MEMS Material Properties

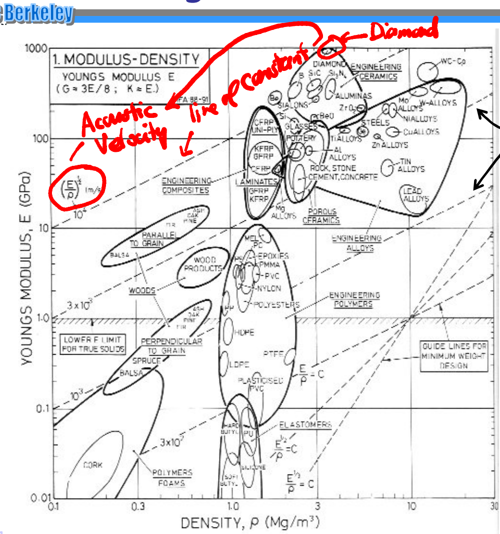
Material Properties for MEMS

Material	Density, ρ, Kg/m³	Modulus, E, GPa	E/ρ GN/kg-m
Silicon	2330	165	72
Silicon Oxide	2200	73	36
Silicon Nitride	3300	304	92
Nickel	8900	207	23
Aluminum	2710	69	25
Aluminum Oxide	3970	393	99
Silicon Carbide	3300	430	130
Diamond	3510	1035	295

Units: $(m/s)^2$ → $\sqrt{(E/\rho)}$ is acoustic velocity

[Mark Spearing, MIT]

Young's Modulus Versus Density



Lines of constant acoustic velocity

[Ashby, Mechanics of Materials, Pergamon, 1992]

Yield Strength

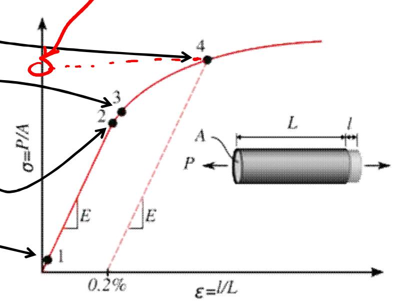
- **Definition**: the stress at which a material experiences significant plastic deformation (defined at 0.2% offset pt.)
- **Below the yield point**: material deforms elastically → returns to its original shape when the applied stress is removed
- **Beyond the yield point**: some fraction of the deformation is permanent and non-reversible

Yield Strength: defined at 0.2% offset pt.

Elastic Limit: stress at which permanent deformation begins

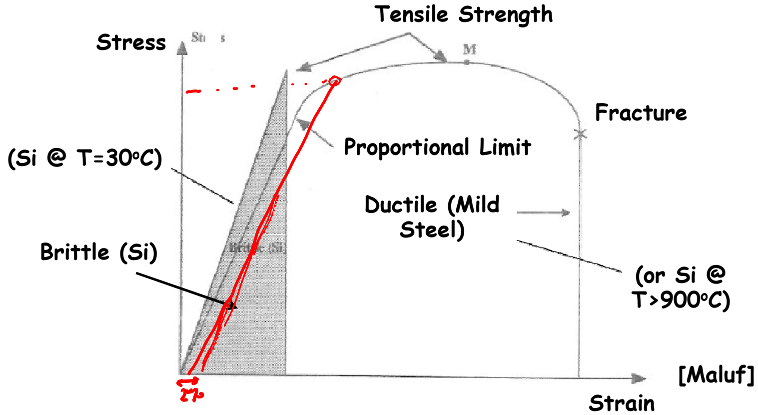
Proportionality Limit: point at which curve goes nonlinear

True Elastic Limit: lowest stress at which dislocations move



Yield Strength (cont.)

- Below: typical stress vs. strain curves for brittle (e.g., Si) and ductile (e.g. steel) materials



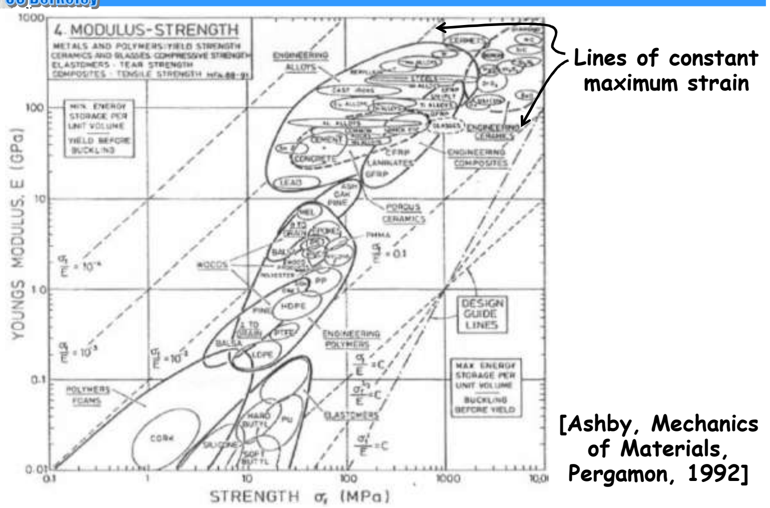
Young's Modulus and Useful Strength

Stored mechanical energy

Material	Modulus, E, GPa	Useful Strength*, σ_f, MPa	$\frac{\sigma_f}{E}$ (-) x 10^{-3}	$\frac{\sigma_f^2}{E}$ MJ/m³
Silicon	165	4000	24	97
Silicon Oxide	73	1000	13	14
Silicon Nitride	304	1000	3	4
Nickel	207	500	2	1.2
Aluminum	69	300	4	1.3
Aluminum Oxide	393	2000	5	10
Silicon Carbide	430	2000	4	9.3
Diamond	1035	1000	1	0.9

From Mark Spearing, MIT, *Future of MEMS Workshop*, Cambridge, England, May 2003

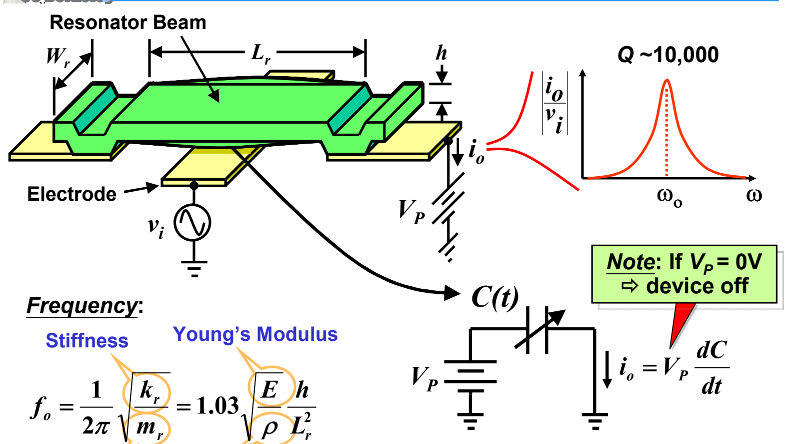
Young's Modulus Versus Strength



[Ashby, Mechanics of Materials, Pergamon, 1992]

Quality Factor (or Q)

Clamped-Clamped Beam μResonator



Note: If V_P = 0V ⇨ device off

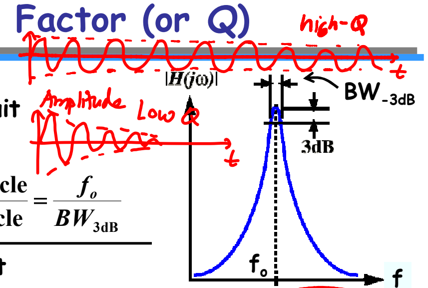
Frequency:

Stiffness · Young's Modulus

$$f_o = \frac{1}{2\pi}\sqrt{\frac{k_r}{m_r}} = 1.03\sqrt{\frac{E}{\rho}}\frac{h}{L_r^2}$$

Density · Mass ➡ (e.g., $m_r = 10^{-13}$ kg) ➡ Smaller mass ⇨ higher freq. range and lower series R_x

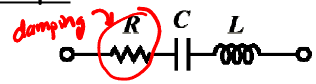
Quality Factor (or Q)



- Measure of the frequency selectivity of a tuned circuit
- **Definition**:

$$Q = \frac{\text{Total Energy Per Cycle}}{\text{Energy Lost Per Cycle}} = \frac{f_o}{BW_{3dB}}$$

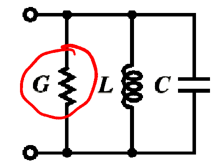
- **Example**: series LCR circuit



$$\Rightarrow Q = \frac{\text{Im}(Z)}{\text{Re}(Z)} = \frac{\omega_o L}{R} = \frac{1}{\omega_o CR}$$

mass · mechanics: $\frac{\omega_o m}{c}$ · damping

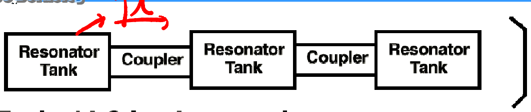
- **Example**: parallel LCR circuit



$$\Rightarrow Q = \frac{\text{Im}(Y)}{\text{Re}(Y)} = \frac{\omega_o C}{G} = \frac{1}{\omega_o LG}$$

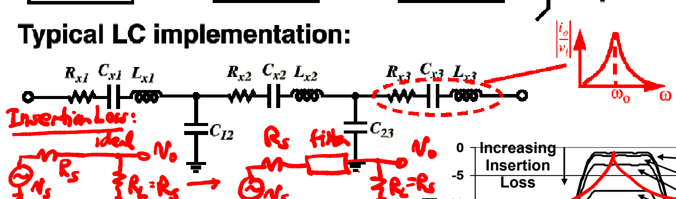
$\sim \frac{1}{2Q}$

Selective Low-Loss Filters: Need Q



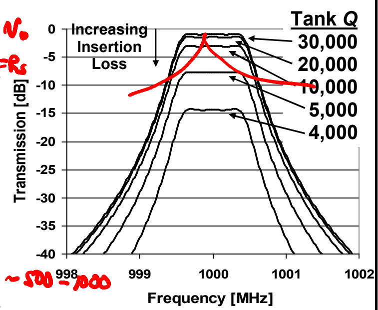
General BPF Implementation

Typical LC implementation:



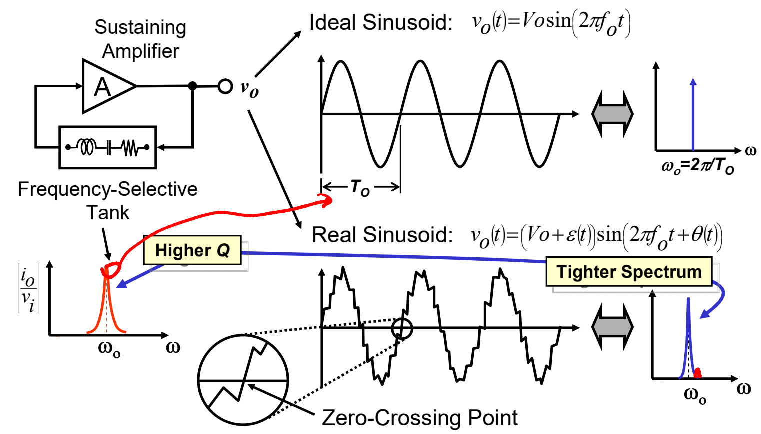
- In resonator-based filters: high tank Q ⇔ low insertion loss
- **At right**: a 0.1% bandwidth, 3-res filter @ 1 GHz (simulated)
  ⇘ heavy insertion loss for resonator Q < 10,000

Filter Today: % BW ~ 3% ← need Q ~ 500–2000



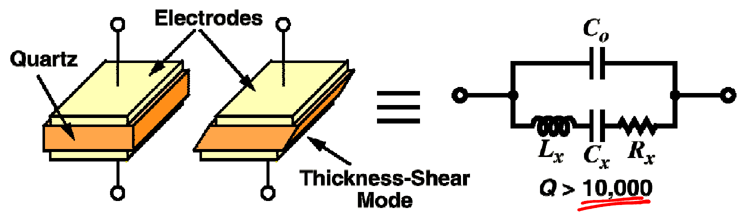
Oscillator: Need for High Q

- **Main Function**: provide a stable output frequency
- **Difficulty**: superposed noise degrades frequency stability



Attaining High Q

- Problem: IC's cannot achieve Q's in the thousands
  - transistors ⇨ consume too much power to get Q
  - on-chip spiral inductors ⇨ Q's no higher than ~10
  - off-chip inductors ⇨ Q's in the range of 100's
- Observation: vibrating mechanical resonances ⇨ Q > 1,000
- Example: quartz crystal resonators (e.g., in wristwatches)
  - extremely high Q's ~ 10,000 or higher (Q ~ 10^6 possible)
  - mechanically vibrates at a distinct frequency in a thickness-shear mode



Energy Dissipation and Resonator Q

Material Defect Losses

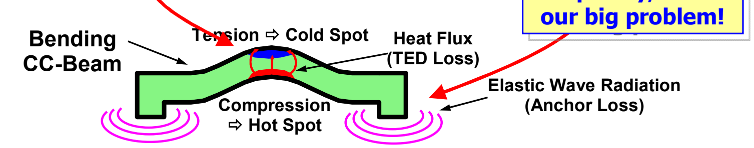
Gas Damping

$$\frac{1}{Q}=\frac{1}{Q_{\text{defects}}}+\frac{1}{Q_{\text{TED}}}+\frac{1}{Q_{\text{viscous}}}+\frac{1}{Q_{\text{support}}}$$

Thermoelastic Damping (TED)

Anchor Losses

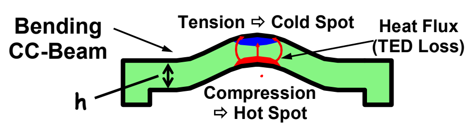
At high frequency, this is our big problem!



Thermoelastic Damping (TED)

- Occurs when heat moves from compressed parts to tensioned parts → heat flux = energy loss

Q ~ 1/2ς



$$\varsigma=\Gamma(T)\Omega(f)=\frac{1}{2Q}$$

$$\Gamma(T)=\frac{\alpha^2 TE}{4\rho C_p}$$

$$\Omega(f_o)=2\left[\frac{f_{TED}f}{f_{TED}^2+f^2}\right]$$

$$f_{TED}=\frac{\pi K}{2\rho C_p h^2}$$

ζ = thermoelastic damping factor
α = thermal expansion coefficient
T = beam temperature
E = elastic modulus
ρ = material density
C_p = heat capacity at const. pressure
K = thermal conductivity
f = beam frequency
h = beam thickness
f_{TED} = characteristic TED frequency

TED Characteristic Frequency

$$f_{TED}=\frac{\pi K}{2\rho C_p h^2}$$

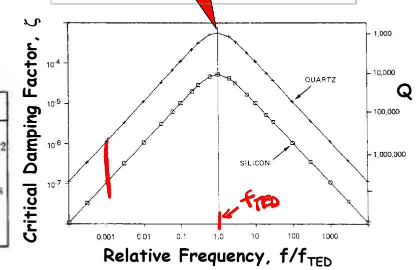
ρ = material density
C_p = heat capacity at const. pressure
K = thermal conductivity
h = beam thickness
f_{TED} = characteristic TED frequency

- Governed by
  - Resonator dimensions
  - Material properties

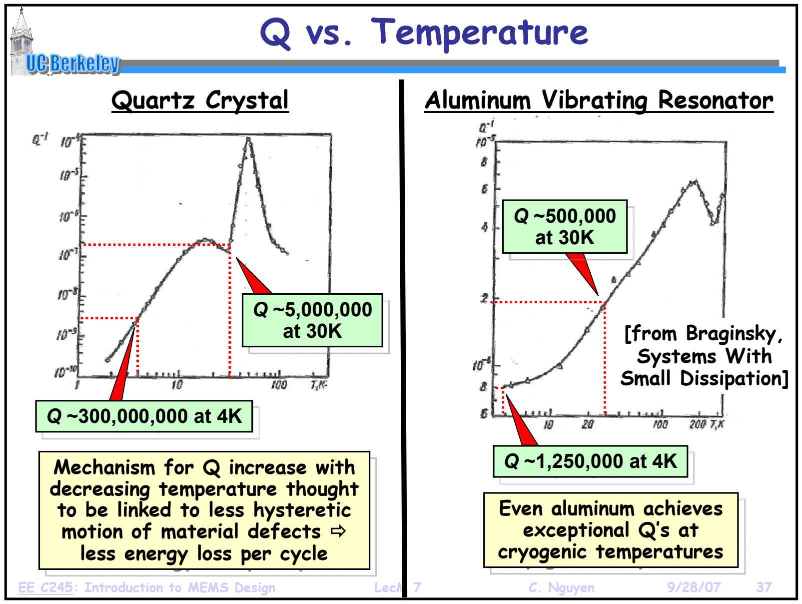
TABLE 1. MATERIAL PROPERTIES

Property	Silicon	Quartz	Units
Thermal expansion	2.60	13.70	ppm/°K
Elastic modulus	1.70	0.78	10^{12} dyne/cm^2
Material density	2.33	2.60	g/cm^3
Heat capacity	0.70	0.75	J/g/°K
Thermal conductivity	1.50	0.10	10^7 dyne/°K/s
Peak damping @ 300°k	1.06	11.34	10^{-4}

Peak where Q is minimized



[from Roszhart, Hilton Head 1990]


Q vs. Temperature
UC Berkeley
Quartz Crystal
Aluminum Vibrating Resonator
Q ~500,000 at 30K
Q ~5,000,000 at 30K
[from Braginsky, Systems With Small Dissipation]
Q ~300,000,000 at 4K
Q ~1,250,000 at 4K
Mechanism for Q increase with decreasing temperature thought to be linked to less hysteretic motion of material defects ⇨ less energy loss per cycle
Even aluminum achieves exceptional Q's at cryogenic temperatures
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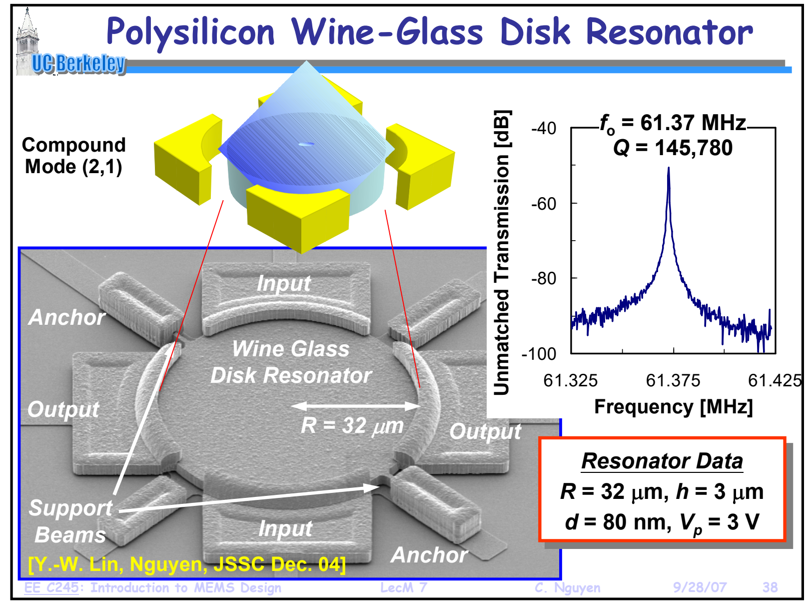
Polysilicon Wine-Glass Disk Resonator
UC Berkeley
Compound Mode (2,1)
Input
Anchor
Wine Glass Disk Resonator
Output
R = 32 μm
Output
Support Beams
Input
Anchor
[Y.-W. Lin, Nguyen, JSSC Dec. 04]
Unmatched Transmission [dB]
-40
-60
-80
-100
f_o = 61.37 MHz
Q = 145,780
61.325
61.375
61.425
Frequency [MHz]
Resonator Data
R = 32 μm, h = 3 μm
d = 80 nm, V_p = 3 V
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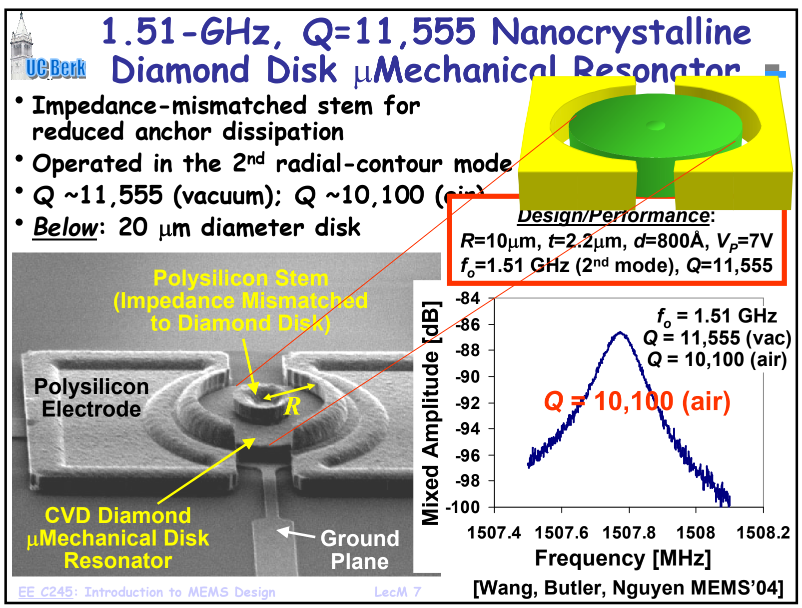
1.51-GHz, Q=11,555 Nanocrystalline Diamond Disk μMechanical Resonator
UC Berk
• Impedance-mismatched stem for reduced anchor dissipation
• Operated in the 2nd radial-contour mode
• Q ~11,555 (vacuum); Q ~10,100 (air)
• Below: 20 μm diameter disk
Design/Performance:
R=10μm, t=2.2μm, d=800Å, V_P=7V
f_o=1.51 GHz (2nd mode), Q=11,555
Polysilicon Stem (Impedance Mismatched to Diamond Disk)
Polysilicon Electrode
R
CVD Diamond μMechanical Disk Resonator
Ground Plane
Mixed Amplitude [dB]
-84
-86
-88
-90
-92
-94
-96
-98
-100
f_o = 1.51 GHz
Q = 11,555 (vac)
Q = 10,100 (air)
Q = 10,100 (air)
1507.4
1507.6
1507.8
1508
1508.2
Frequency [MHz]
[Wang, Butler, Nguyen MEMS'04]
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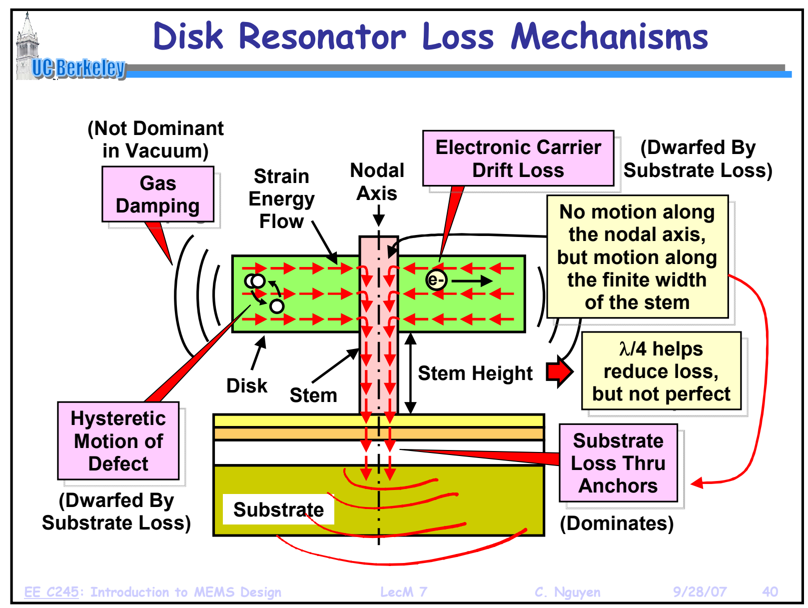
Disk Resonator Loss Mechanisms
UC Berkeley
(Not Dominant in Vacuum)
Gas Damping
Strain Energy Flow
Nodal Axis
Electronic Carrier Drift Loss
(Dwarfed By Substrate Loss)
No motion along the nodal axis, but motion along the finite width of the stem
e-
Disk
Stem
Stem Height
λ/4 helps reduce loss, but not perfect
Hysteretic Motion of Defect
(Dwarfed By Substrate Loss)
Substrate
Substrate Loss Thru Anchors
(Dominates)
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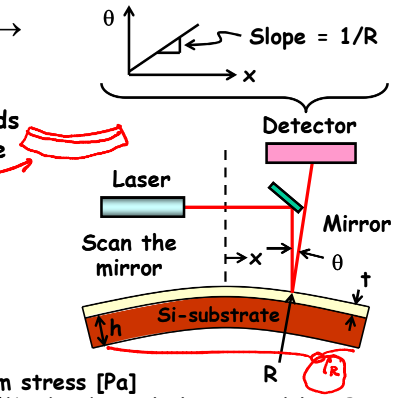
UC Berkeley

MEMS Material Property Test Structures

UC Berkeley

Stress Measurement Via Wafer Curvature

- Compressively stressed film → bends a wafer into a convex shape
- Tensile stressed film → bends a wafer into a concave shape
- Can optically measure the deflection of the wafer before and after the film is deposited
- Determine the radius of curvature R, then apply:



$$\sigma = \frac{E'h^2}{6Rt}$$

σ = film stress [Pa]
E' = E/(1-ν) = biaxial elastic modulus [Pa]
h = substrate thickness [m]
t = film thickness
R = substrate radius of curvature [m]

UC Berkeley

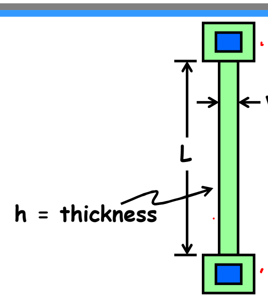
MEMS Stress Test Structure

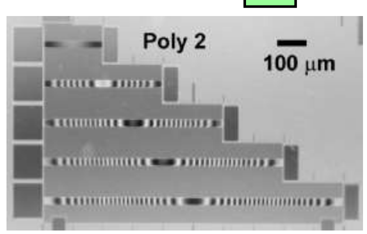
- Simple Approach: use a clamped-clamped beam
  - Compressive stress causes buckling
  - Arrays with increasing length are used to determine the critical buckling load, where

$$\sigma_{critical} = -\frac{\pi^2}{3}\frac{Eh^2}{L^2}$$

E = Young's modulus [Pa]
I = (1/12)Wh³ = moment of inertia
L, W, h indicated in the figure

  - Limitation: Only compressive stress is measurable





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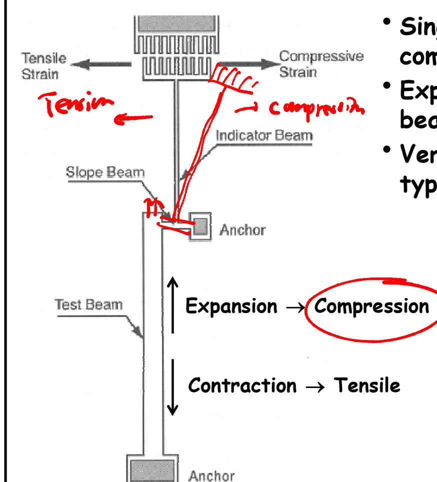
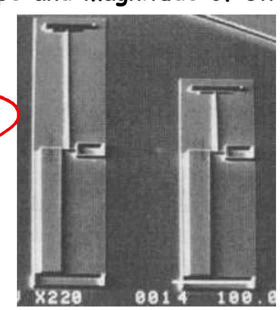
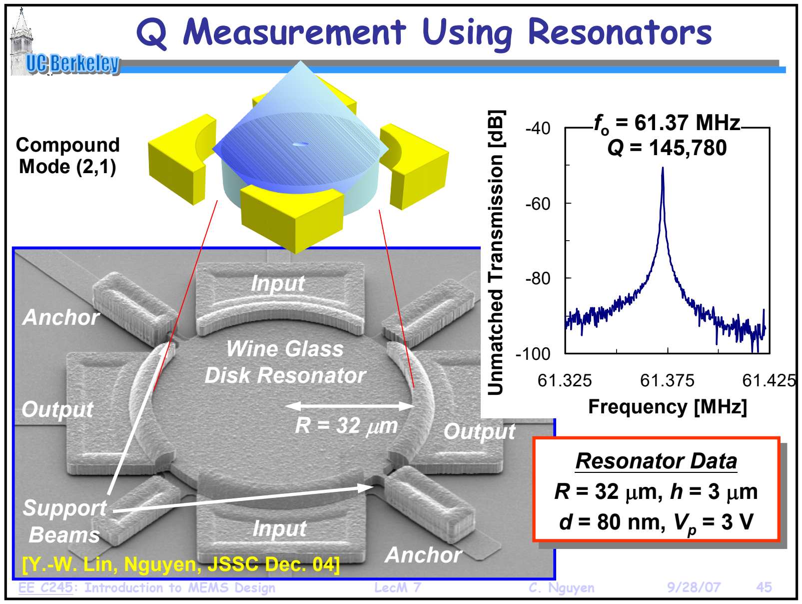
More Effective Stress Diagnostic

- Single structure measures both compressive and tensile stress
- Expansion or contraction of test beam → deflection of pointer
- Vernier movement indicates type and magnitude of stress






Q Measurement Using Resonators
Compound Mode (2,1)
f_o = 61.37 MHz
Q = 145,780
Unmatched Transmission [dB]
-40
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-100
61.325
61.375
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Frequency [MHz]
Input
Anchor
Wine Glass Disk Resonator
Output
R = 32 μm
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Support Beams
Input
Anchor
[Y.-W. Lin, Nguyen, JSSC Dec. 04]
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R = 32 μm, h = 3 μm
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