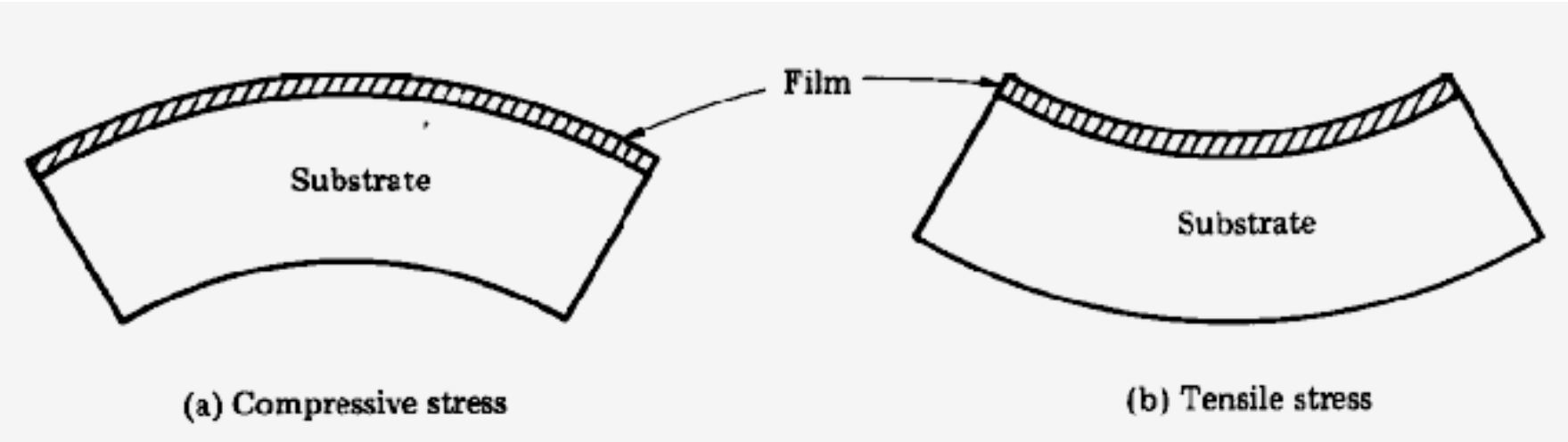
G. Stoney, "The tensions of metalic films deposited by electroplating,' Proc. Roy. Soc. Lond. A82, 1909



See handout for derivation

Typical Thin Film stress: 10^8 to $5x10^{10}$ dynes/cm^2 (10^7 dynes/cm^2 = 1 MPa)

- Compressive (ε <0)
  - film tends to expand upon release
    --> buckling, blistering, delamination
- Tensile (ε >0)
  - film tends to contract upon release
    --> cracking if forces > fracture limit



Example: Al Deposition

500 nm Al on a 500 μm wafer with ΔT=400 °C

Stress and Strain

$\varepsilon_f = (\alpha_f - \alpha_s)\Delta T = (25 - 2.6)x10^{-6} \times 400 = 8.96x\ 10^{-3}$

$\sigma_f = E_f \times \varepsilon_f = 70\ GPa \times 8.96x\ 10^{-3} = 6.3 \times 10^8\ N/m2$

Wafer Radius

$$r = \frac{E_s \cdot t_s^2}{(1-\upsilon)_s \cdot 6 \cdot \sigma_f \cdot t_f}$$

ν_{si} = 0.272
E_{si} = 190 GPa

$t_f = 0.5 \times 10^{-6}m$; $t_s = 5 \times 10^{-4}m$

$$r = \frac{1.9x10^{11} \cdot (5x10^{-4})^2}{(1-0.272) \cdot 6 \cdot 6.3x10^8 \cdot 5x10^{-7}} = 34.5m$$

Example: CVD Oxide and Nitride Stresses

A 500 µm thick wafer originally has a radius of curvature of +300m.

A 300 nm oxide is deposited and r = 200 m.

The oxide stress is **compressive** since r changes from 300m to 200m (Si wafer more curved)

$$\sigma_f = \frac{1.9x10^{11} \cdot (5x10^{-4})^2}{(1-0.272)\cdot 6\cdot 3x10^{-7}}\left(\frac{1}{300}-\frac{1}{200}\right) = -6.05x10^7\, N/m^2$$

A 600nm nitride is deposited and r = 240 m.

Use t_f (total) = 9 x 10^{-7} m

$$\sigma_f = \frac{1.9x10^{11} \cdot (5x10^{-4})^2}{(1-0.272)\cdot 6\cdot 9x10^{-7}}\left(\frac{1}{300}-\frac{1}{240}\right) = -1.0x10^7\, N/m^2$$

$$\sigma_n = \sigma_f - \sigma_{ox} = (-1.0-(6.05))\ x\ 10^7 = 5.05\ x\ 10^7 N/m^2$$

The wafer is less curved than with oxide alone .
Therefore, the nitride film has a **tensile** stress.
However, the total stress of the dual films is still **compressive** since r = 240 m and is still smaller than the original curvature of 300 m

Deflection of Microstructures - Thin Plate approximation

Cantilever Beam with length L, width w, and thickness t

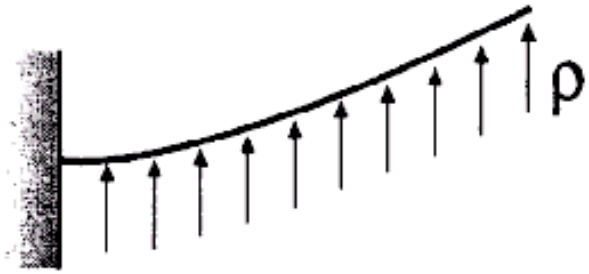
* Assumes L >> w and t, small deflection approximation

Point Load

$$y(x) = \frac{F}{6EI}\left(3x^2L - x^3\right)$$

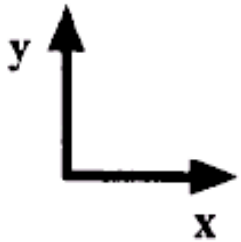
$$\sigma_{max} = \frac{FLt}{2I}$$

Distributed Load



$$y(x) = \frac{\rho x^2}{24EI}\left(6L^2 - 4Lx + x^2\right)$$

$$\sigma_{MAX} = \frac{\rho L^2 t}{4I}$$



where

L = length of beam (in meter)

t =thickness of beam (in meter)

I = bending moment of inertia

= $wt^3/12$ (in $meter^4$)

F in Newton

ρ in N/meter

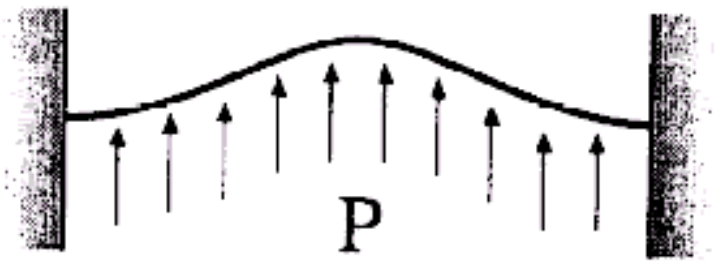
For reference only

Deflection of Circular thin membrane

r = radius, t=thickness, P= uniform pressure (in N/m^2)

For **small** deflections, maximum deflection in center

$$\delta_{max} = \delta_{center} = \frac{3Pr^4(1-\nu^2)}{16Et^3}$$



A more accurate relationship

the deflection of the center can be related to the pressure, P, and other physical (design) parameters by,

$$\frac{Pr^4}{Eh^4} = \frac{16}{3(1-\nu^2)}\left(\frac{y}{h}\right) + \frac{7-\nu}{3(1-\nu)}\left(\frac{y}{h}\right)^3$$

where,
P = applied pressure, in Pa
r = diaphragm radius, in m
E = Young's modulus, in Pa
h = diaphragm thickness, in m
ν = Poisson's ratio
y = deflection at the diaphragm's center, in m

For reference only

Fundamental mode resonant frequency of a beam

$$F_o = 0.216\,(t/L^2)\,(E/\rho)^{1/2}$$

See Kovacs pp. 201 and work backwards.

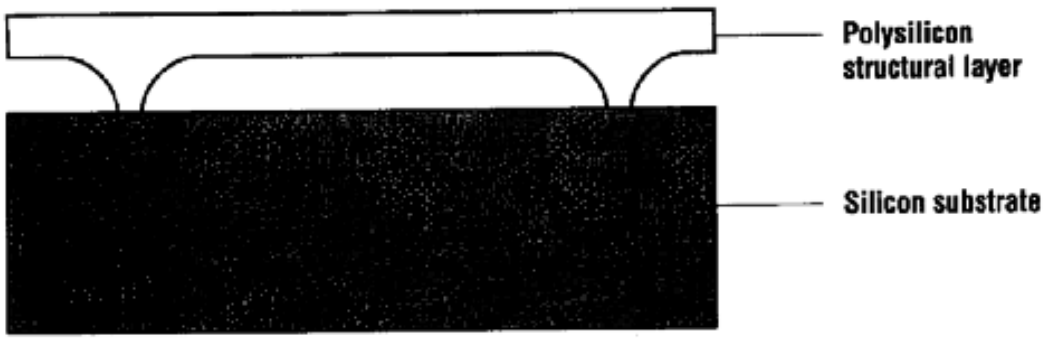
where L=length, t =thickness, E=Young's modulus, ρ =density

Example Poly-Si beam , 1000 um long, 100 um wide, 3 um thick

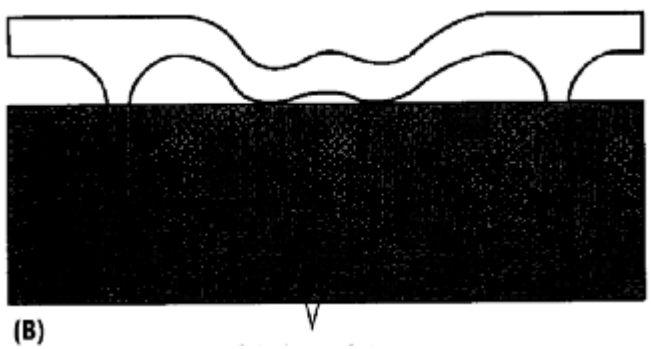
$\rho = 2.3\ gm/cm^3$, $E = 190GPa = 190 \times 10^9\ N/m^2$

$F_o = 5.89\ kHz$

Stiction



Poly-Si beam released without stiction after sacrificial layer etching



Poly-Si beam
with two stiction points
after sacrificial layer etching

As the etching liquid is removed during a dehydration cycle, a liquid bridge is formed between the suspended member and the substrate. An attractive capillary force which may be sufficiently strong to collapse it. Even after drying, the inter-solid adhesion will not release the structure.

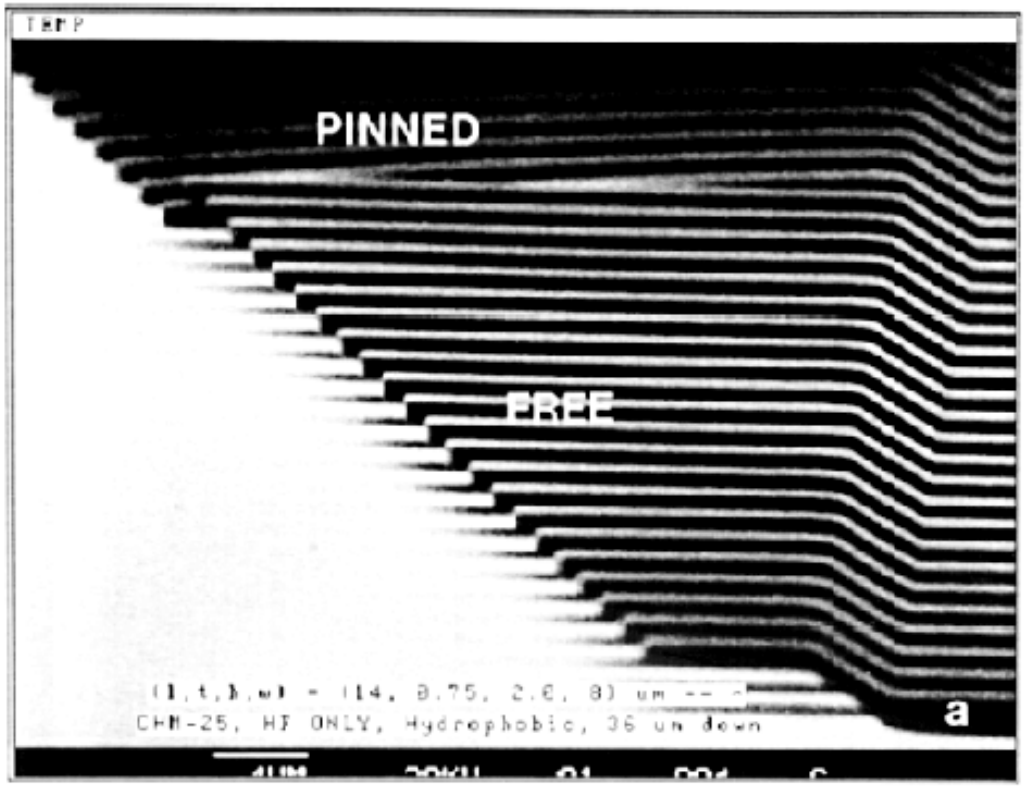


Fig. 1. SEM of micromachined polysilicon cantilever beams of increasing length. The photograph shows clearly the onset of the pinning state for beams larger than 34 μm.

Solutions

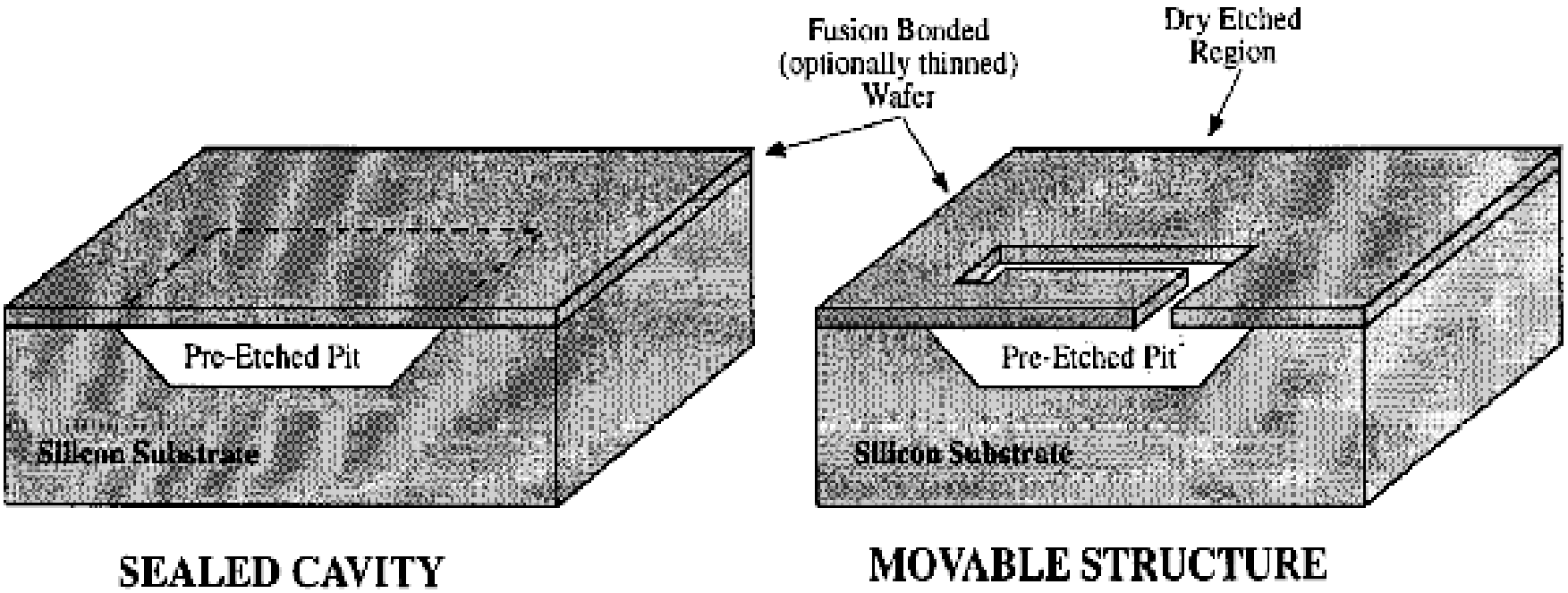
- Dry etching (e.g. XeF_2)
- Super-critical drying
  (e.g. rinse solution gradually replaced by liquid CO_2 under high pressure)
- Hydrophobic Coatings
- Use textured surfaces

See C. H. Mastrangelo, “Adhesion-Related Failure Mechanisms in Micromechanical Devices”, Tribology Letters, 1997

Wafer Bonding

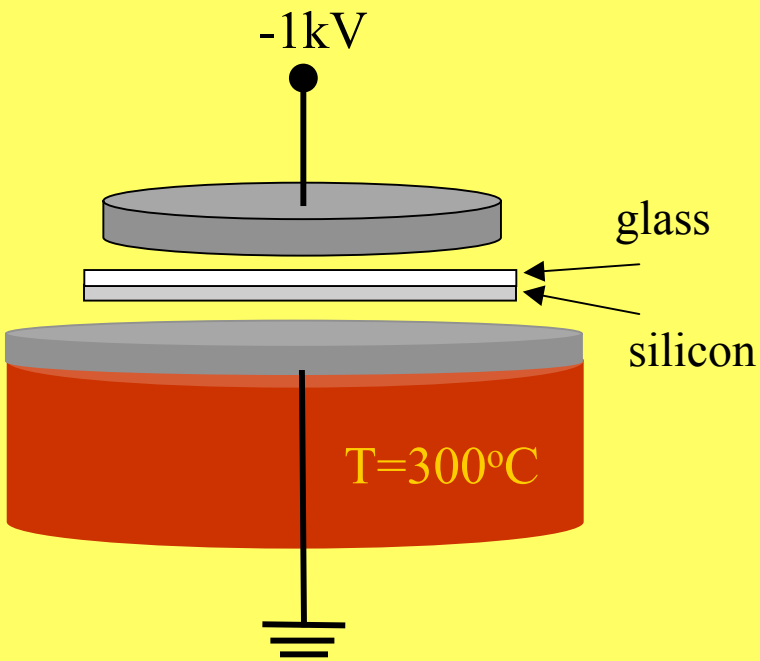
- Anodic bonding (E-field enhanced)
- Adhesive bonding (molten metal, epoxy)
- Direct wafer bonding

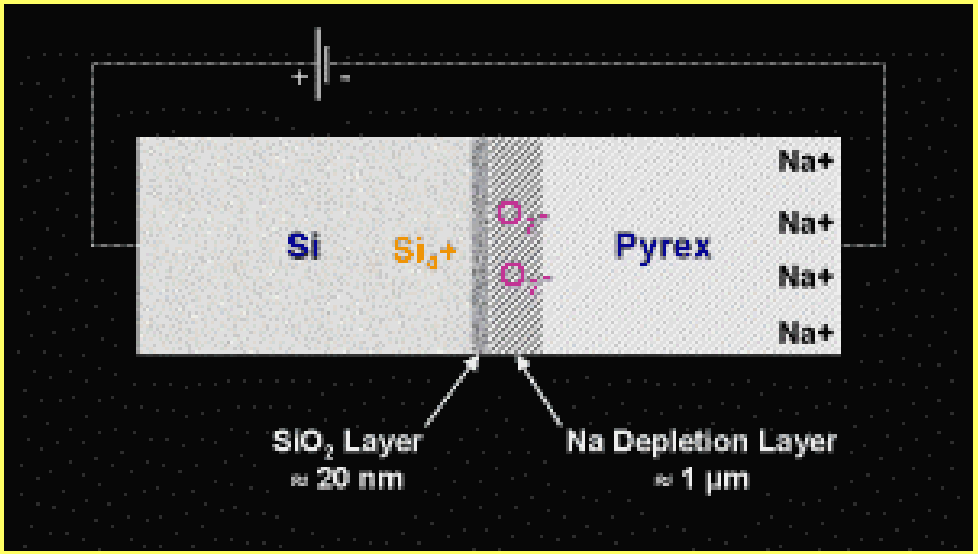
*can produce unique MEMS structures



Anodic Bonding

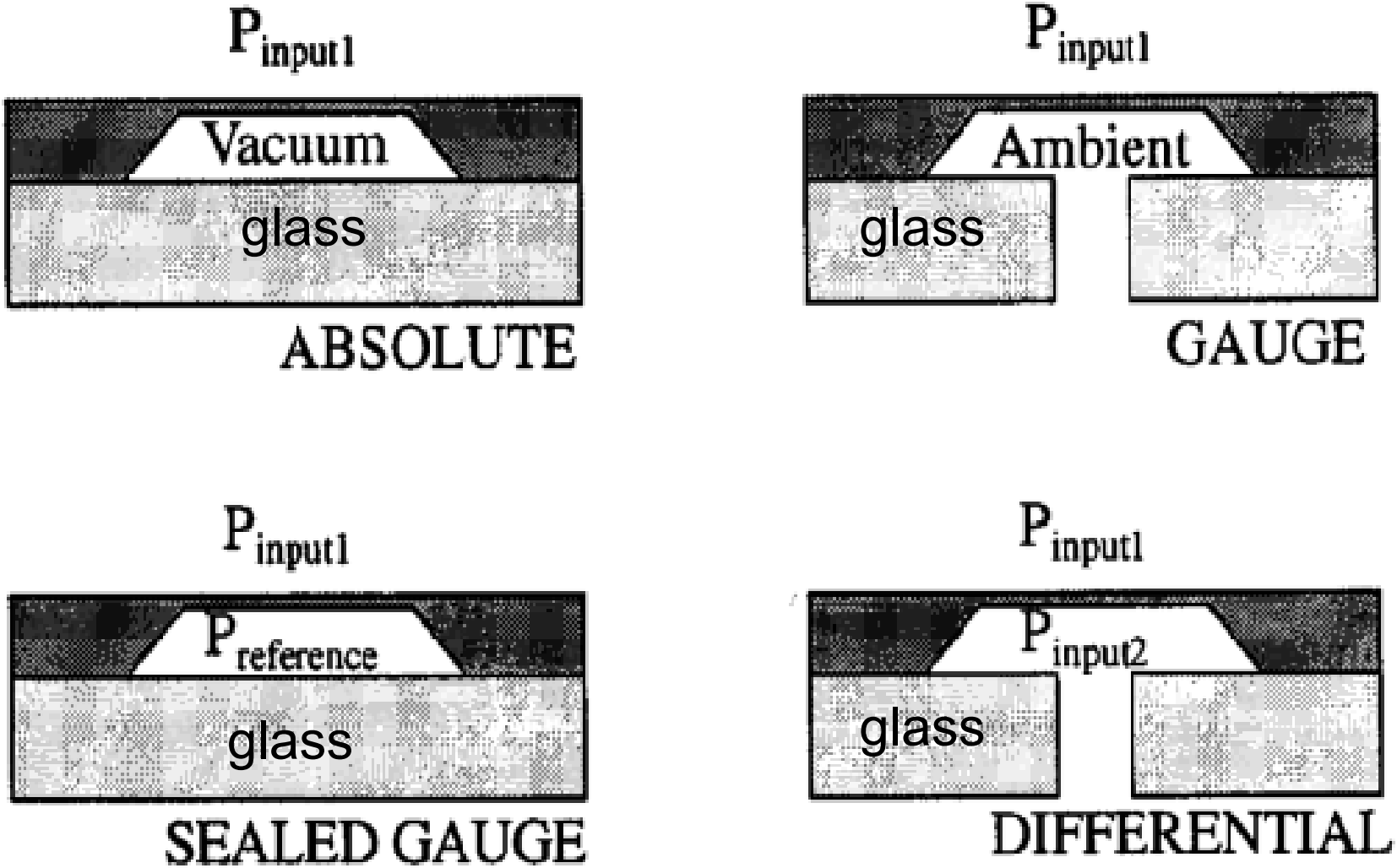
Anodic Bonding: Low to moderate Temp, Rapid Process





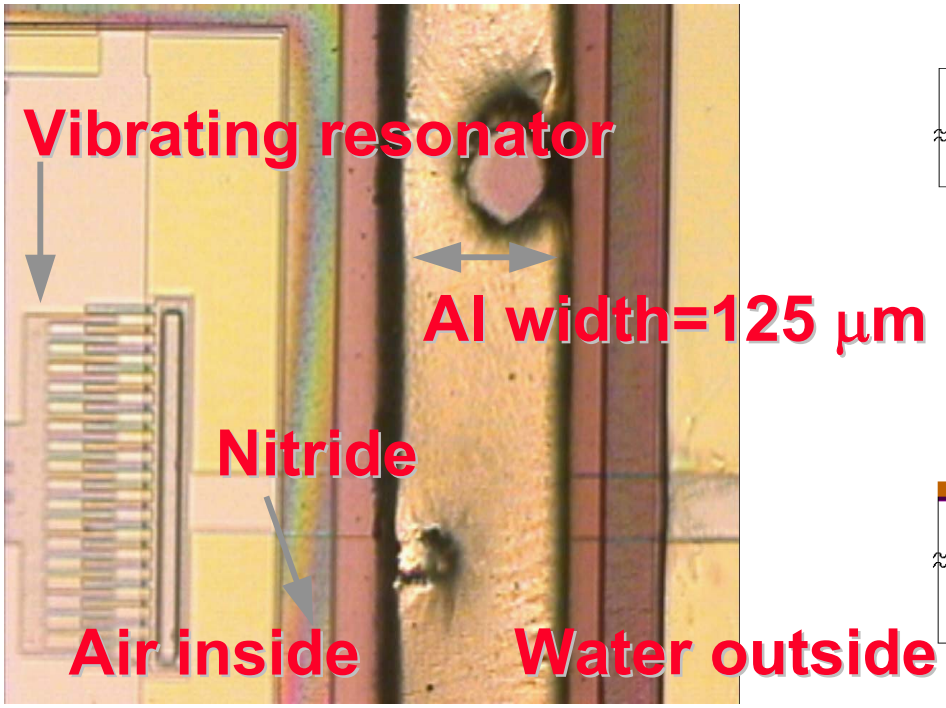
* works mainly with alkaline-containing glass

Example of Anodic Bonding
Pressure Transducer using membrane deflection

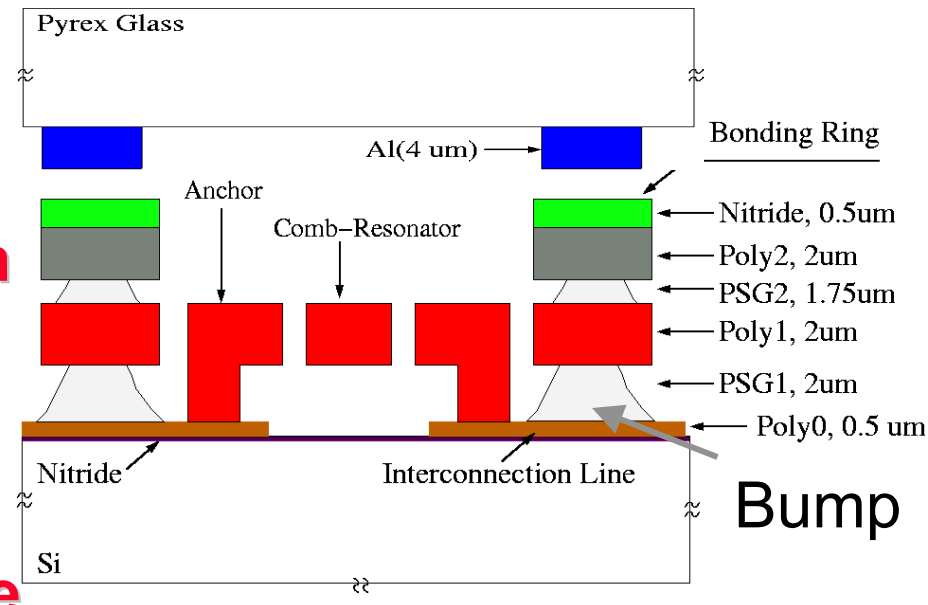


Liquid Phase Bonding

- **After RTP for 750°C/10secs**
- **Al sealing ring width=125μm**
- **Water is blocked outside**
- **Al does not wet glass well. Add Cr adhesion layer between Al and glass**



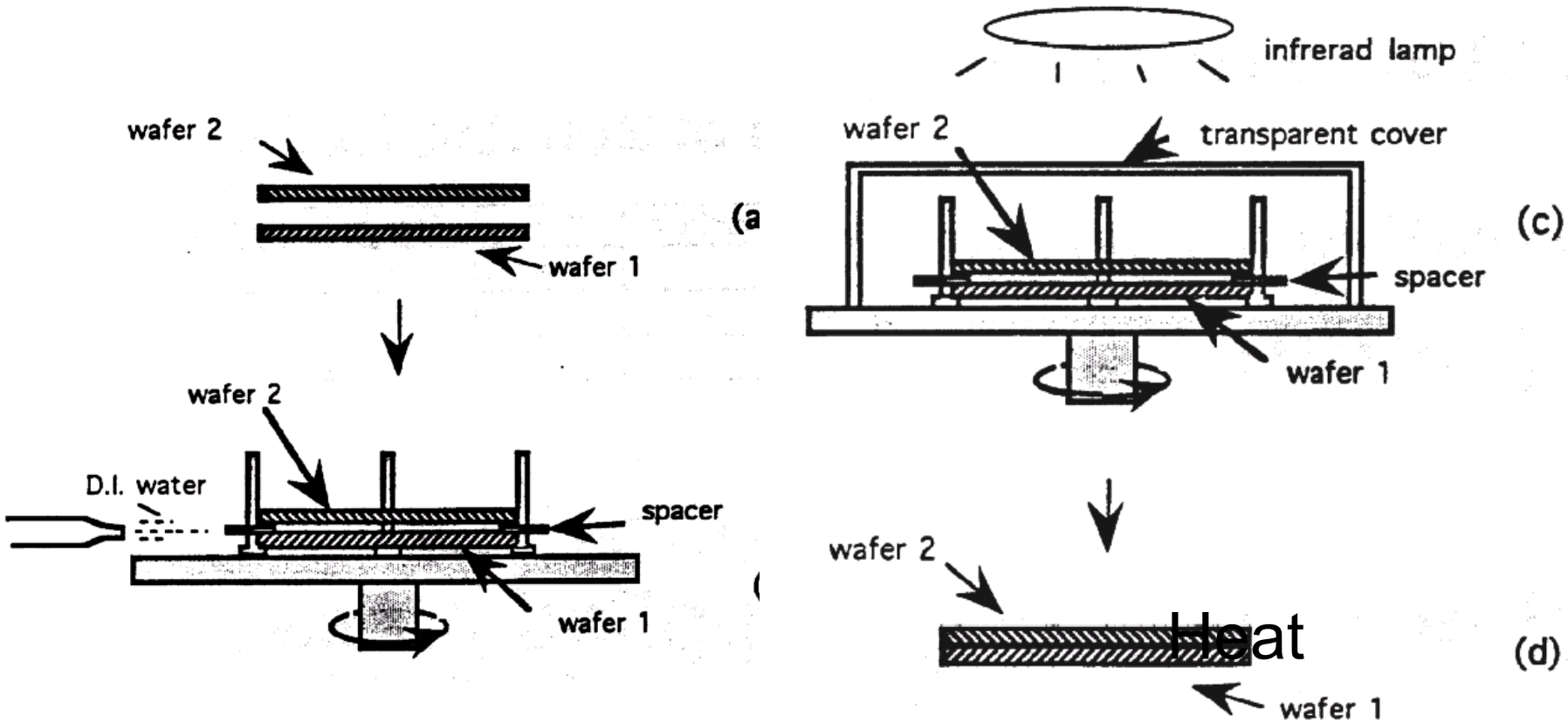
Top view



Cross-section

Chiao and Lin, UCB

Direct Bonding



Examples: Si-Si bonding and Si-SiO2 bonding

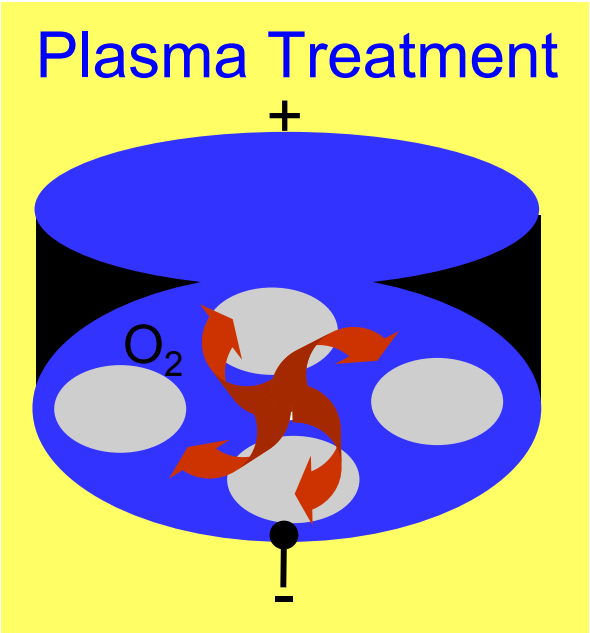
Direct Bonding

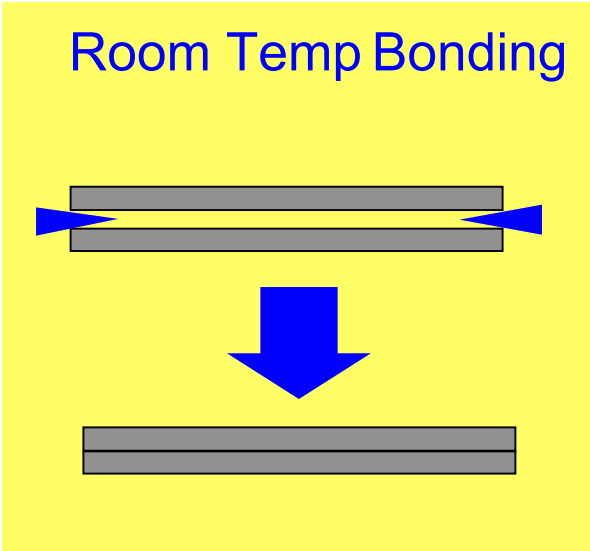
Gases Used:
O_2, He, N_2, Ar

Pressure
200mTorr

Power
50W-300W

Time
15-30 seconds



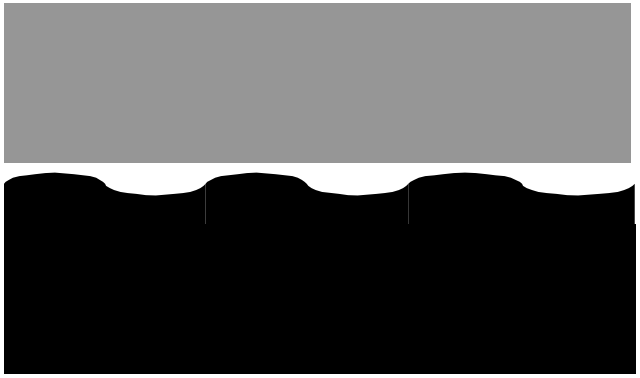


Chemical Cleaning:
Piranha + RCA

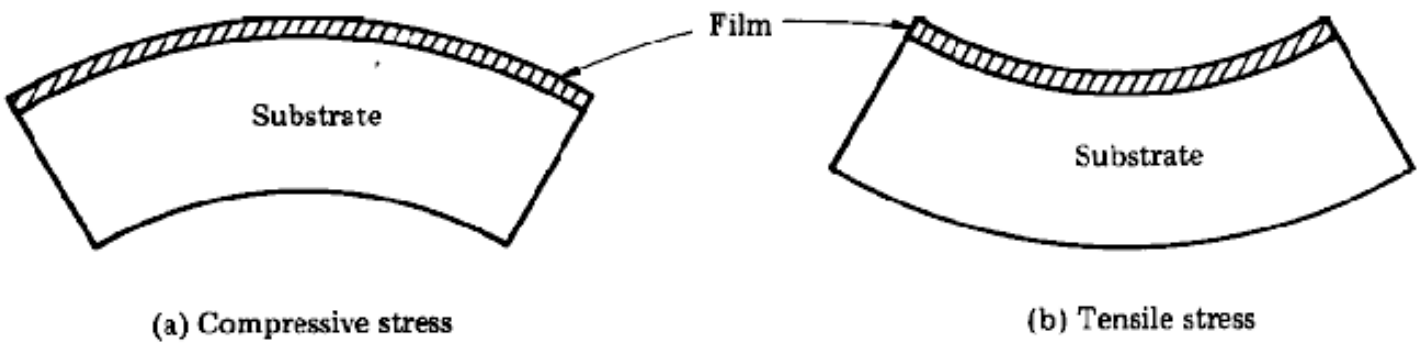
Bond Strengthening Annealing

Requirements of Direct Bonding Surfaces

- Surface micro-roughness ~ nm



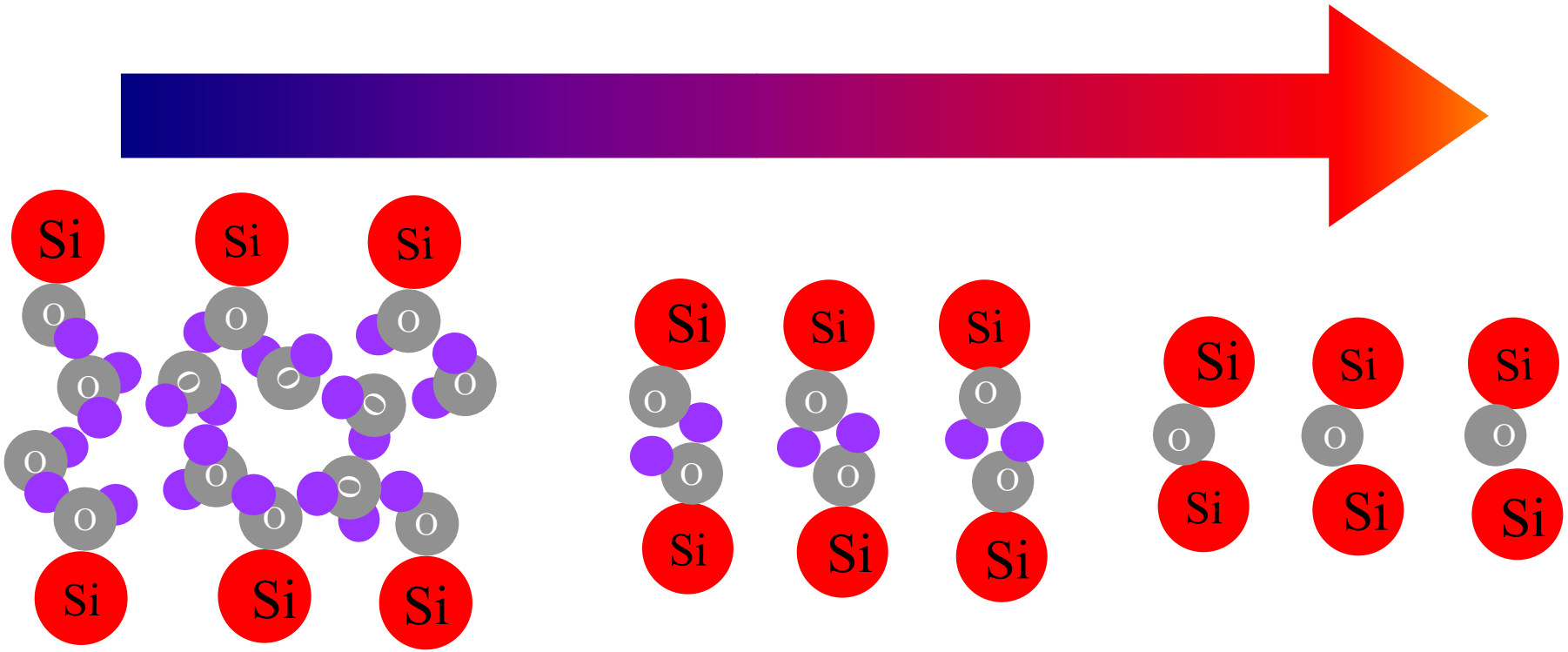
- No macroscopic wafer warpage



- Minimal particle density and size: 1μm particle will give 1000μm void

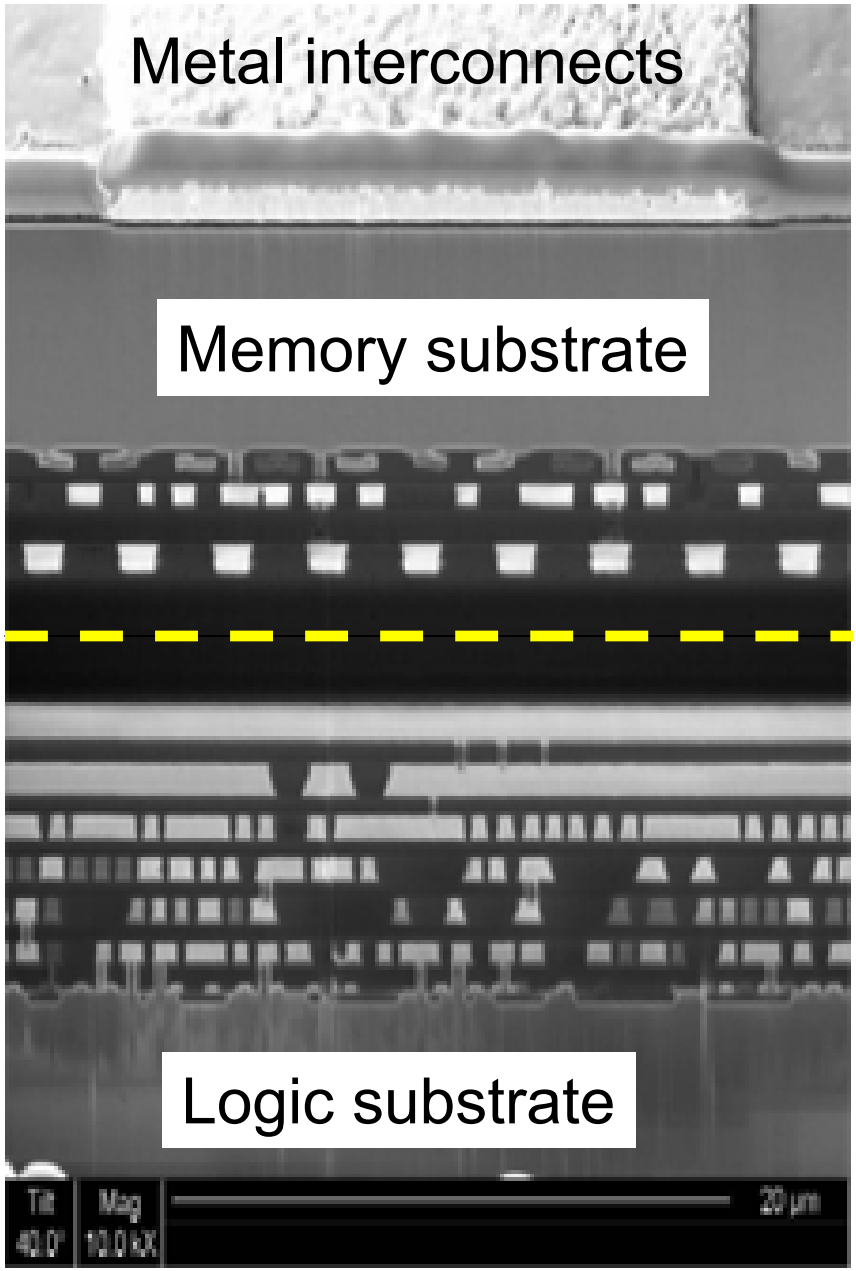
- Contamination free surface

Permanent Bond Formation



3-D circuit with a metal interconnect (at top), followed by a memory substrate, a bond interface, then logic metal, logic transistors and a logic substrate.

- Bond memory substrate and logic substrate.
- Thin both substrates with grinding and CMP.
- Etch vias and metallization to connect the two die.



http://www.ziptronix.com