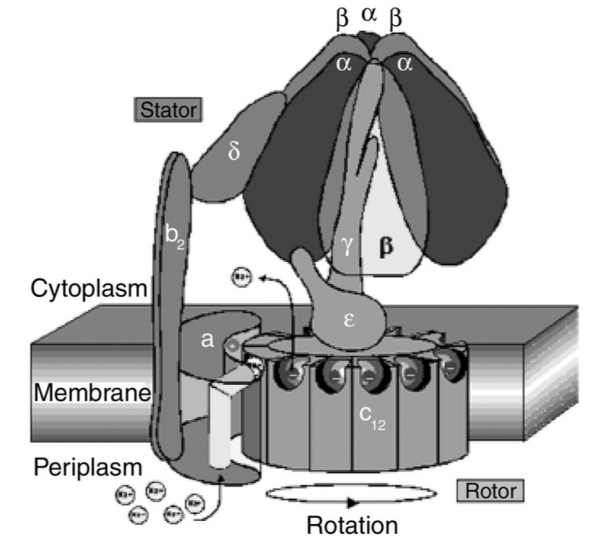
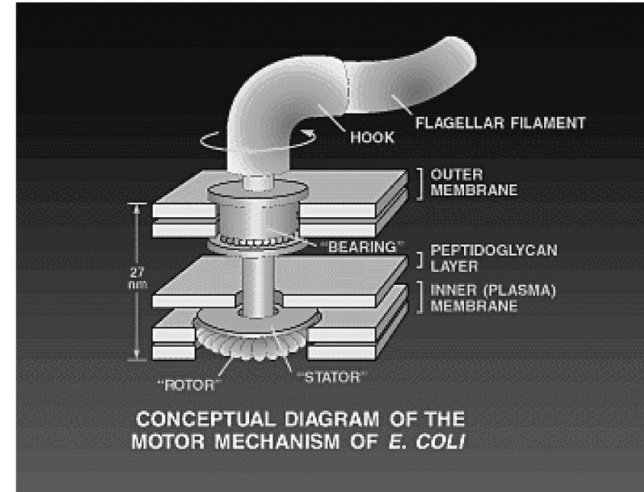
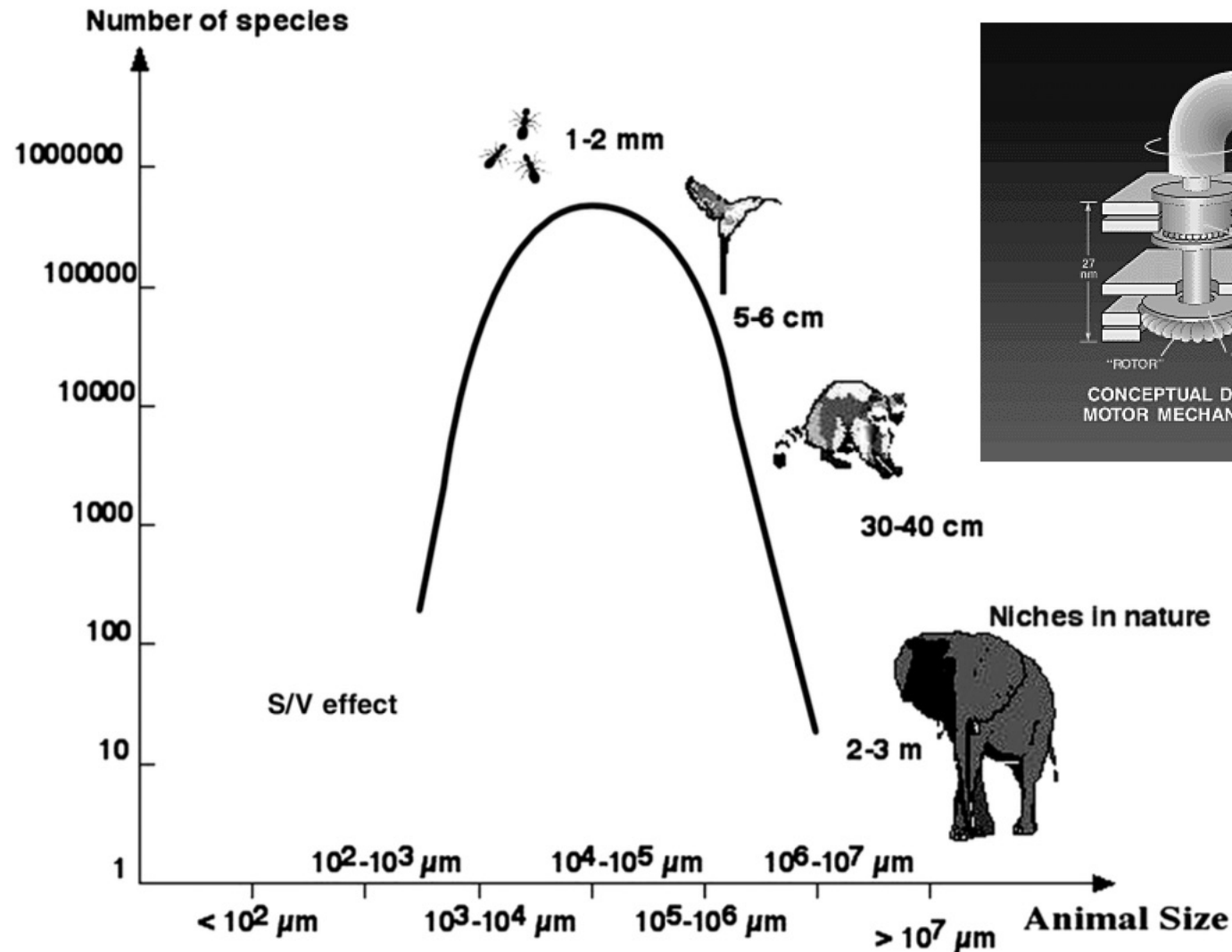


Micro and Nanomechanical systems

Nature prefers Small Structures



Micro-Electro Mechanical Systems

- Energy is converted from one system to another
- In mems, an actuator converts Electrical/Optical energy into mechanical action
 - Electrical
 - Magnetic
 - Fluidic
 - Thermal
 - Chemical/Electro chemical

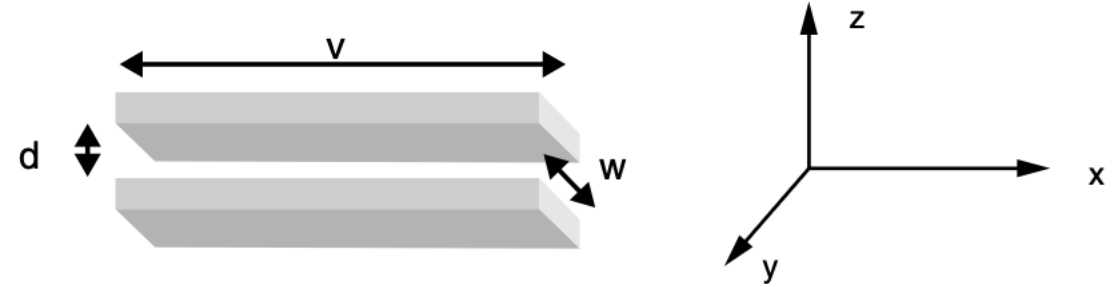
A simple example of micro-actuator

- Maximum electrostatic energy stored

$$E = -\frac{1}{2}CV^2 = \frac{\epsilon w v V^2}{2d}$$

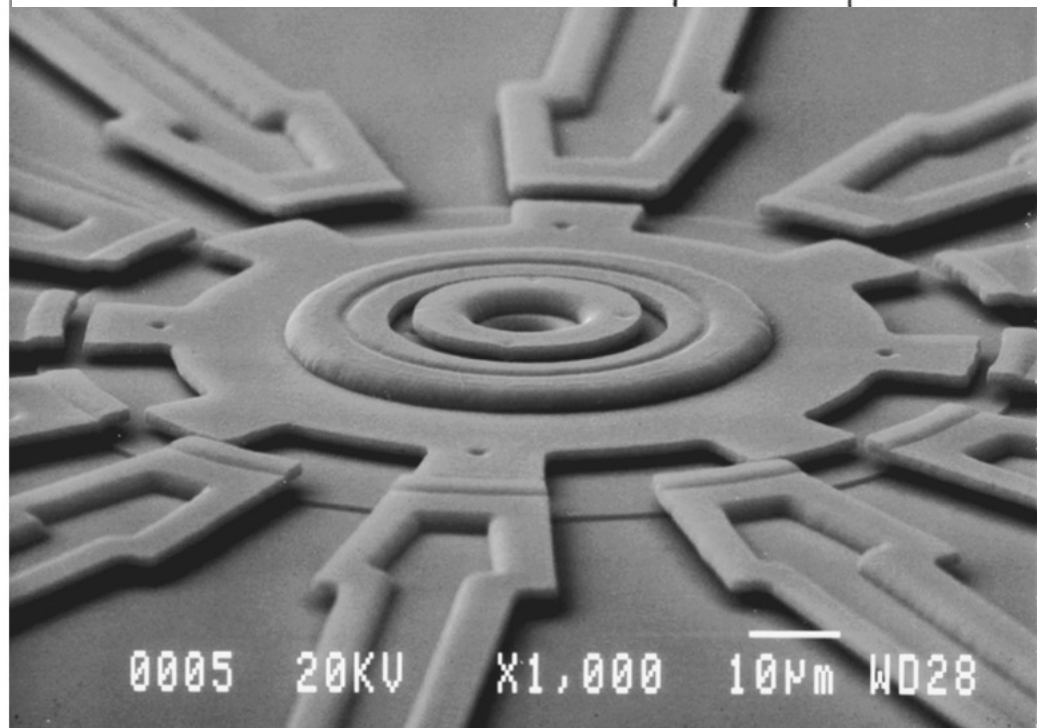
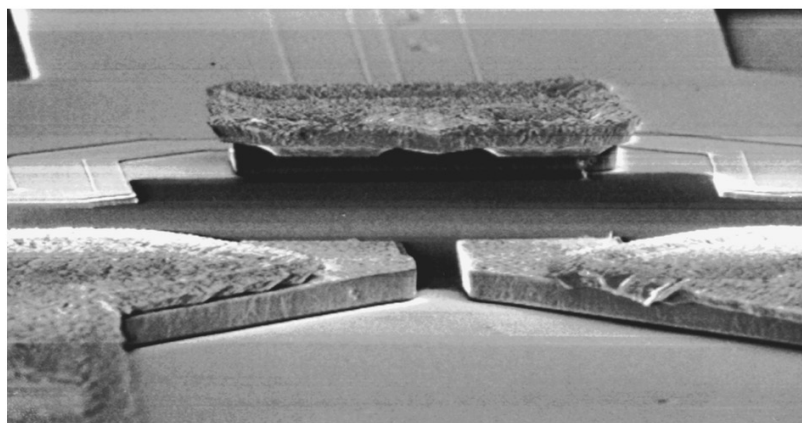
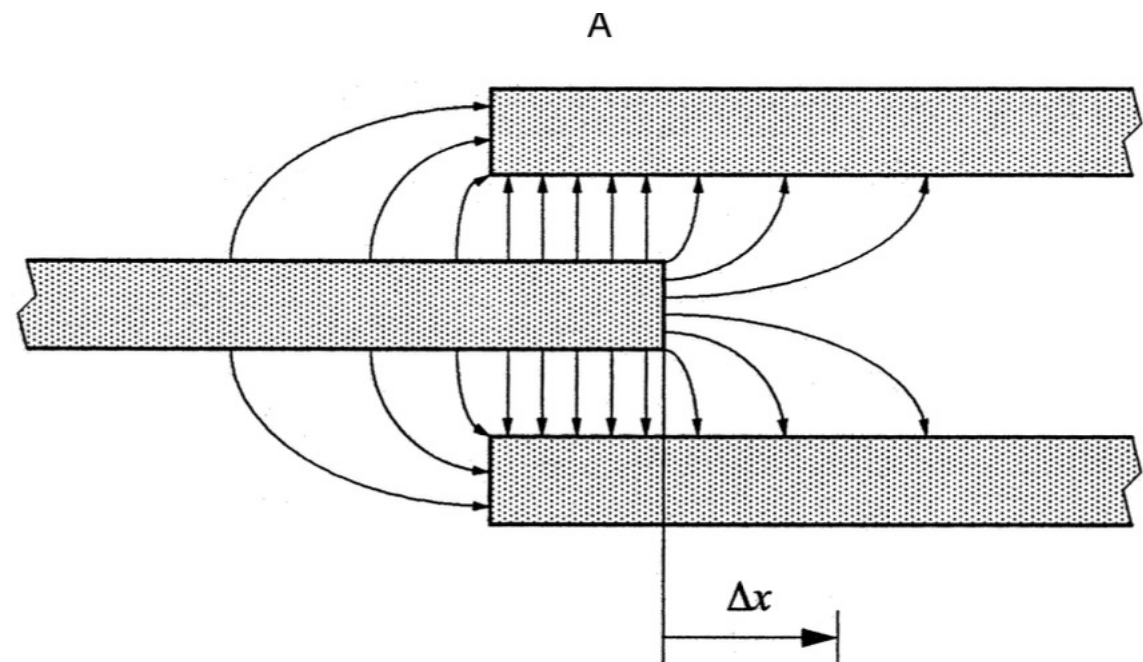
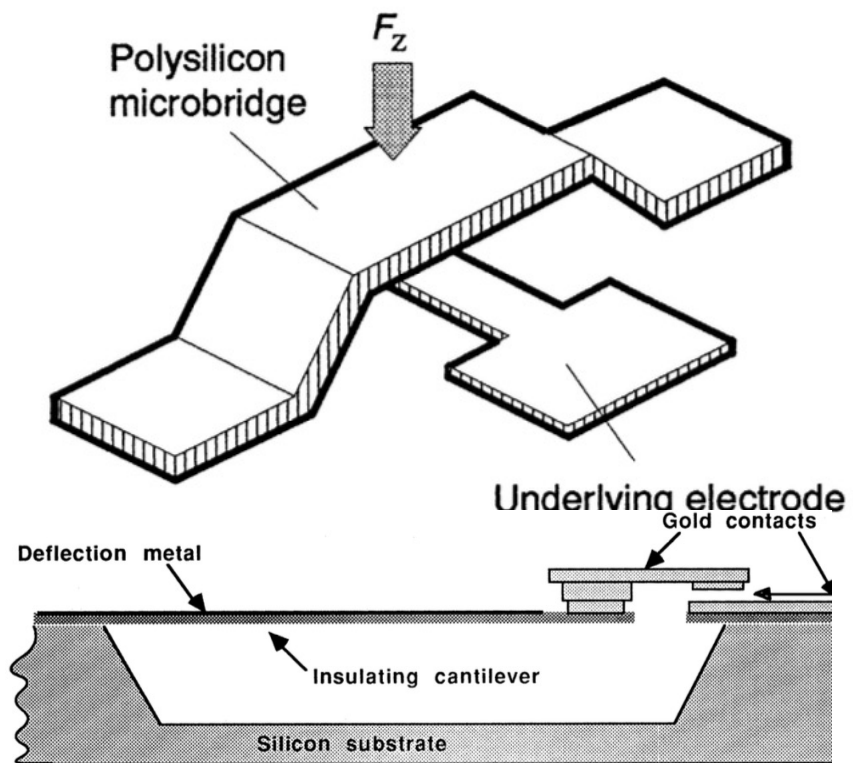
- When there is a change in one of the dimension (say d)

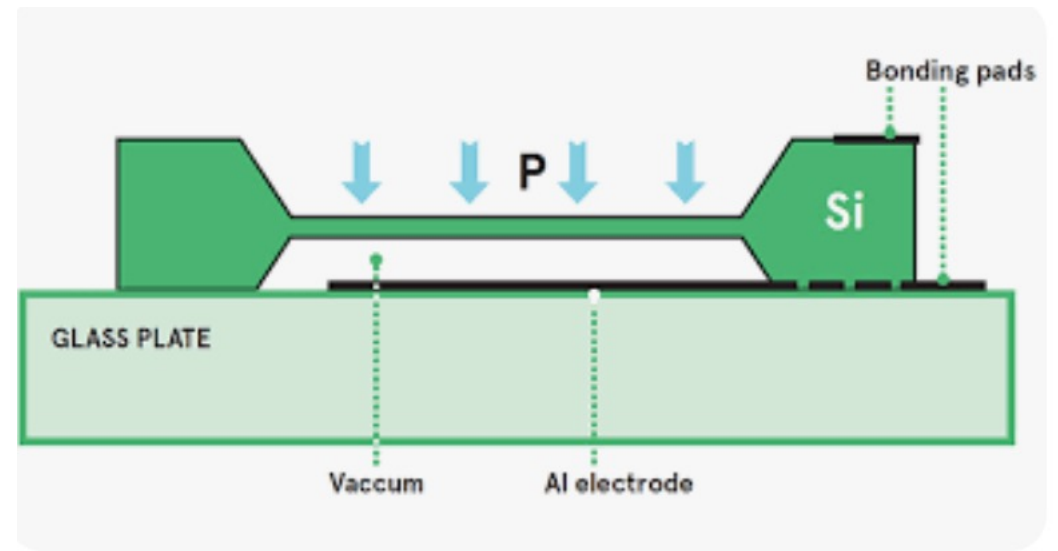
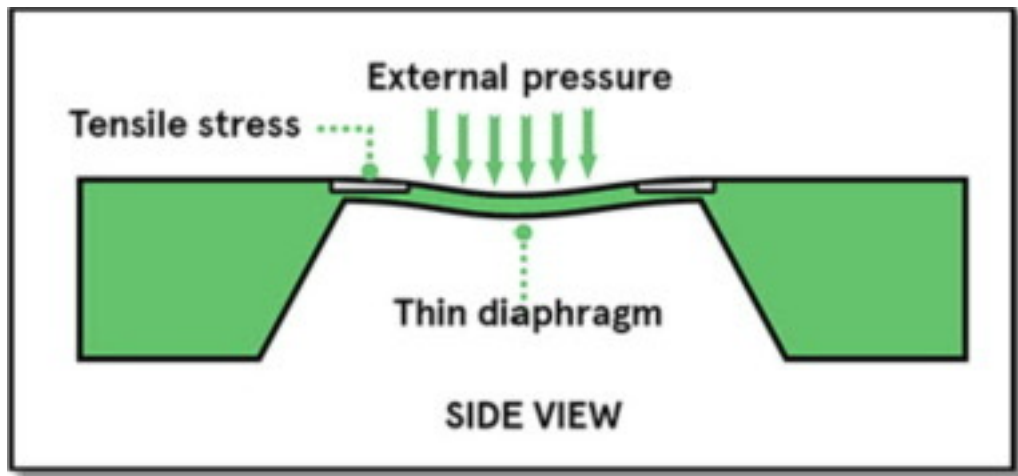
$$\frac{\partial E}{\partial z} = -\frac{V^2}{2} \frac{\partial C}{\partial z} = f_z$$



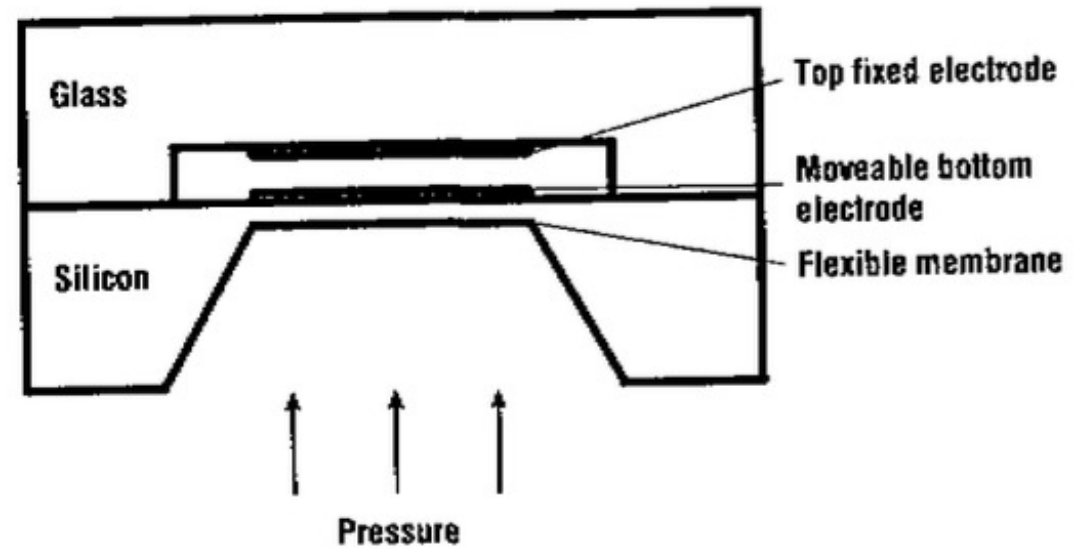
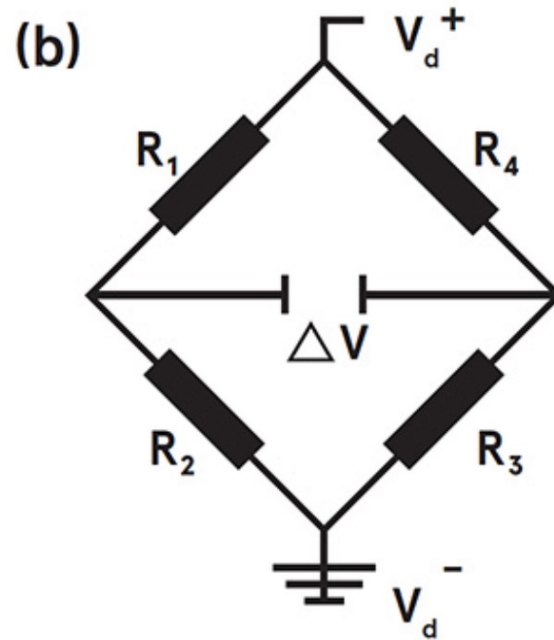
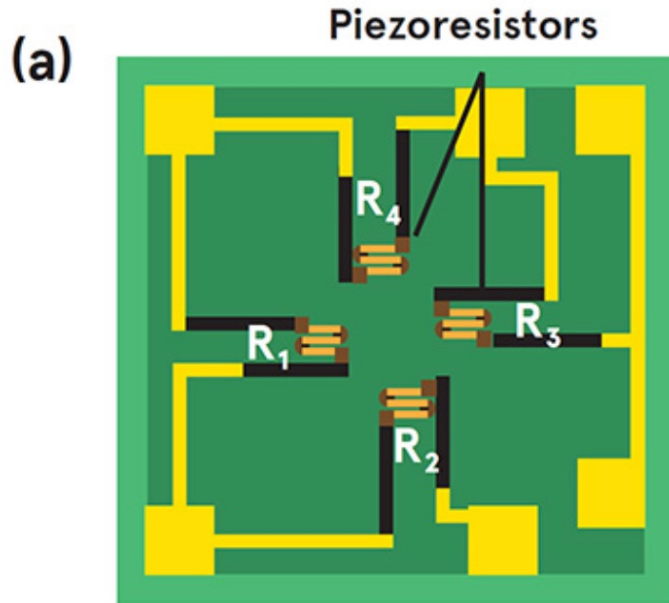
Thus, when a voltage is applied, the structure experiences a force f_z
alternatively,

When a force f_z is applied, a change in the potential V is experienced.





Simplest form of pressure sensor



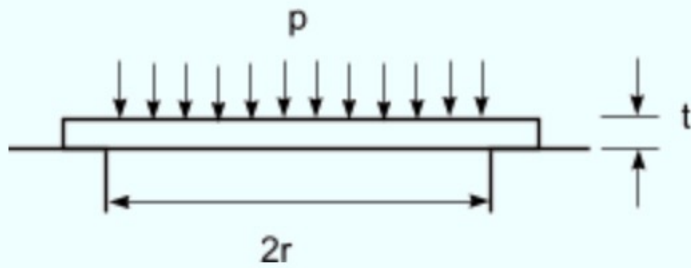
Mechanics of Structures

Table 19.1 Properties of materials

	Yield Strength (10^9 Pa)	Young's Modulus (10^9 Pa)	Density (g/cm³)	Thermal Conductivity (W/cm °C)	Thermal Expansion ($10^{-6}/^{\circ}\text{C}$)
Diamond (single crystal)	53.0	1035.0	3.5	20.0	1.0
SiC (single crystal)	21.0	700.0	3.2	3.5	3.3
Si (single crystal)	7.0	190.0	2.3	1.6	2.3
Al ₂ O ₃	15.4	530.0	4.0	0.5	5.4
Si ₃ N ₄ (single crystal)	14.0	385.0	3.1	0.2	0.8
Gold	—	80.0	19.4	3.2	14.3
Nickel	—	210.0	9.0	0.9	12.8
Steel	4.2	210.0	7.9	1.0	12.0
Aluminum	0.2	70.0	2.7	2.4	25.0

From Petersen [3].

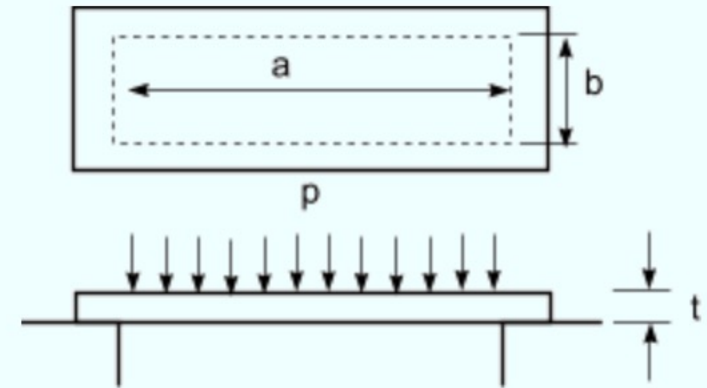
Deflection of a plate



$$\sigma_m = \frac{3(3 + \nu) pr^2}{8 t^2} = \frac{1,238 pr^2}{t^2} \quad \text{At centre}$$

$$y_m = \frac{(5 + \nu) pr^4}{64(1 + \nu) D} = \frac{0,696 pr^4}{E.t^3} \quad \text{At centre}$$

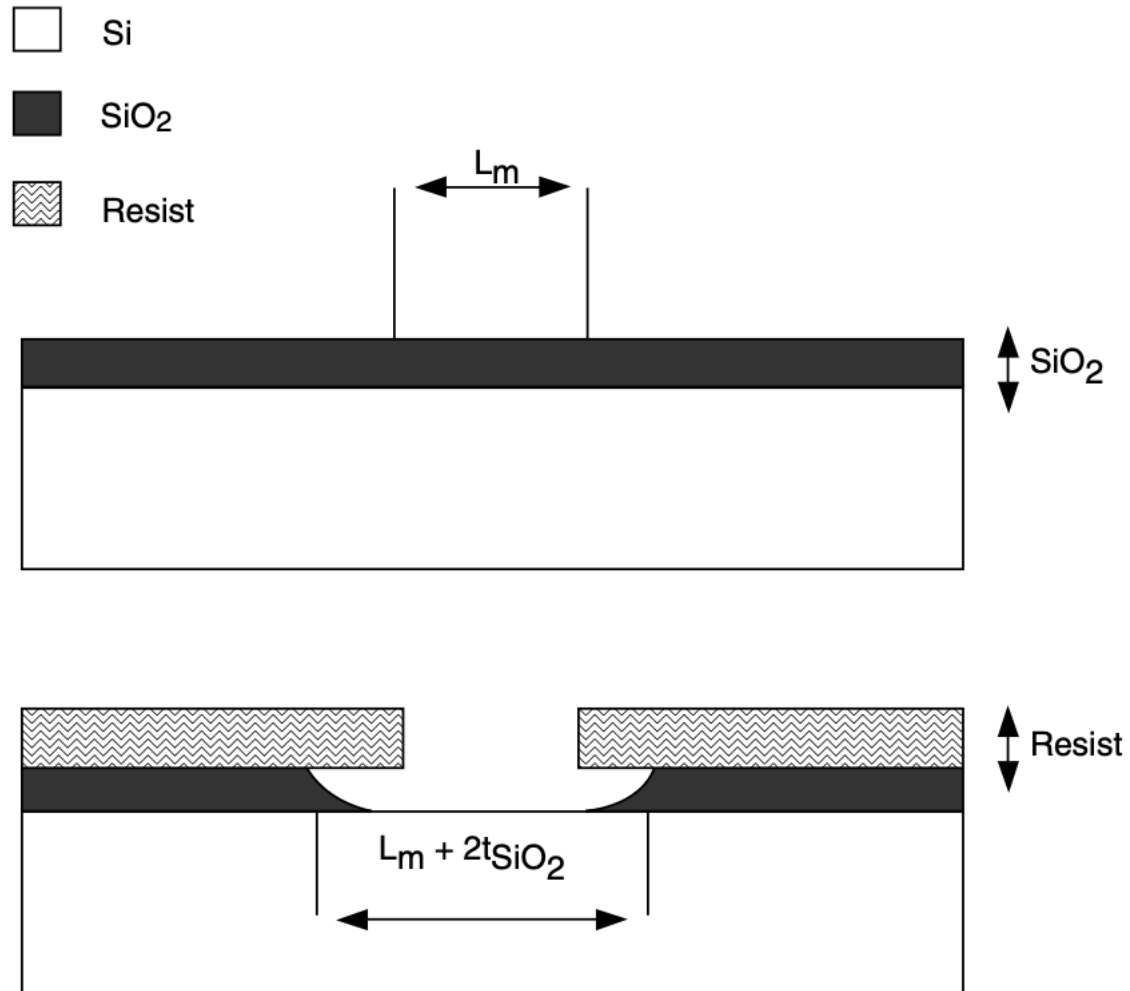
Rectangular Plate (simply supported)



$$\sigma_m = \frac{0,75 pb^2}{t^2 [1,61(b/a)^3 + 1]} \quad \text{At centre}$$

$$y_m = \frac{0,142 pb^4}{Et^3 [2,21(b/a)^3 + 1]} \quad \text{At centre}$$

Cantilever



- Deflection of a cantilever:

$$\delta x = \frac{PL^3}{3EI}$$

Or if there is a uniform load

$$\delta x = \frac{wL^4}{8EI}$$

The resonant frequency

$$f = \frac{1}{2\pi} \sqrt{\frac{K}{m}}$$

Si as a Mechanical Material

- Si is a brittle material.
- Dislocations do not move, E – remains large constant at large strains.
- Si has a higher yield strength than SS, lower density than Al.
- Si – Specific strength (Yield Strength/density) is among the highest
- Si hardness is higher than SS
- Si Young's modulus is close to that of SS

TABLE 4.6 Mechanical Properties of Single-Crystal Silicon (SCS) among Technological Materials

	Yield strength ($10^9 \text{ N/m}^2 = \text{GPa}$)	Specific strength [$10^3 \text{ m}^2 \text{ s}^{-2}$]	Knoop hardness (kg/mm^2)	Young's modulus ($10^9 \text{ N/m}^2 = \text{GPa}$)	Density (10^3 kg/m^3)	Thermal conductivity at 300 K (W/cmK)	Thermal expansion ($10^{-6}/^\circ\text{C}$)
Diamond (SC)	53	15000	7000	10.35	3.5	20	1.0
Si (SCS)	2.8–6.8	3040	850–1100	190(111)	2.32	1.56	2.616
GaAs (SC)	2.0			.75	5.3	0.81	6.0
Si_3N_4	14	4510	3486	323	3.1	0.19	2.8
SiO_2 (fibers)	8.4		820	73	2.5	0.014	0.4–0.55
SiC (6H-SiC)	21	6560	2480	448	3.2	5	4.2
Iron	12.6		400	196	7.8	0.803	12
Tungsten (W)	4	210	485	410	19.3	1.78	4.5
Al	0.17	75	130	70	2.7	2.36	25
AlN	16			340		1.60	4.0
Al_2O_3	15.4		2100	275	4.0	0.5	5.4–8.7
Stainless steel	0.5–1.5		660	206–235	7.9–8.2	0.329	17.3
Quartz values //Z ⊥Z	9		850	107	2.65	0.014	7.1 13.2 (increases with T)
Polysilicon	1.8 (annealed)			161			2.8

Notes: SC = single crystal; SCS = single-crystal silicon; T = temperature; //Z = parallel with Z-axis; ⊥Z = perpendicular to Z-axis.

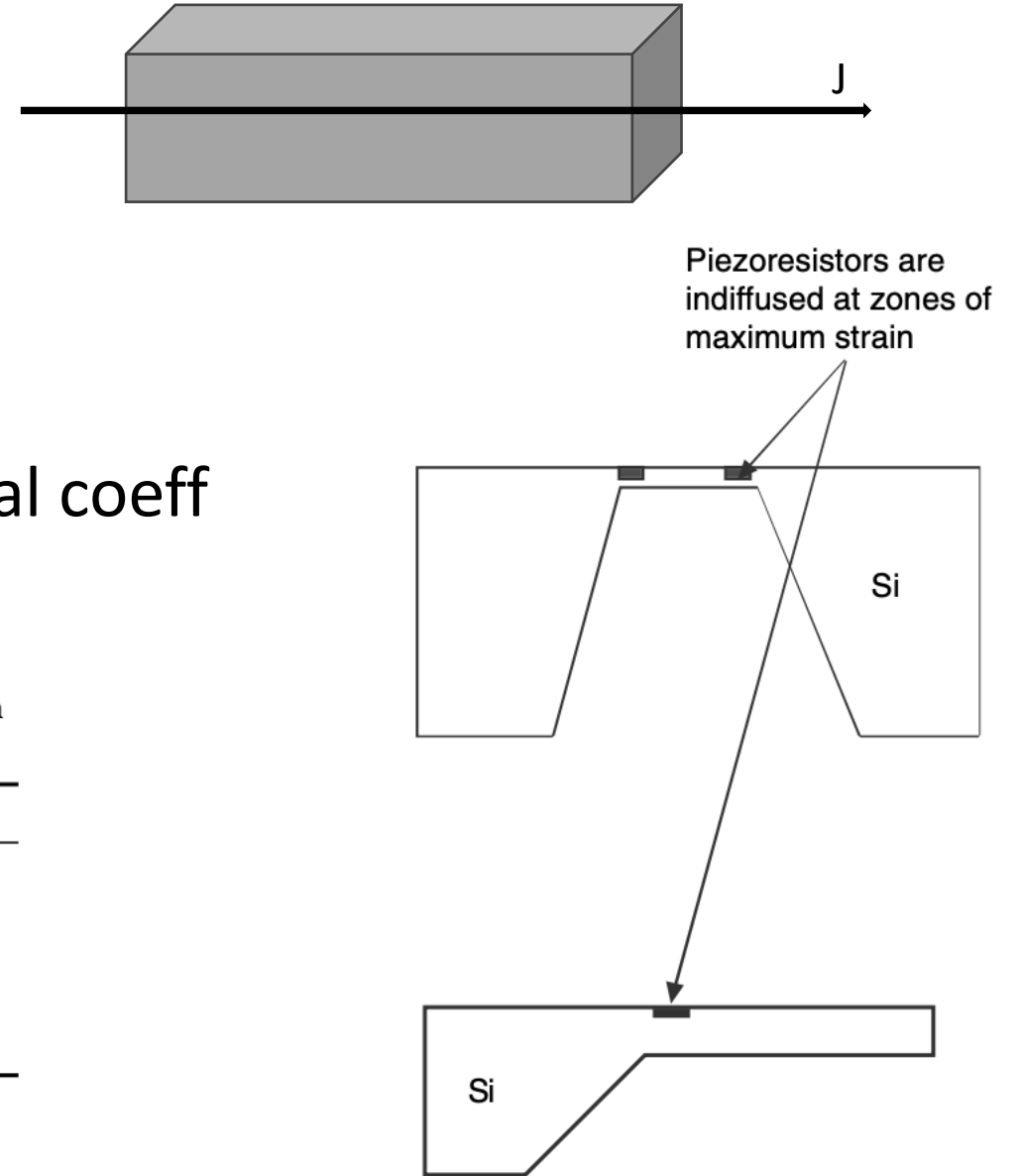
Piezoresistances

- A Piezo resistance $\frac{\Delta R}{R} = \sigma_l \pi_l + \sigma_t \pi_t$
- σ_1 Longitudinal stress and π_1 longitudinal coeff

TABLE 4.5 Resistivity and Piezoresistivity Coefficients at Room Temperature (in 10^{-11} Pa^{-1}), <100> Si Wafers and Doping Levels Below 10^{18} cm^{-3}

	$\rho (\Omega \cdot \text{cm})$	Direction	π_{11}	π_{12}	π_{44}	π_t	π_l
p-Si	7.8	<100>				-1.1	+6.6
		<110>	+6.6	-1.1	+138.1	-66	72
n-Si	11.7	<100>				+53.4	-102.2
		<110>	-102.2	+53.4	-13.6	-18	-31

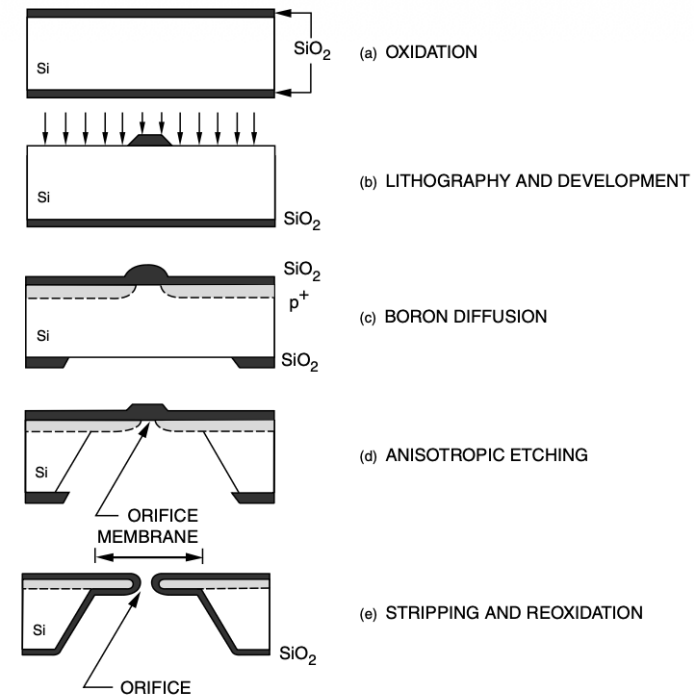
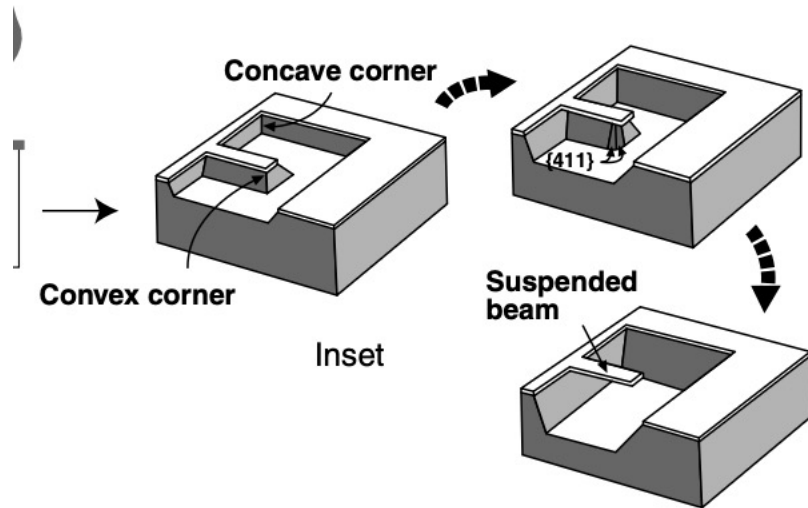
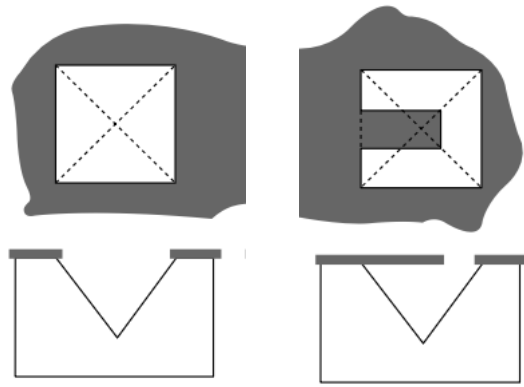
Source: Adapted from C. S. Smith, *Phys. Rev.*, 94, 42–49, 1954, and A. D. Khazan, *Transducers and Their Elements*. Englewood Cliffs, N.J.: PTR Prentice Hall, 1994.



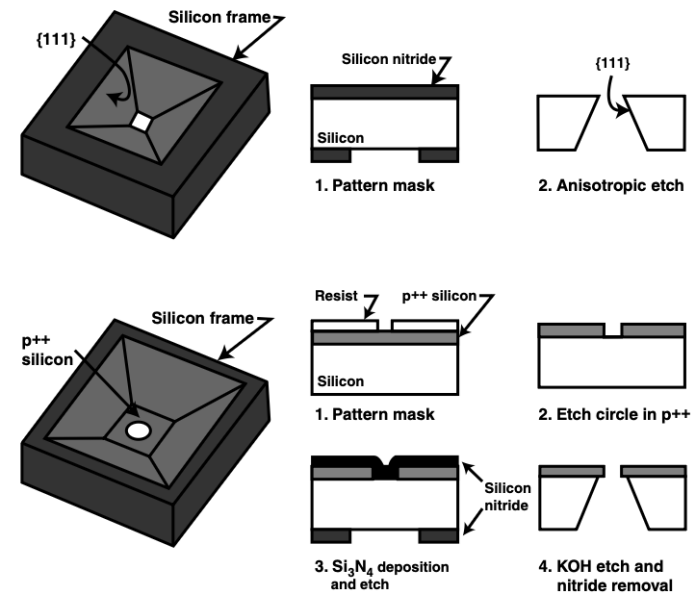
How do we fabricate such structures ?

- Bulk Micromachining
 - Predominantly wet-etching
 - Requires careful choice of etchants, etch-stops
 - Not easily integratable in a longer process flows.
- Surface micromachining
 - Works largely with thin films
 - Gas-phase etching
 - Dominant issues with thin-film stresses.

Bulk Micromachining



A



B

Etch stops:

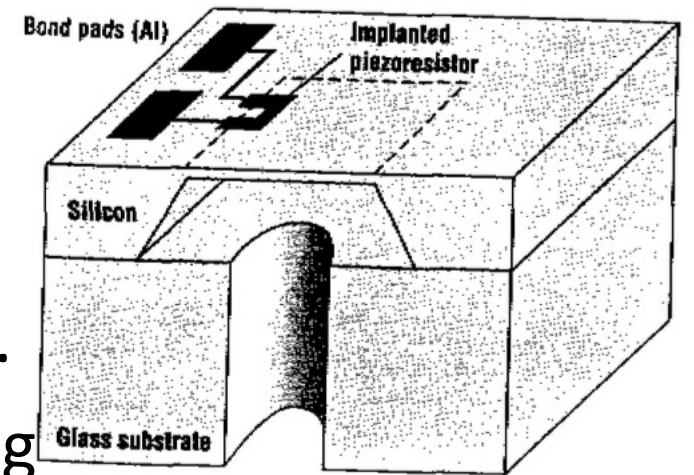
1. Highly doped layer
2. SiN/SiO_2 layer

A sample calculation

- Consider a 600 μm thick Si wafer.
- A Pressure sensor is to be made. It requires a membrane thickness of say 30 μm . What is the dimension of the square that you will need ?

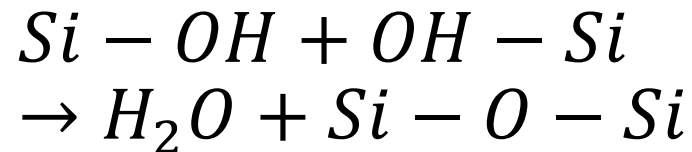
The need for a handle layer

- The final fabricated structure is very sensitive.
- Requires a handle layer.
- Typically glass is used.
- Glass with holes for access to membranes are used.
- The glass is bonded to the substrate using a bonding

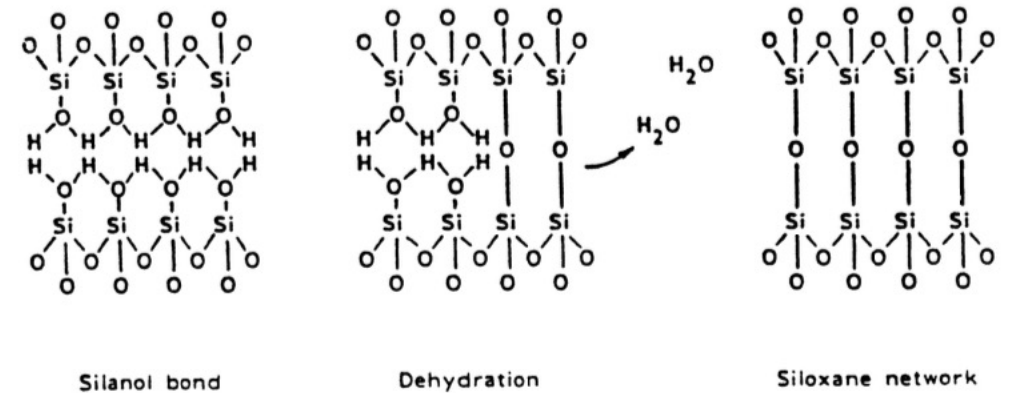
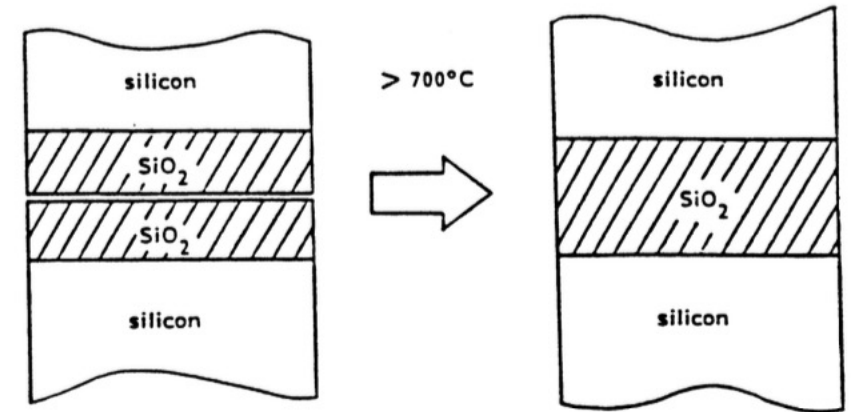


Si – fusion bonding

- Si- surface is often terminated with SiO_x or Si-OH bonds
- When two such interfaces are brought together

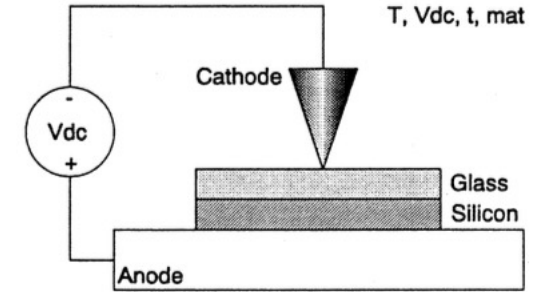


The wafers are heated to dehydrate.



Anodic bonding

- Bonding of Si/Metal to glass (Na-rich glass)
- Temperatures below 500 C>
- The contact region is made flat and smooth
- Glass kept at negative bias.
- At increasing temperature,
 - The Na⁺ ions move out, leaving a space-charge region.
 - Strong electric field at the interface, leads to local heating and bond formation at the SiO₂-Si interface.



Eutectic bonding

- Insensitive to surface properties
- Lower temperature

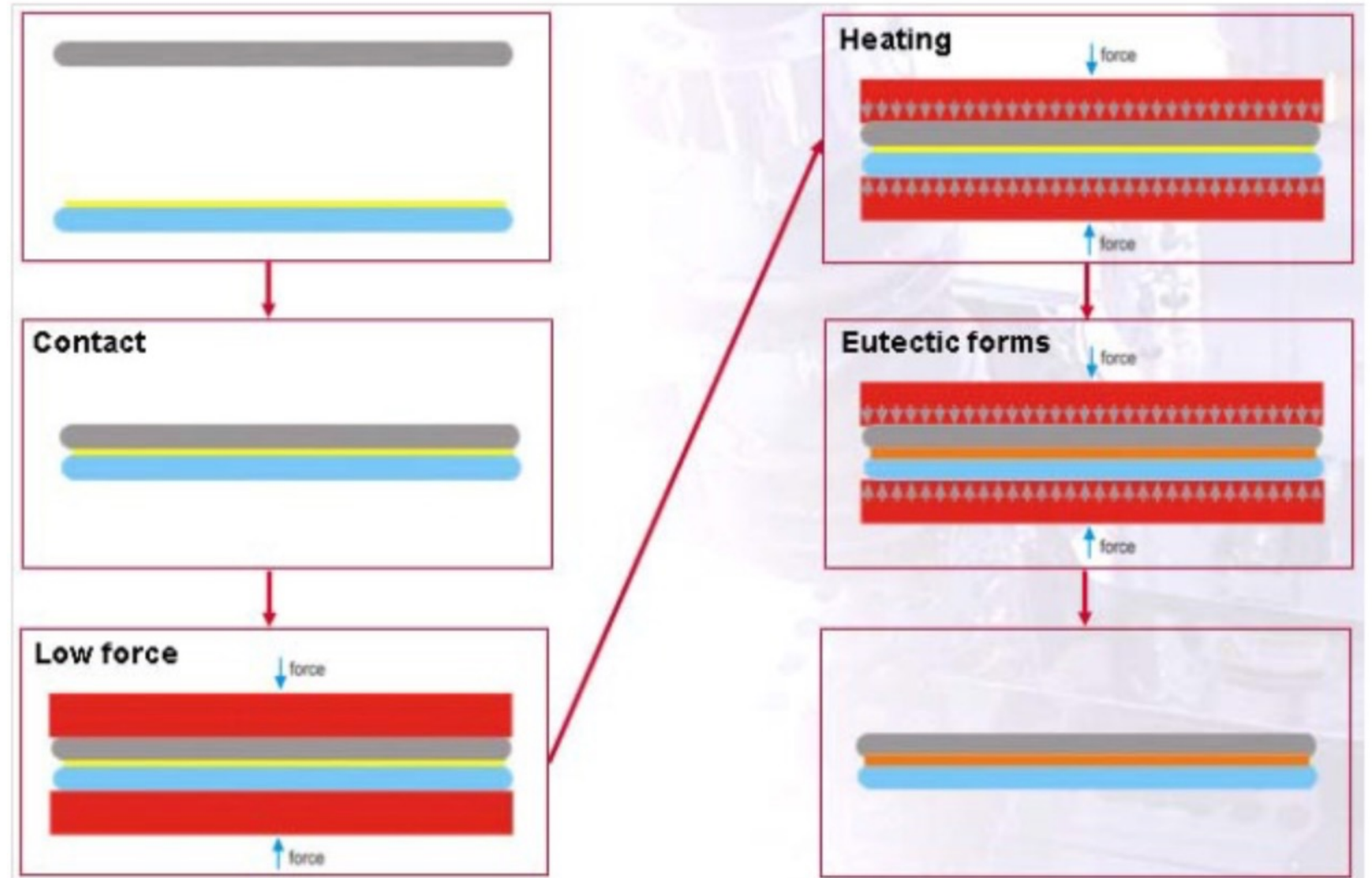
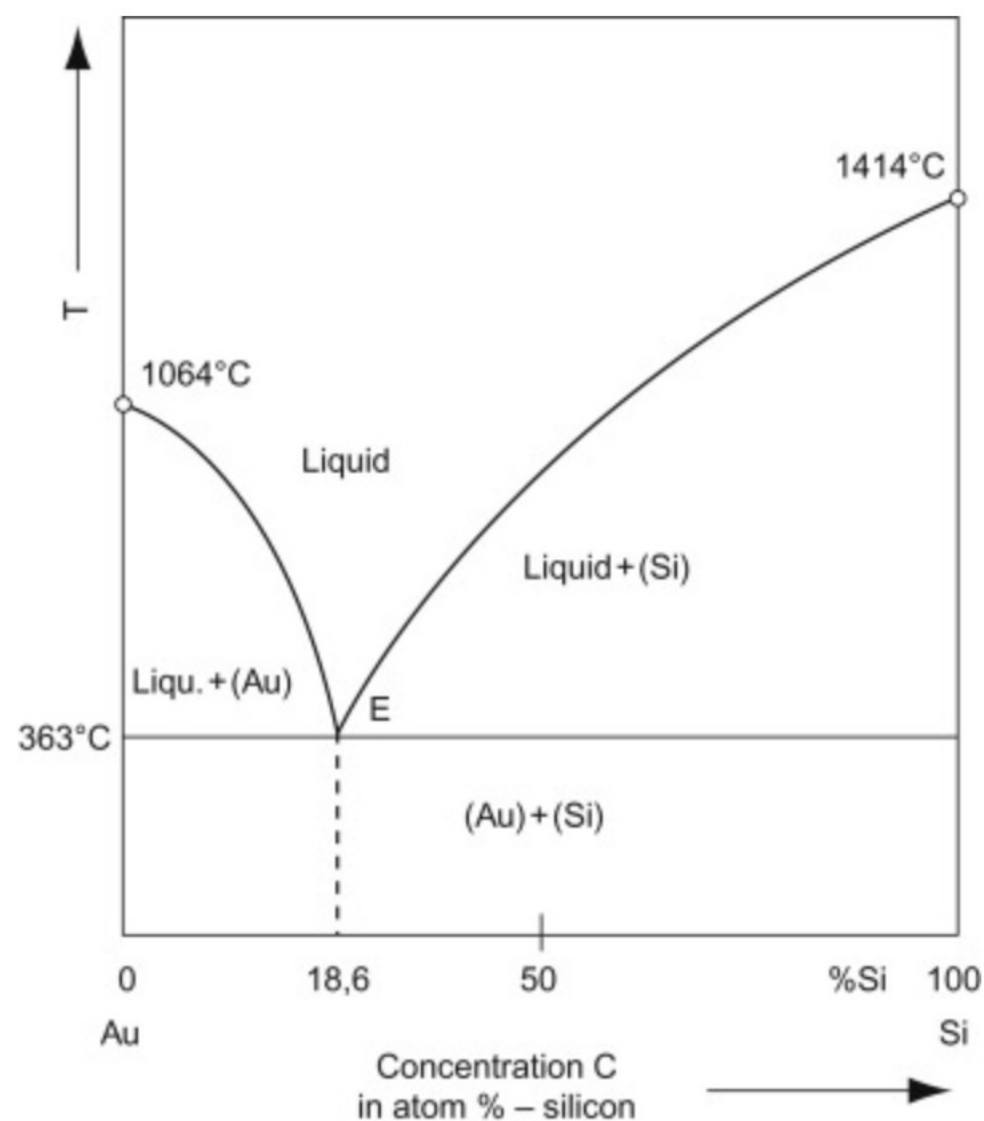


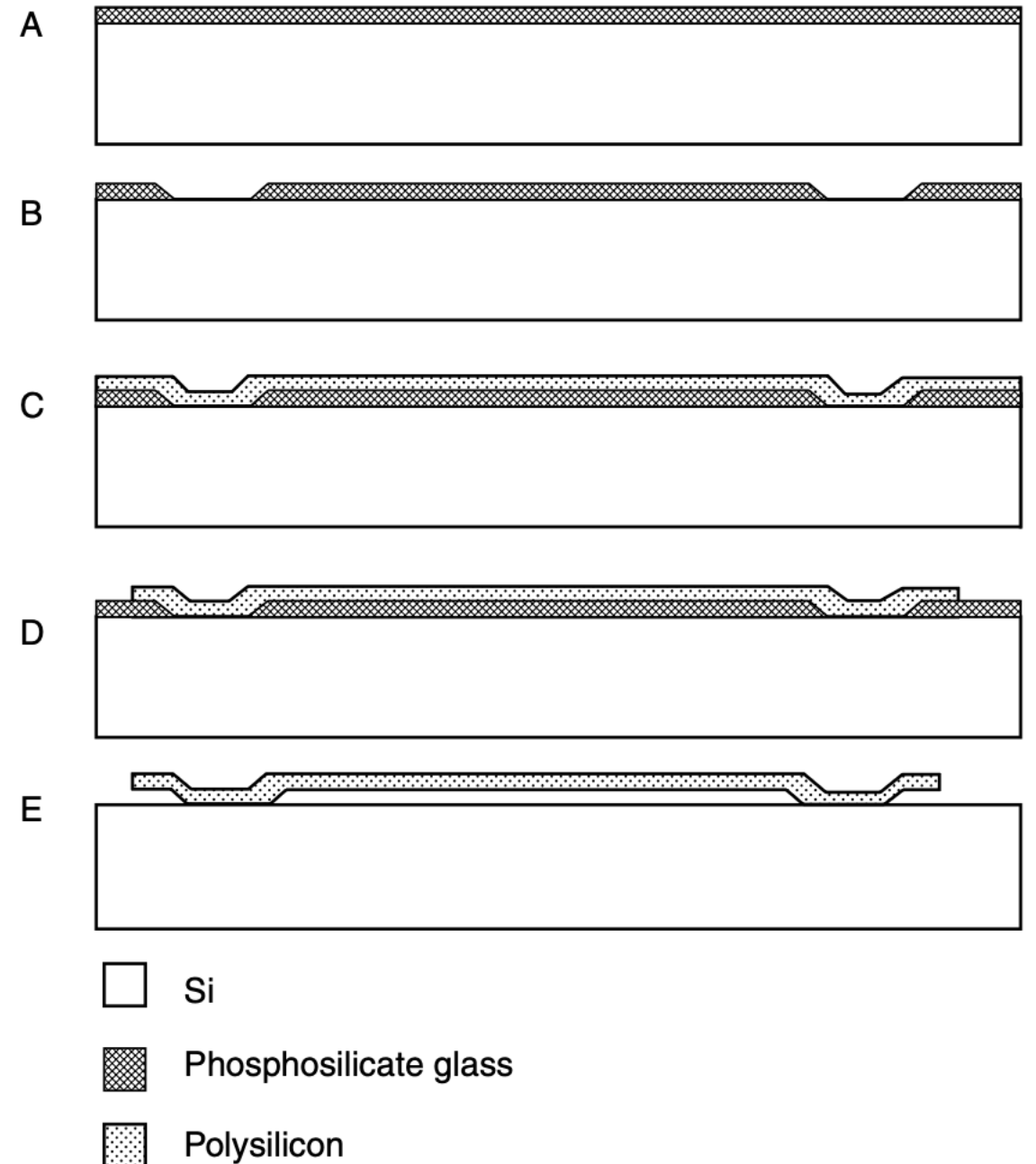
Table 1 - Main eutectic combinations used for wafer bonding

Eutectic System	Eutectic Temperature	Bonding Temperature (recommended)
Au:Sn (80:20)	Au:Sn- 300°C	290°C
Au:Si	363°C	375°C
Au:Ge	380°C	390°C
Al:Ge	423°C	435°C
Au:In	510°C	520°C



Surface micromachining

- Step 1: Deposition of glass [sacrificial layer]
- Step 2: Patterning of Glass
- Step 3: Deposition of Poly-Silicon [structural layer]
- Step 4: Selective Etching of Glass



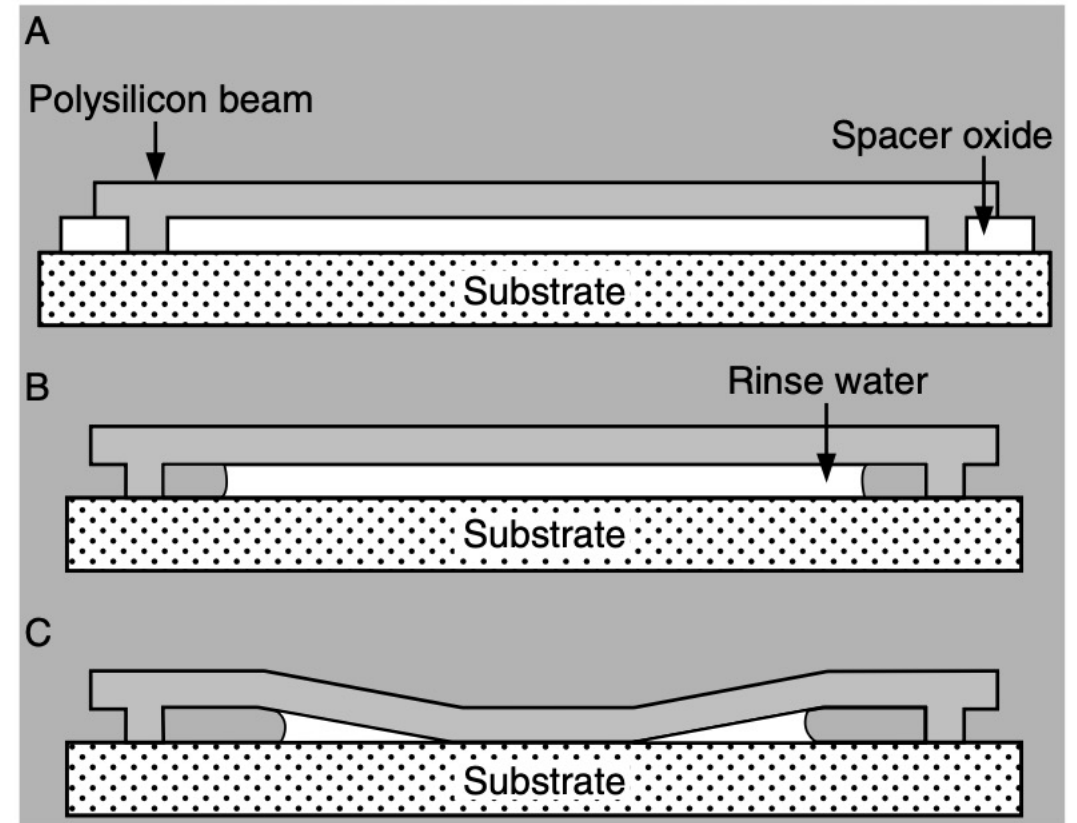
Choice of microstructure, spacer and its etchant

TABLE 5.5 Etchants-Spacer and Microstructural Layer

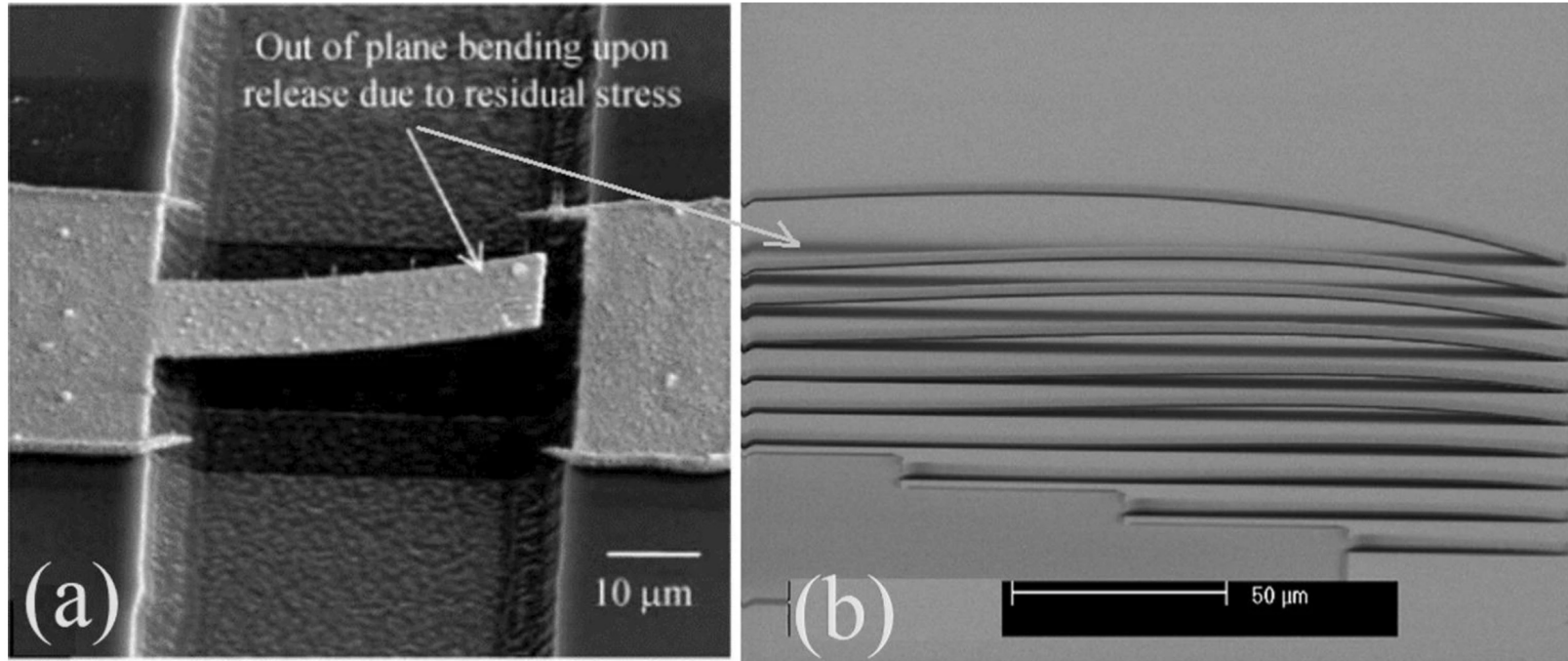
Etchant	Buffer/isolation	Spacer	Microstructure
Buffered HF (5:1,NH ₄ F:conc.HF)	LPCVD Si ₃ N ₄ /thermal SiO ₂	PSG	Poly-Si ^{60,61,88}
RIE using CHF ₃ BHF (6:1)	LPCVD Si ₃ N ₄	LPCVD SiO ₂	CVD tungsten ⁸⁹
KOH	LPCVD Si ₃ N ₄ /thermal SiO ₂	Poly-Si, porous Si (at room temperature)	Si ₃ N ₄ ^{90,91} SOI ⁸⁷
Ferric chloride	Thermal SiO ₂	Cu	Polyimide ⁹²
HF	LPCVD Si ₃ N ₄ /thermal SiO ₂	PSG	Polyimide ⁹³
Phosphoric/acetic acid/nitric acid (PAN or 5:8:1:1 water:phosphoric:acetic:nitric)	Thermal SiO ₂	Al	PE CVD Si ₃ N ₄ Nickel ^{94,95}
Ammonium iodide /iodine alcohol	Thermal SiO ₂	Au	Ti ⁹⁶
Ethylene-diamine/pyrocathocol (EDP)	Thermal SiO ₂	Poly-Si	SiO ₂

Problem of Stiction

- A sacrificial layer is wet-chemically etched.
- Washed by DI- water
- When the water dries, A droplet of water can remain, between the suspended structure and substrate.
- A surface tension develops
 - That can collapse the entire structure

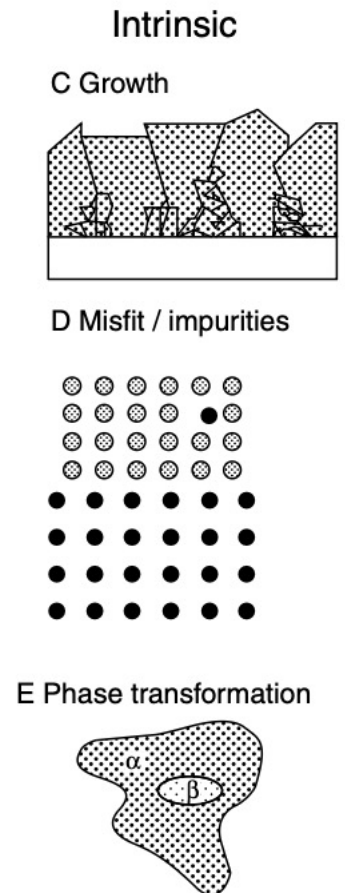
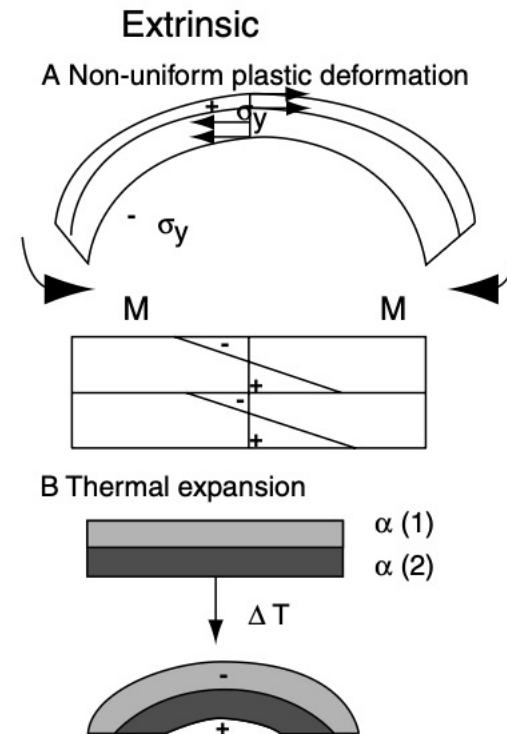


Problem of Stresses



Residual Stresses

- Extrinsic
 - Non-uniform plastic deformation
 - Thermal expansion mismatch
- Intrinsic
 - Growth stresses
 - Misfit dislocations
 - Volume change due to phase transformation



Cantilever stresses

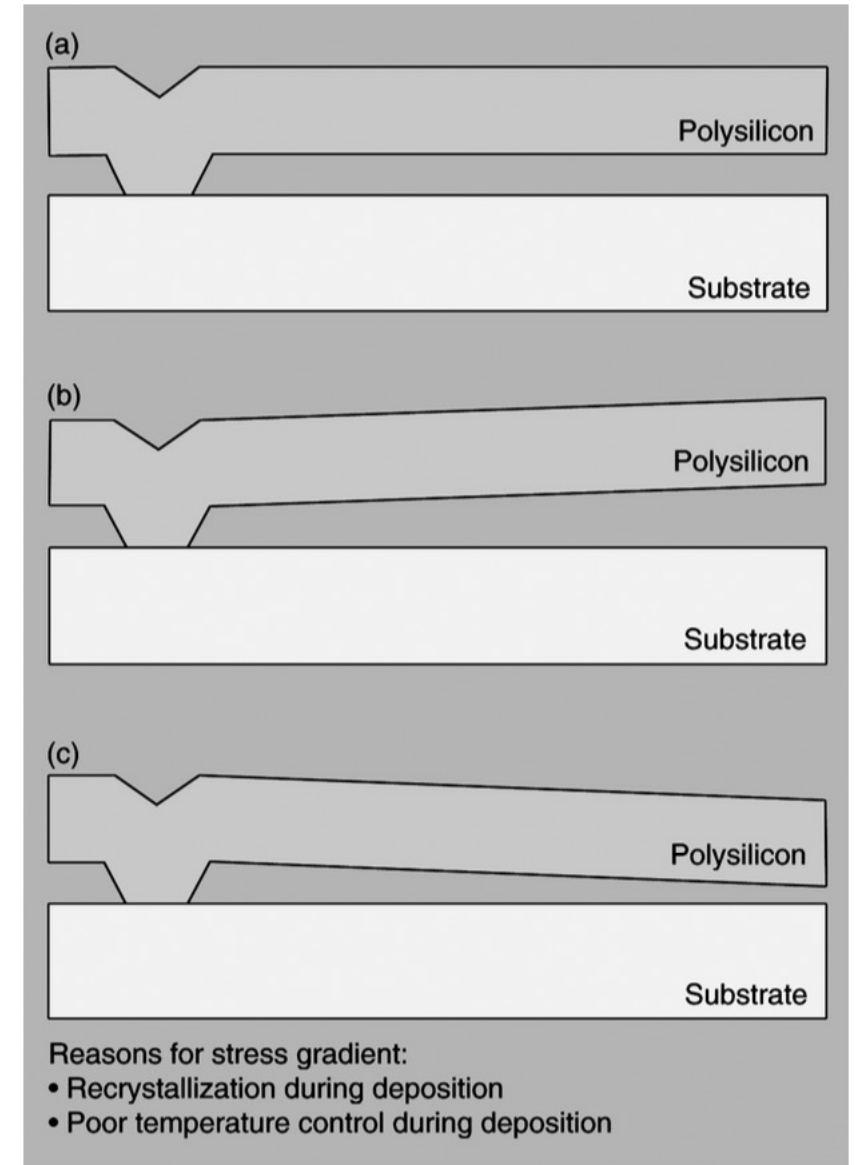
- Imagine a simple cantilever
- If there exists a bending moment

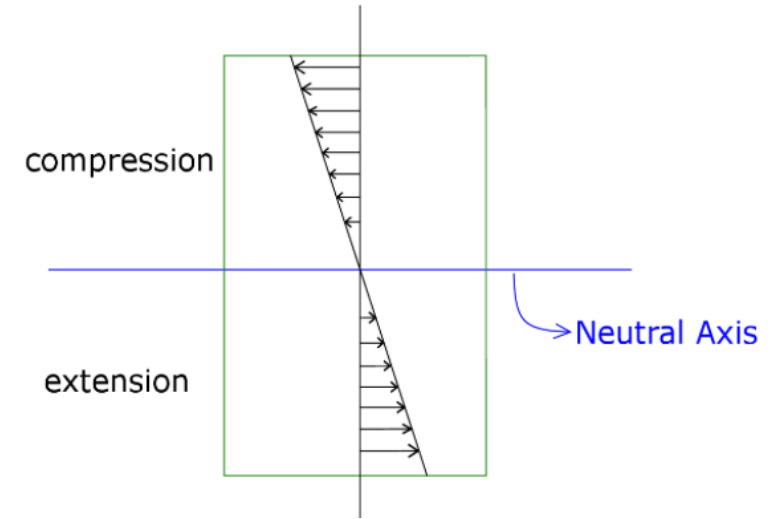
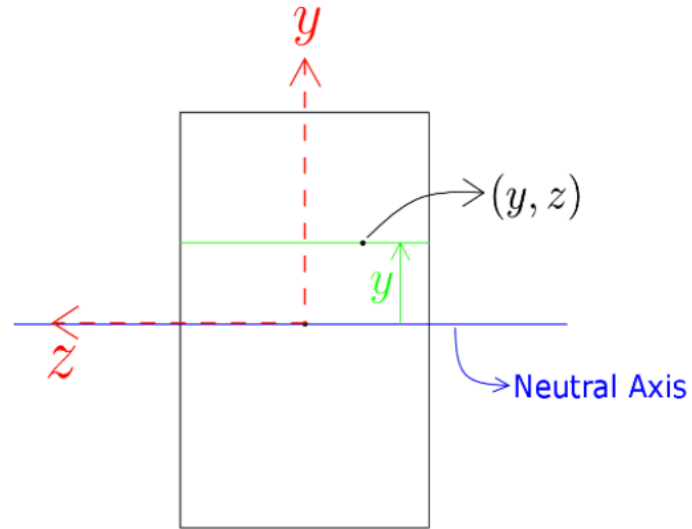
$$M = \int_{-\frac{t}{2}}^{\frac{t}{2}} zb\sigma(z)dz$$

b – cantilever width

t – thickness

$\sigma(z)$ - Stress at point z





- A strain gradient across

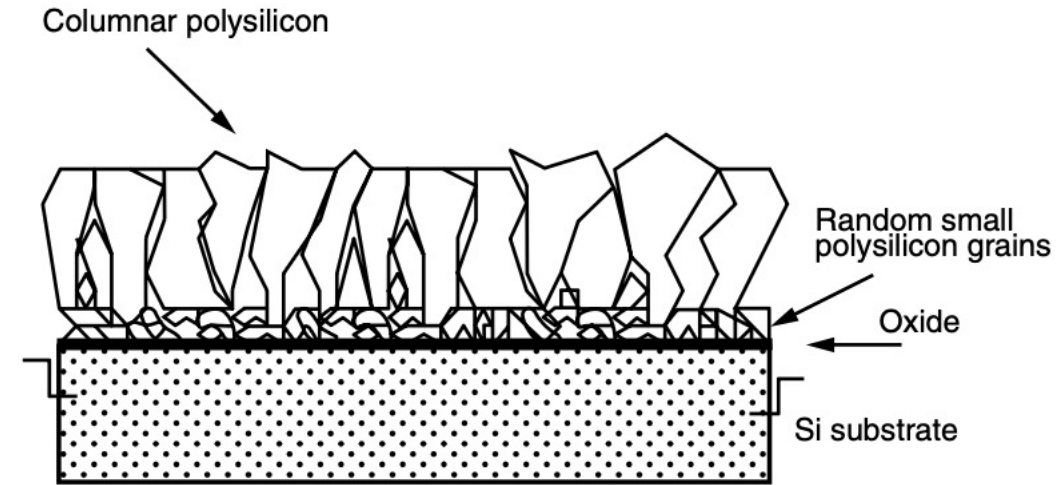
$$\sigma(z) = E\Gamma z$$

$$M = \frac{\Gamma E b t^3}{12}$$

The final deflection can be calculated to be $z = \frac{ML^2}{2EI}$

Control on Residual Stresses

- Poly-Si is typically deposited at 625 C
 - Have large columnar grains
 - Leading to compressive stresses
- Poly-Si deposited below 625 C,
 - Are amorphous, extra-fine (smooth) surfaces
 - Can be tensile
- Doping Si leads to different stresses
- SiNx can be grown under various stress conditions.



- Post deposition annealing is a good option

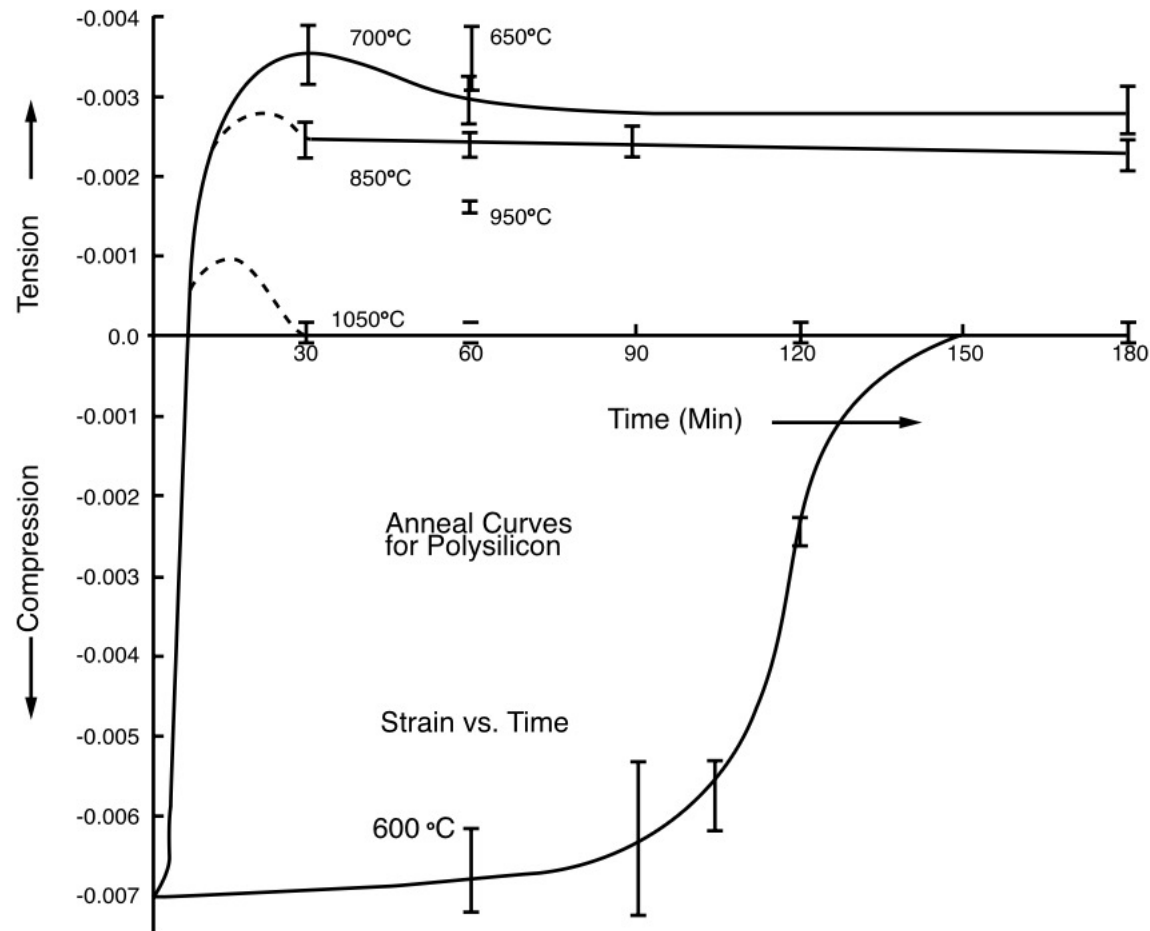


TABLE 5.13 Properties of Silicon Nitride

Deposition	LPCVD	PECVD
Temperature (°C)	700–800	250–350
Density (g/cm ³)	2.9–3.2	2.4–2.8
Pinholes	No	Yes
Throughput	High	Low
Step coverage	Conformable	Poor
Particles	Few	Many
Film quality	Excellent	Poor
Dielectric constant	6–7	6–9
Resistivity (Ω-cm)	10 ¹⁶	10–10 ¹⁵
Refractive index	2.01	1.8–2.5
Atom % H	4–8	20–25
Energy gap	5	4–5
Dielectric strength (10 ⁶ V/cm)	10	5
Etch rate in conc. HF	200 Å/min	
Etch rate in BHF	5–10 Å/min	
Residual stress (10 ⁹ dyne/cm ²)	1T	2 C–5T
Poisson ratio	0.27	
Young's modulus	270 GPa	
TCE	1.6 × 10 ⁻⁶ /°C	

Properties	SiO ₂	Poly Si	SiN _x
Temperature of deposition	900-100 (CVD) 200 (PECVD)	500 – 650	350-400
Etchants	BHF	KOH	H ₃ PO ₄ – 10:1:0.3
Stresses	Compressive - tensile		
Resistivity		10 ¹⁰	10 ¹⁶
Young's modulus	73	160	270
TCE	0.35E-6	2.8E-6	1.6E-6

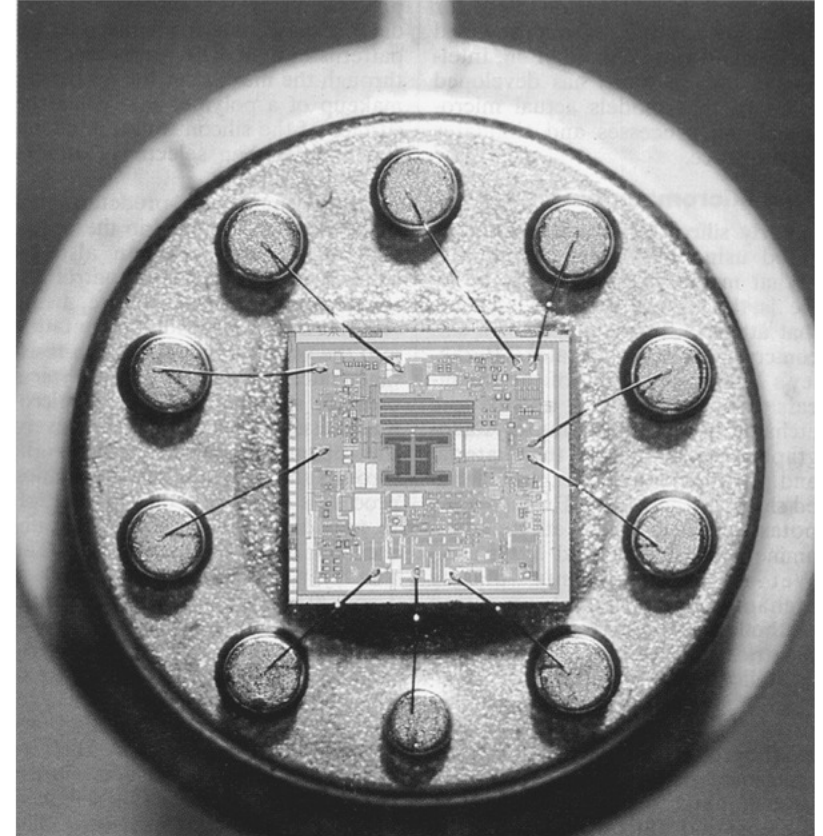
Bulk Micromachining	Surface Micromachining
Large features with substantial mass and thickness	Small features with low thickness and mass
Utilizes both sides of the wafer	Multiple deposition and etching required to build up structures
Vertical dimensions: one or more wafer thicknesses	Vertical dimensions are limited to the thickness of the deposited layers ($\sim 2\text{ }\mu\text{m}$) leading to compliant suspended structures with the tendency to stick to the support
Generally involves laminating Si wafer to Si or glass	Surface micromachined device has its built-in support and is more cost effective
Piezoresistive or capacitive sensing	Capacitive and resonant sensing mechanisms
Wafers may be fragile near the end of the production	Cleanliness critical near end of process
Sawing, packaging, testing is difficult	Sawing, packaging, testing is difficult
Some mature products and producers	No mature products or producers
Not very compatible with IC technology	Natural but complicated integration with circuitry; integration is often required due to the tiny capacitive signals

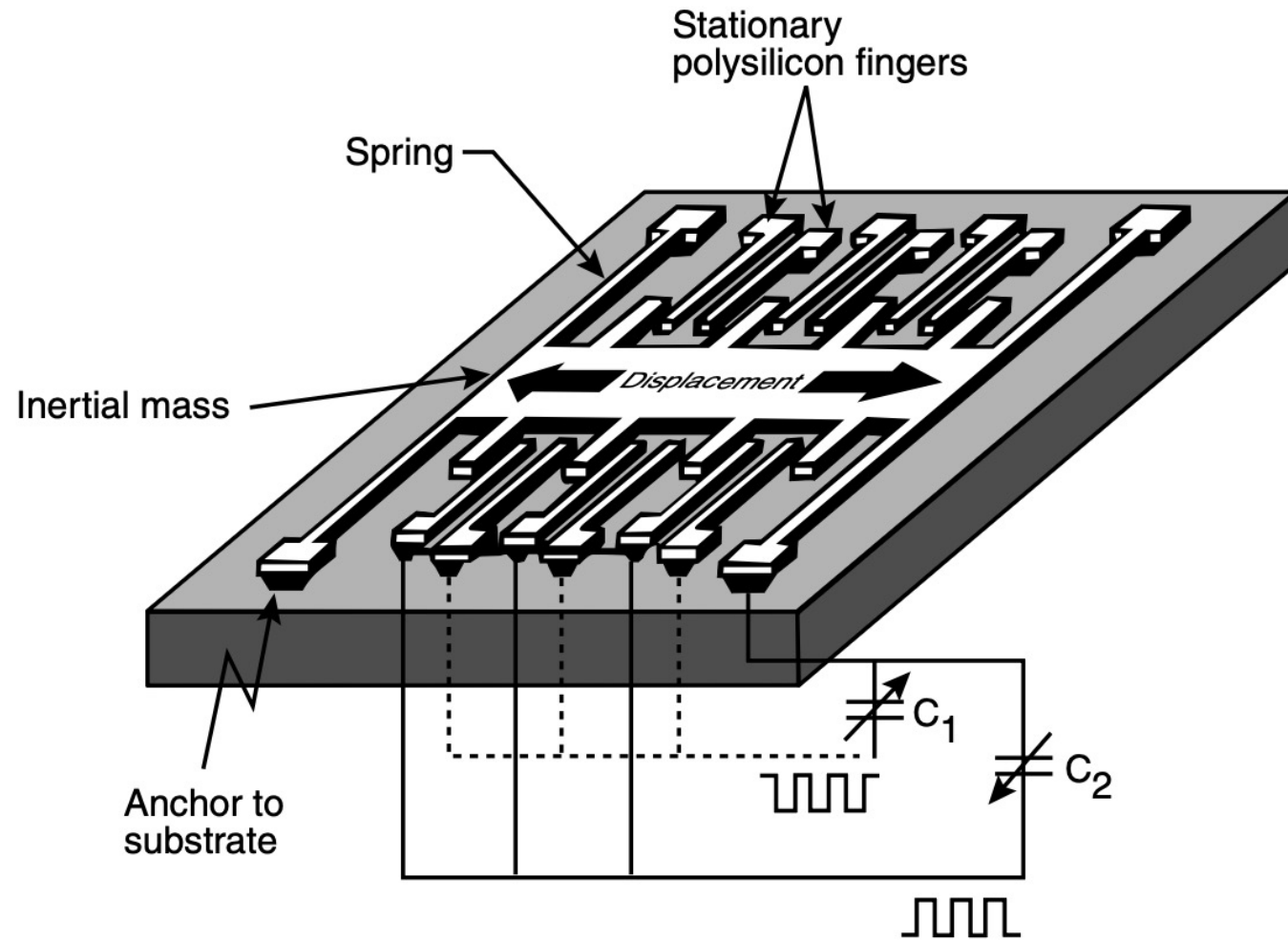
Case Study

- Accelerometer

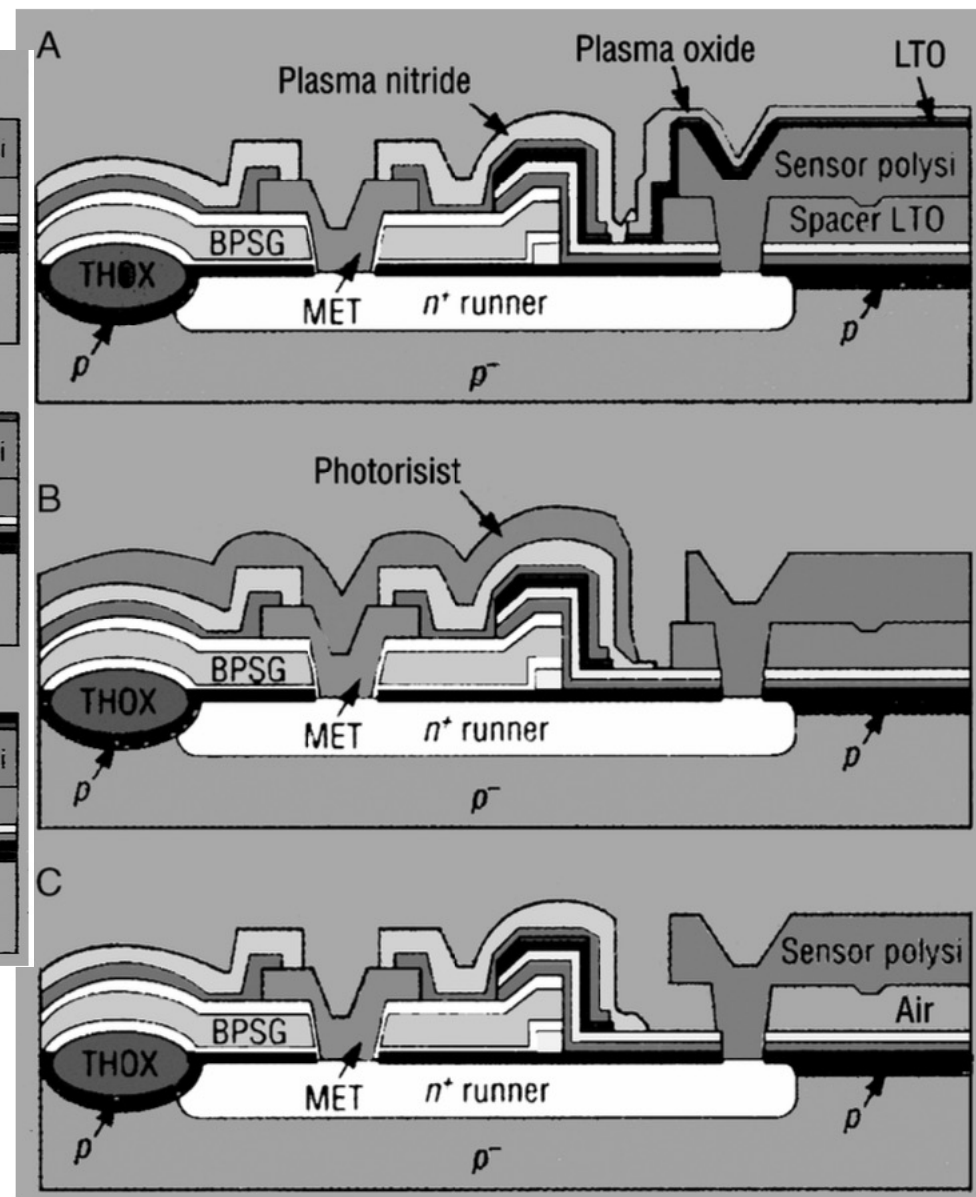
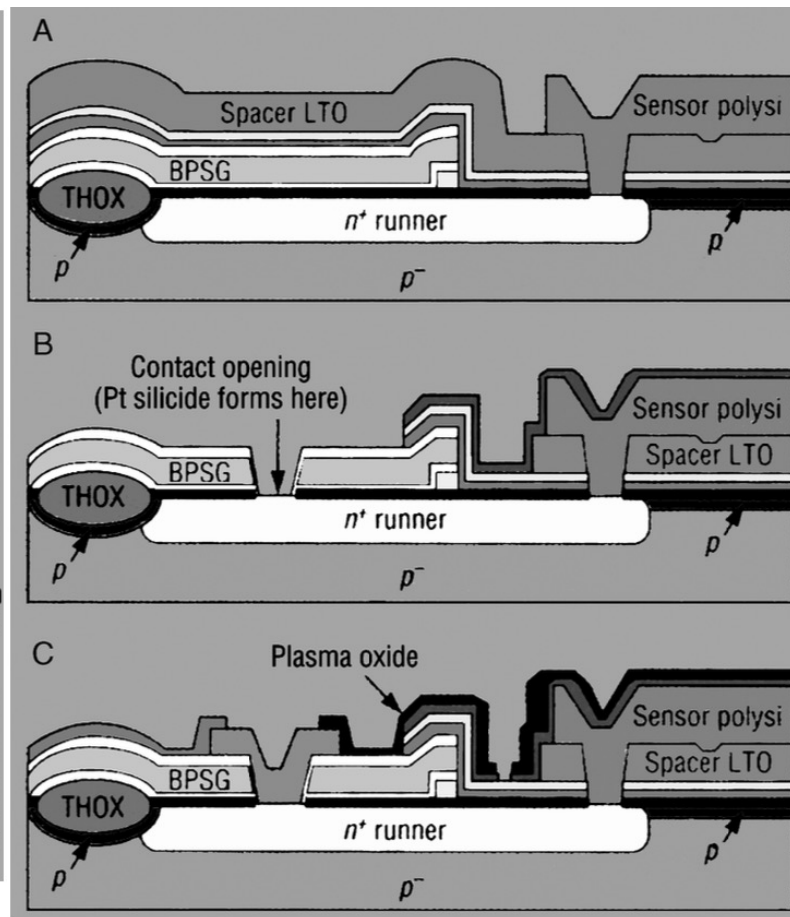
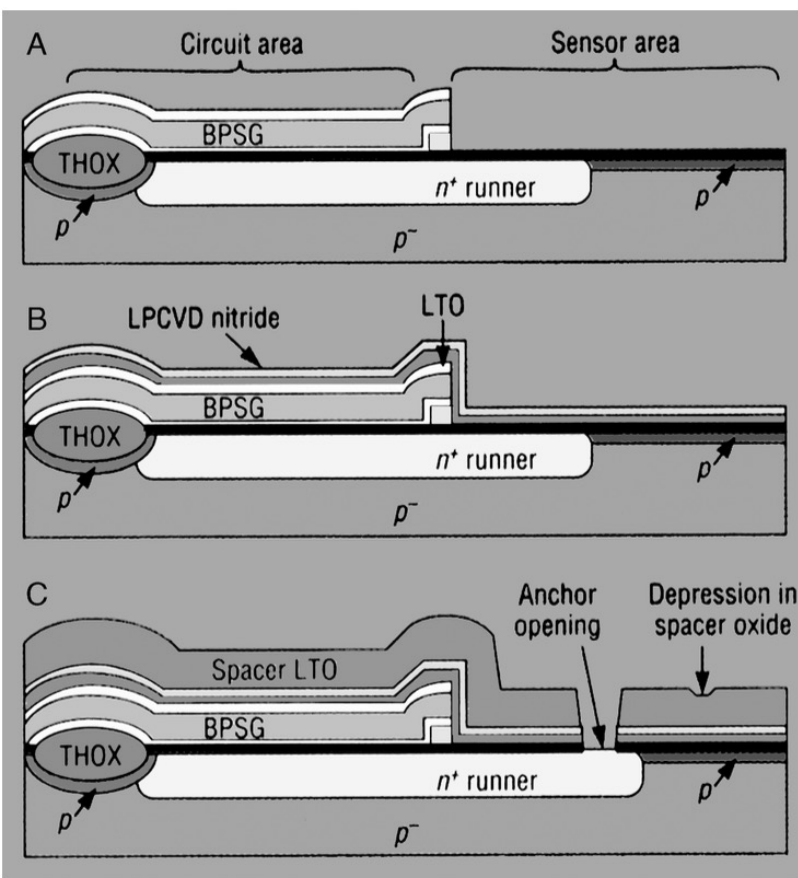
Devices that produces voltage proportional to the acceleration

- Device has on-chip integrated micromachined accelerometer, and on-board electronics
- A 4 μ m process was employed.





- Central proof mass
- Stationary electrodes
- Capacitive readout.
- The sensor takes only 5% of the total die
- The poly-Si features have a thickness of $2\mu\text{m}$.



List of Devices for Term Presentations

1. MEMS Gyroscope
2. Magnetometers
3. MEMS microphone
4. MEMS speakers
5. MEMS Ultrasonic transducers
6. MEMS pressure sensor
7. MEMS Nose – Gas sensing
8. MEMS Humidity sensor
9. Digital micromirror
10. Optical switches
11. RF switch and tuners
12. MEMS Oscillators
13. BAW Filters
14. Microfluidic lab on chip
15. Inkjet printheads
16. micropumps

Polymer Processing Techniques

- Polymers are long-chain repeating monomers.
- Several commonly used polymers are Poly-ethylene, Poly-Vinyl chloride, PTFE (poly tetra-fluoro ethylene), Parylene, PMMA – Poly methyl methacrylate, PDMS – Poly dimethyl siloxanes, etc.
- Two major family of polymers
 - Thermosets (PI, PTFE, Poly ester, ...)
 - Thermoplasts (PE, PC, PMMA, PET, PEEK)
- Some polymers are
 - Amorphous (PMMA, PC, PI)
 - Semi crystalline (PP, PVDF, PET, etc)

Some properties of polymers

Table 18.1 Typical polymer properties

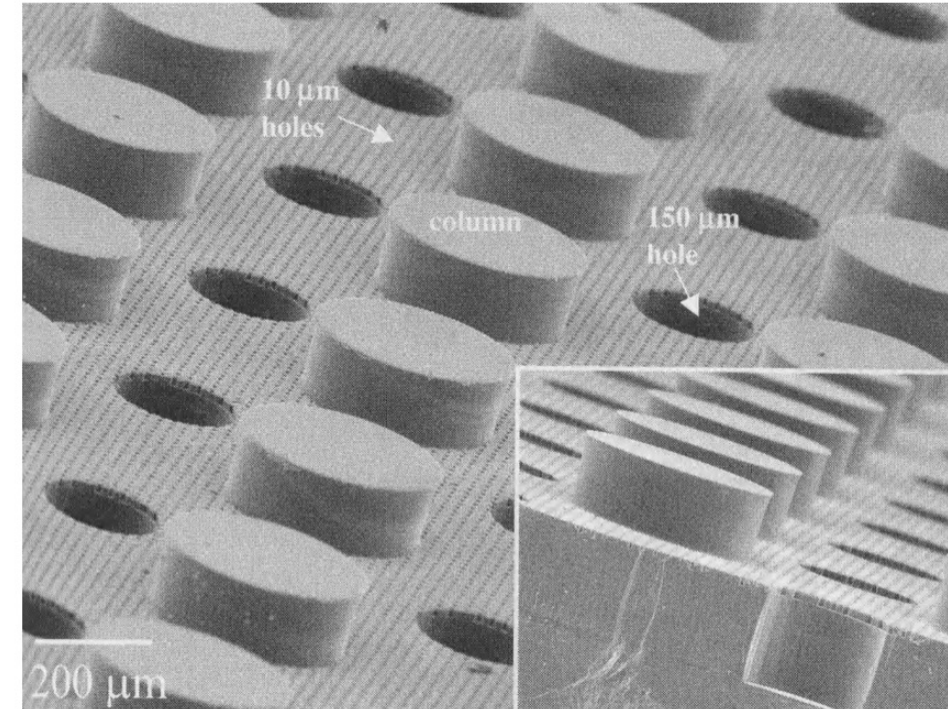
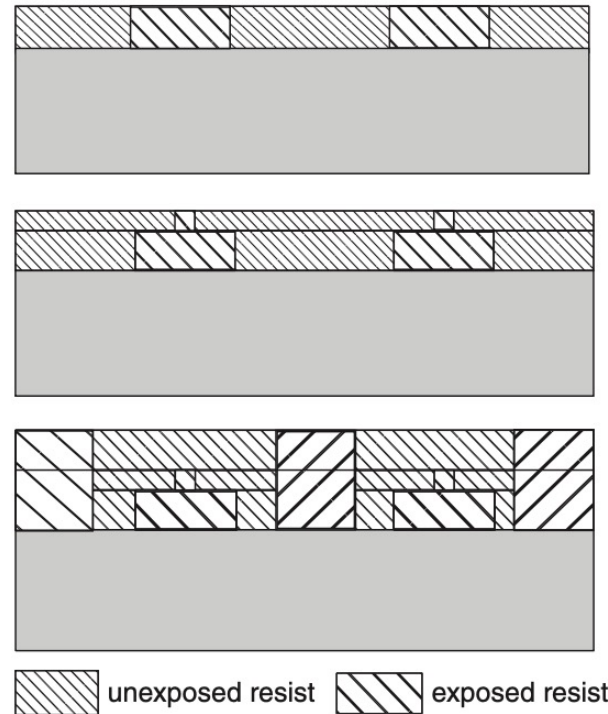
	Value	Comments
Density (kg/m ³)	~1000	Teflon ~2000
Dielectric constant	2–4	SiO ₂ , $\epsilon \sim 4$
Volume resistivity (ohm-cm)	10 ¹⁴ –10 ¹⁷	Similar to SiO ₂ and Si ₃ N ₄
Index of refraction	1.35–1.65	Resists ~1.6
Dielectric strength (MV/cm)	2–3	SiO ₂ ~10
Young's modulus (GPa)	1–5	PDMS ~0.01, SiO ₂ ~76
Tensile strength (MPa)	10–100	Imides even higher
Residual stress (MPa)	10–30	PDMS very low
Water contact angle (deg)	70–100	Imides 50°, PTFE 114°

Table 18.2 Properties of common microfabrication polymers

	T_g (°C)	T_{deg} (°C)	CTE (ppm/°C)	Thermal conductivity (W/K-m)	UV transparency
PMMA	100	200	70	0.2	Opaque
PC	150	230	65	0.2	>350 nm
PDMS	–130	400	300	0.15	>240 nm
SU-8	240	340	100	0.2	>350 nm
Polyimide	400	620	3–50	0.2	Opaque
Parylene	150	290	35	0.1	>300 nm
Teflon	130	330	100	0.1	opaque

Example: High aspect ratio structures

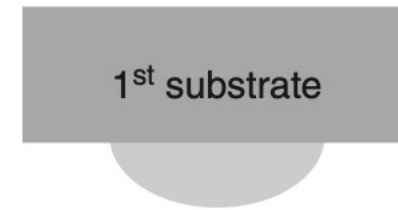
- Very high aspect ratios of 10:1, 50:1 and even 100:1 is possible using special polymer resists such as SU-8.
- multi-layer exposure and baking steps.
- The surface of polymeric materials can also be suitably processed for micro-fluidic examples



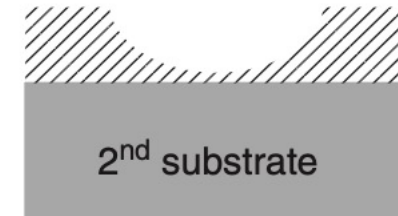
Other processing techniques

- Micromolding:

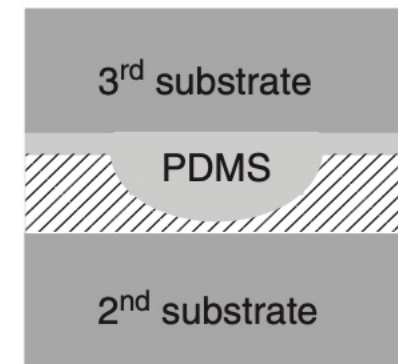
- SU-8 moulds are first made and PDMS replica can be easily formed.
- PDMS is mixed with cross-linking agent
- PDMS being inert, can be cured at 60 – 85 C.



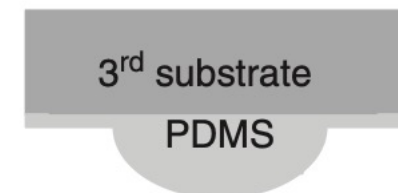
Resist master formed in the first resist by flow above T_g



Stamping 2nd resist by hemispherical 1st resist master



PDMS casting into 2nd resist mould, and bonding to 3rd substrate

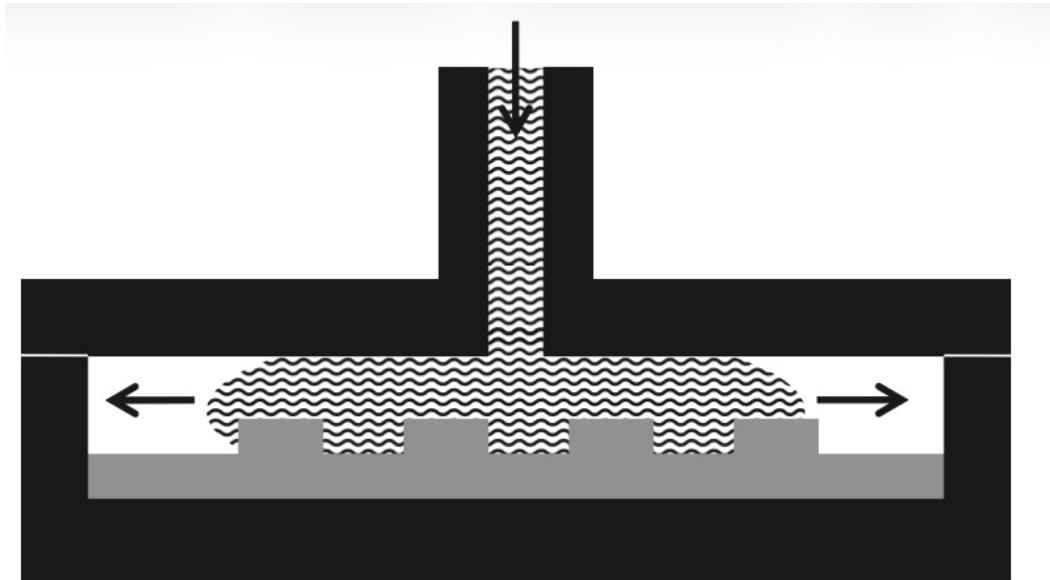


Detachment from mould, PDMS lens ready

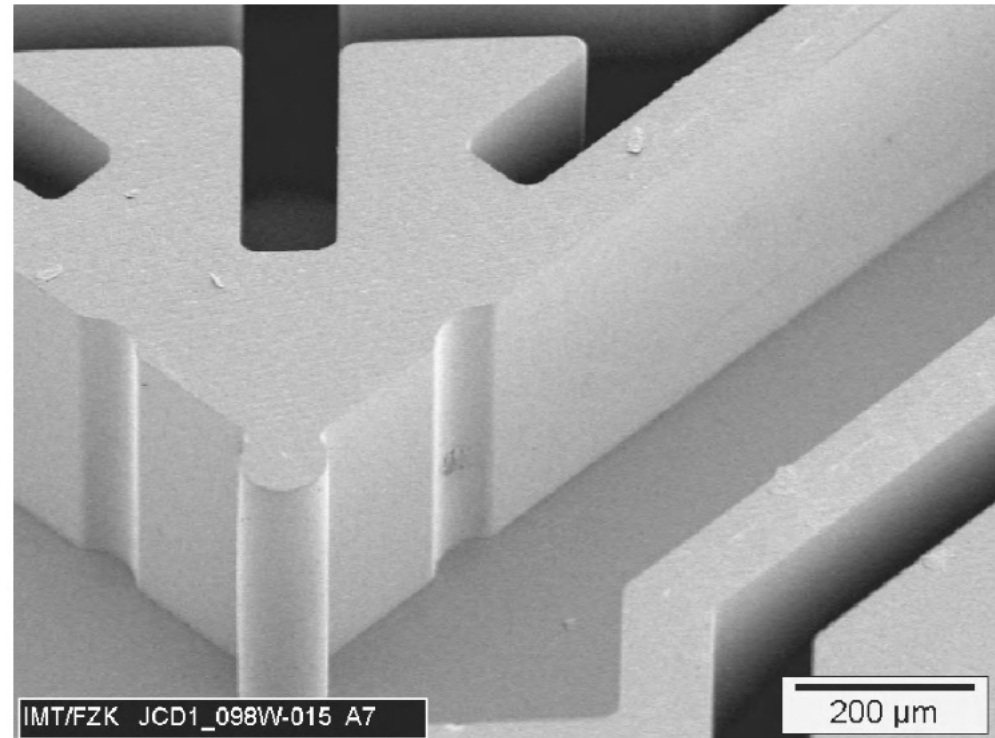
y-direction

x-direction

Injection Molding



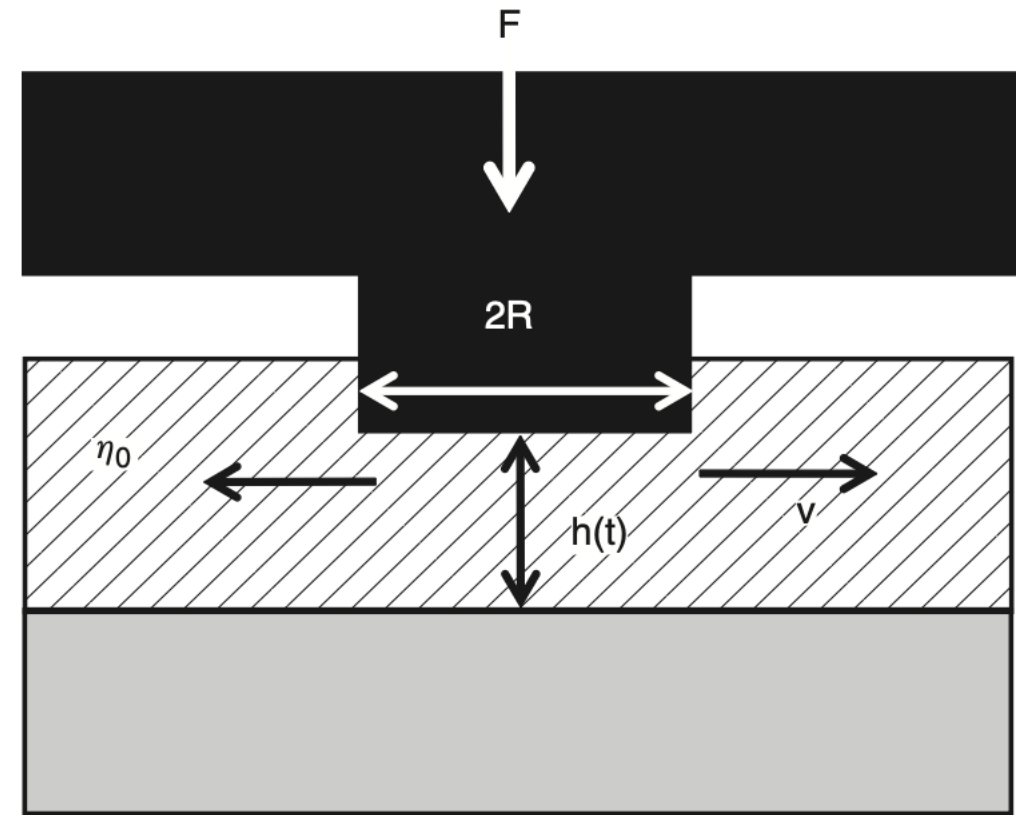
Hot embossing



↓ vacuum pumping

Nanoimprint lithography

- Feature sizes down to 5 nm
- Polymer mold formation at nanoscales
- Thermal imprint lithography works on changing viscosity at increased temperatures
- Pressure-Temperature combination is varied to obtain best results

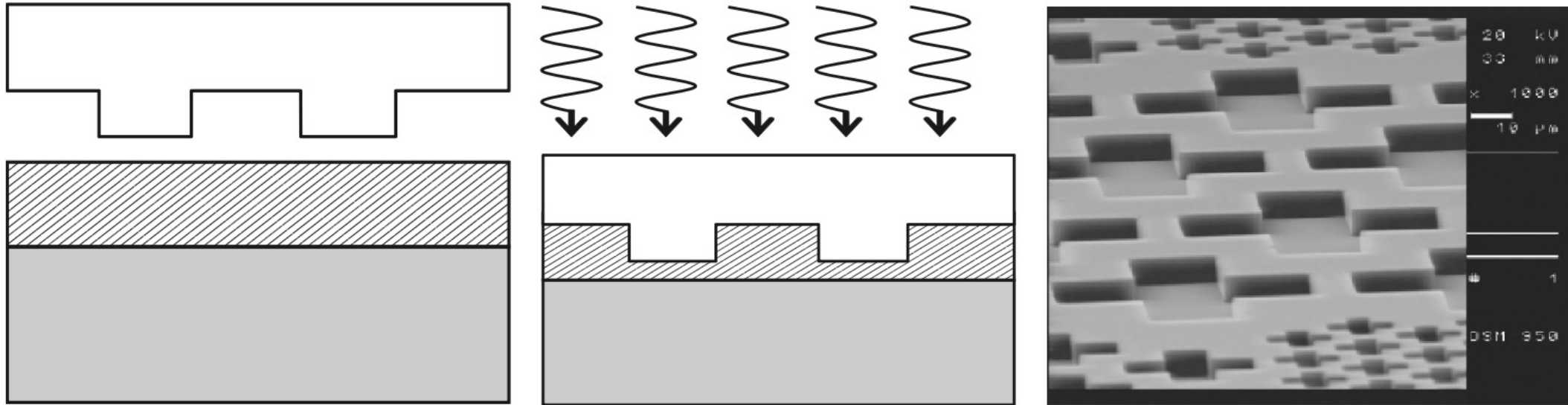


$$F = \eta \frac{3\pi R^4}{2h(t)^3} \frac{dh(t)}{dt}$$

At nanoscales, $h(t)$ is small, one can expect higher F .
But since R is also small, and is in fourth power, it has lower F

Also dh/dt is also small. Therefore, NIL is beneficial at small dimensions

Other improvements



- UV-NIL – The mask is made of transparent material.
 - Once a small indent is made, then the polymer is cured using UV light.
 - UV curing is much faster than thermal curing
 - UV curing does not suffer from thermal mismatches due to polymer shrinkages
 - However, thermal can use stamps made of Si/metals and such.

Processing Polymers

- Polymer deposition:
 - Polymers typically do not adhere well. They do not form out-of-plane bonds.
 - They depend on surface roughness and mechanical interlocking
- Other films can also be deposited on polymers
 - Evaporated films do not stick well
 - Sputtered films stick well on polymers.
- Polymers are not typically etched (Rather molded).
 - If need be, can be etched using Oxygen containing plasma
- Polymers can also be surface polished using a chemical mechanical polishing step.



