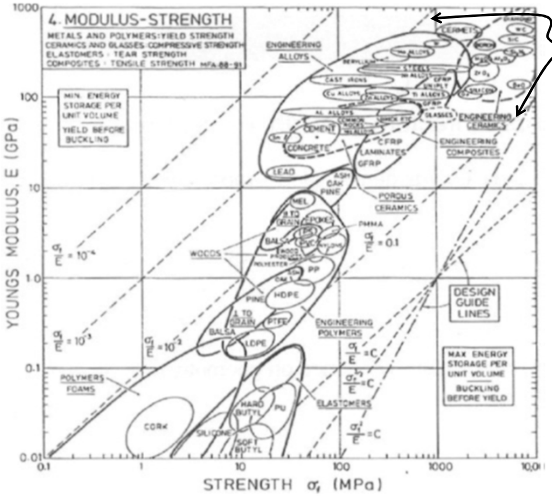
Young's Modulus Versus Strength

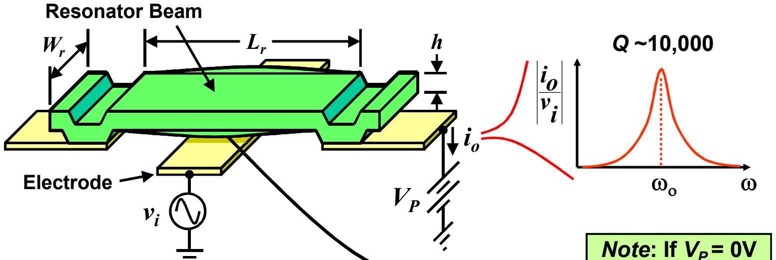


Lines of constant maximum strain

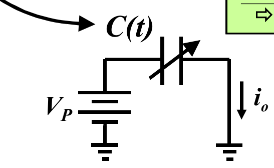
[Ashby, Mechanics of Materials, Pergamon, 1992]

Quality Factor (or Q)

Clamped-Clamped Beam μResonator



Note: If $V_P = 0V$ ⇨ device off



$$i_o = V_P \frac{dC}{dt}$$

Frequency:

Stiffness Young's Modulus

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

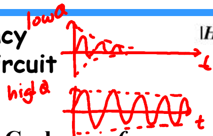
Density

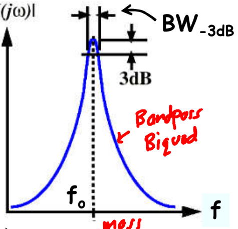
Mass (e.g., $m_r = 10^{-13}$ kg)

Smaller mass ⇨ higher freq. range and lower series R_x

Quality Factor (or Q)

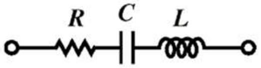
- Measure of the frequency selectivity of a tuned circuit
- Definition:





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

- Example: series LCR circuit



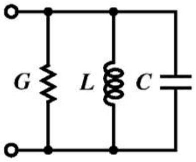
$$⇨ \quad Q = \frac{\mathrm{Im}(Z)}{\mathrm{Re}(Z)} = \frac{\omega_o L}{R} = \frac{1}{\omega_o CR}$$

mass

damping

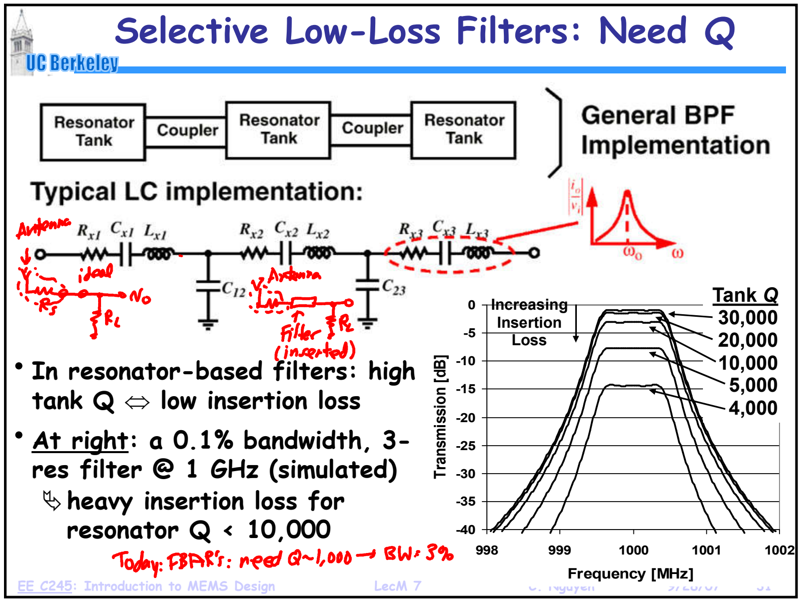
mechanical: $\frac{\omega_o m}{c}$

- Example: parallel LCR circuit



$$⇨ \quad Q = \frac{\mathrm{Im}(Y)}{\mathrm{Re}(Y)} = \frac{\omega_o C}{G} = \frac{1}{\omega_o LG}$$

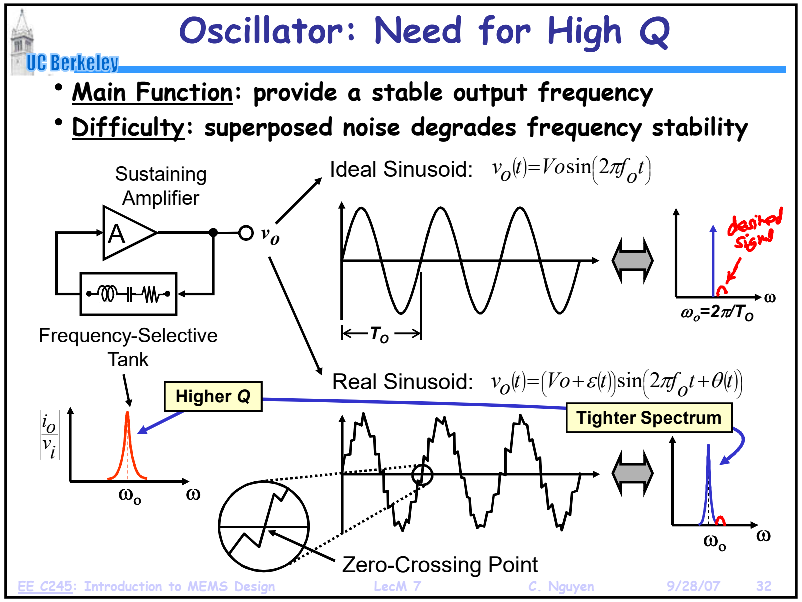
conductance = G = $\frac{1}{R}$



Selective Low-Loss Filters: Need Q

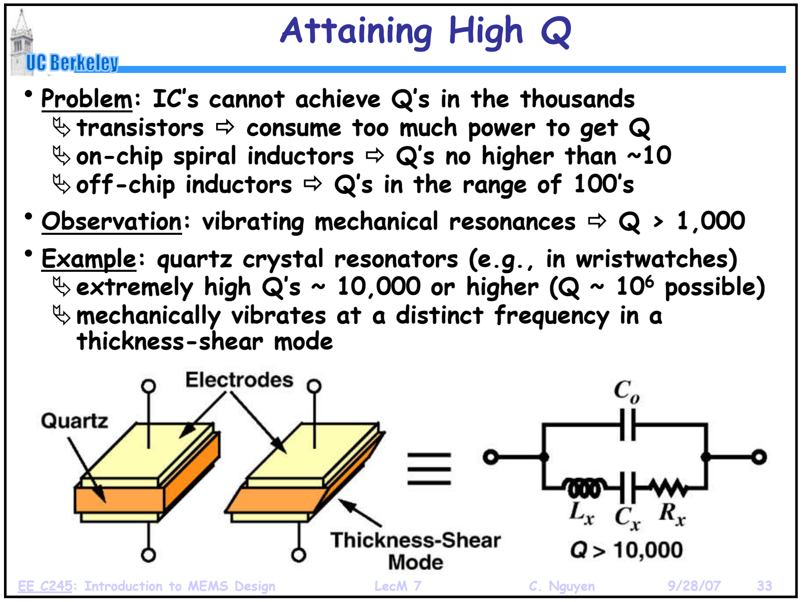
- In resonator-based filters: high tank Q ⇔ low insertion loss
- At right: a 0.1% bandwidth, 3-res filter @ 1 GHz (simulated)
  - heavy insertion loss for resonator Q < 10,000

Today: FBAR's: need Q~1,000 → BW: 3%



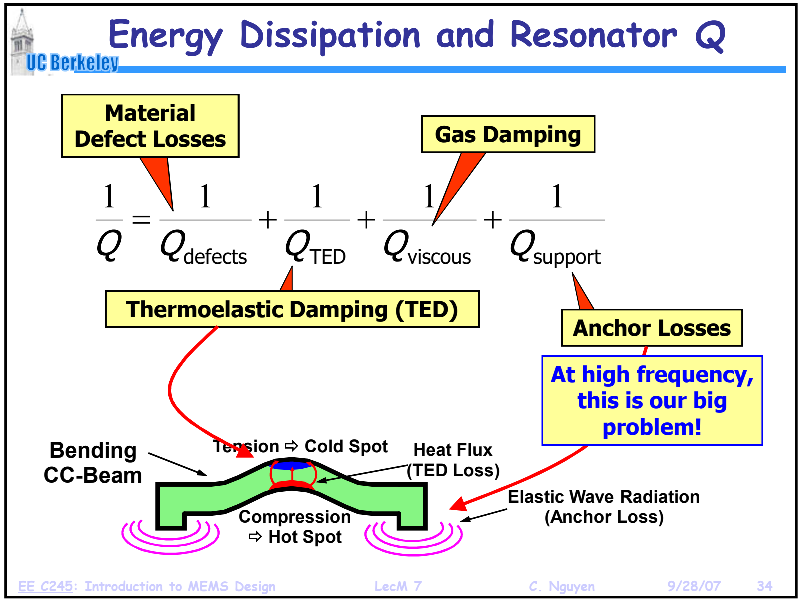
Oscillator: Need for High Q

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



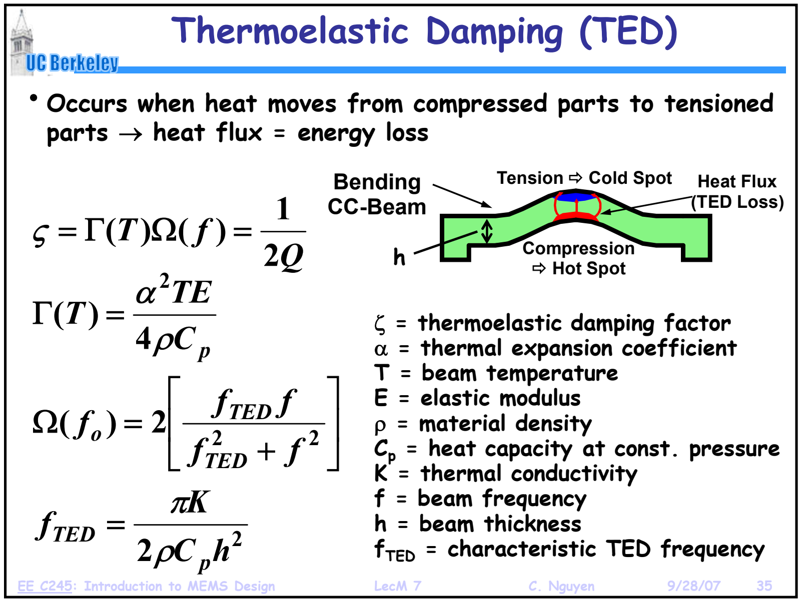
Attaining High Q

- **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

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



Thermoelastic Damping (TED)

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

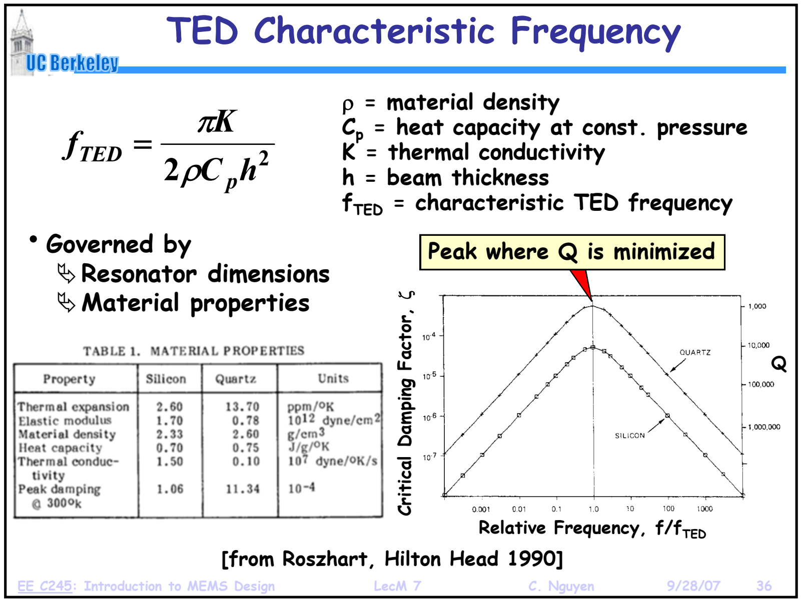
$$\varsigma = \Gamma(T)\Omega(f) = \frac{1}{2Q}$$

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

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

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

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

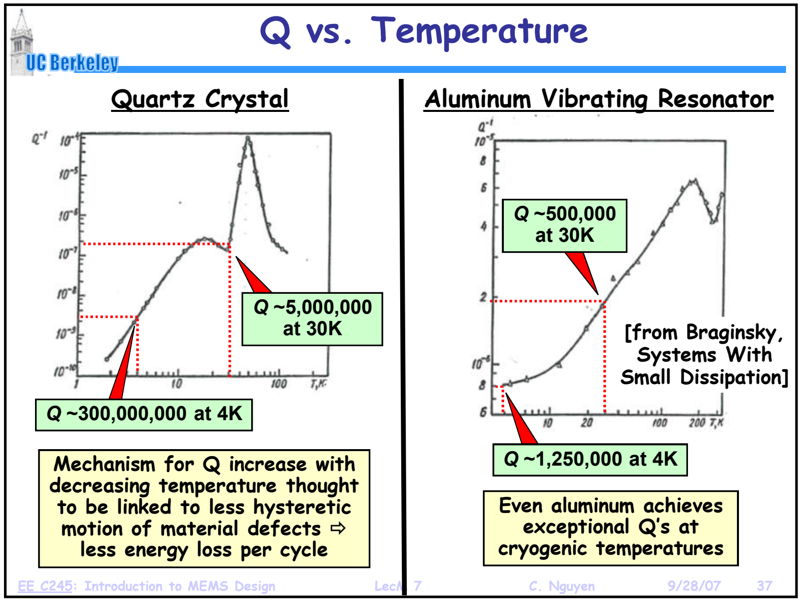
- Governed by
  - Resonator dimensions
  - Material properties

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

Quartz Crystal

Q ~5,000,000 at 30K

Q ~300,000,000 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

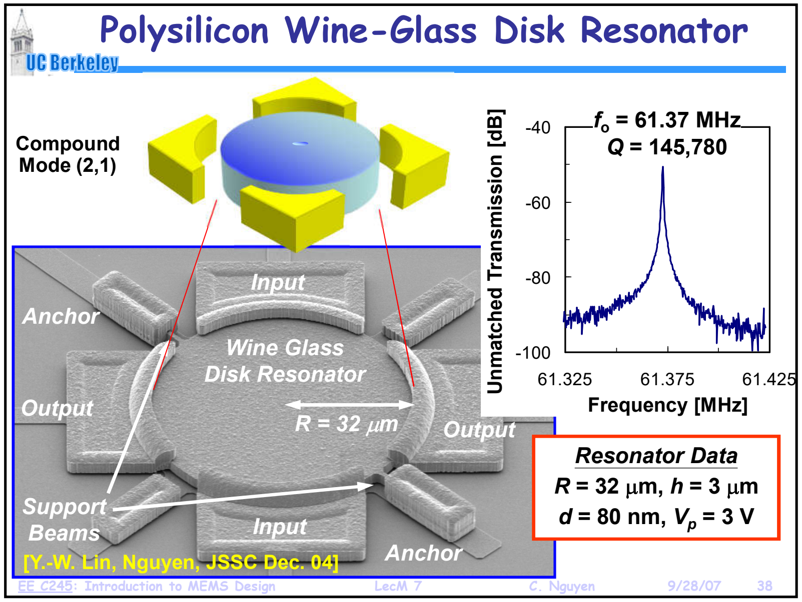
Aluminum Vibrating Resonator

Q ~500,000 at 30K

[from Braginsky, Systems With Small Dissipation]

Q ~1,250,000 at 4K

Even aluminum achieves exceptional Q's at cryogenic temperatures

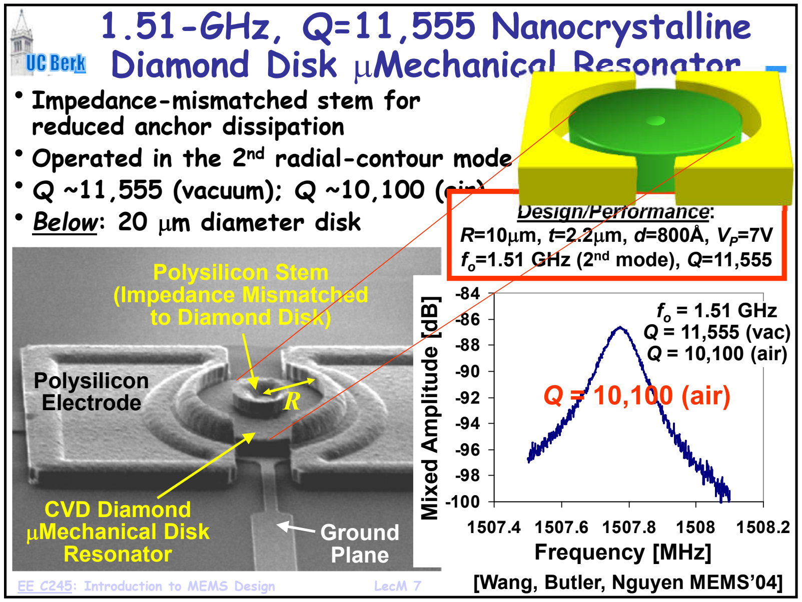


Polysilicon Wine-Glass Disk Resonator

f_o = 61.37 MHz
Q = 145,780

[Y.-W. Lin, Nguyen, JSSC Dec. 04]

Resonator Data
R = 32 μm, h = 3 μm
d = 80 nm, V_p = 3 V

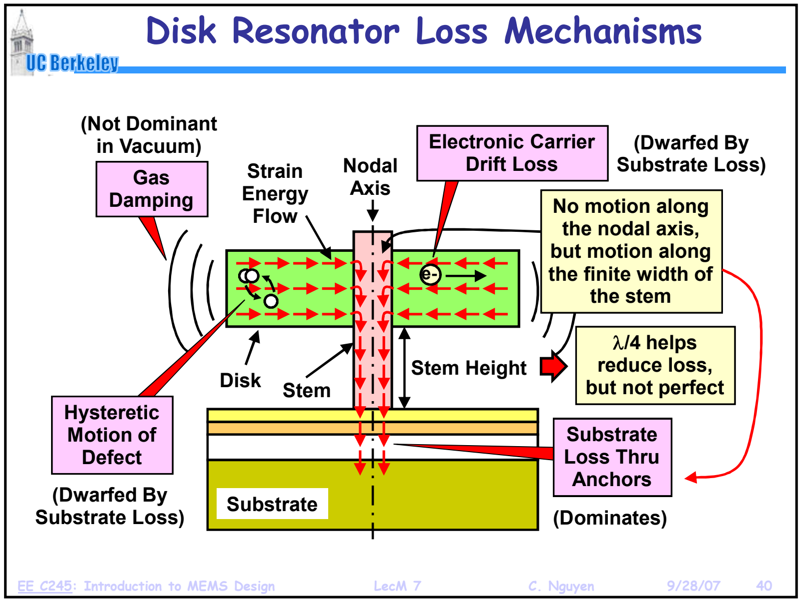


1.51-GHz, Q=11,555 Nanocrystalline Diamond Disk μMechanical Resonator

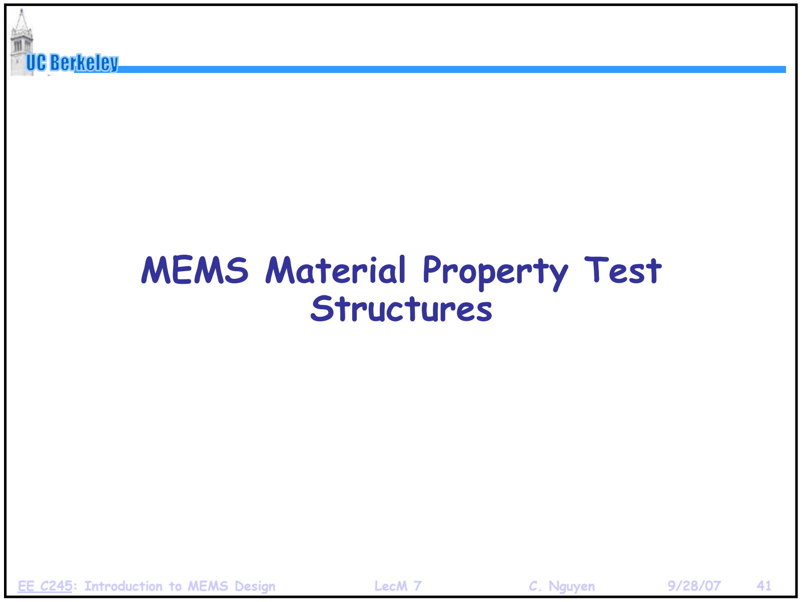
- Impedance-mismatched stem for reduced anchor dissipation
- Operated in the 2nd radial-contour mode
- Q ~11,555 (vacuum); Q ~10,100 (air)
- *Below*: 20 μm diameter disk

Design/Performance:
R=10μm, t=2.2μm, d=800Å, V_P=7V
f_o=1.51 GHz (2nd mode), Q=11,555

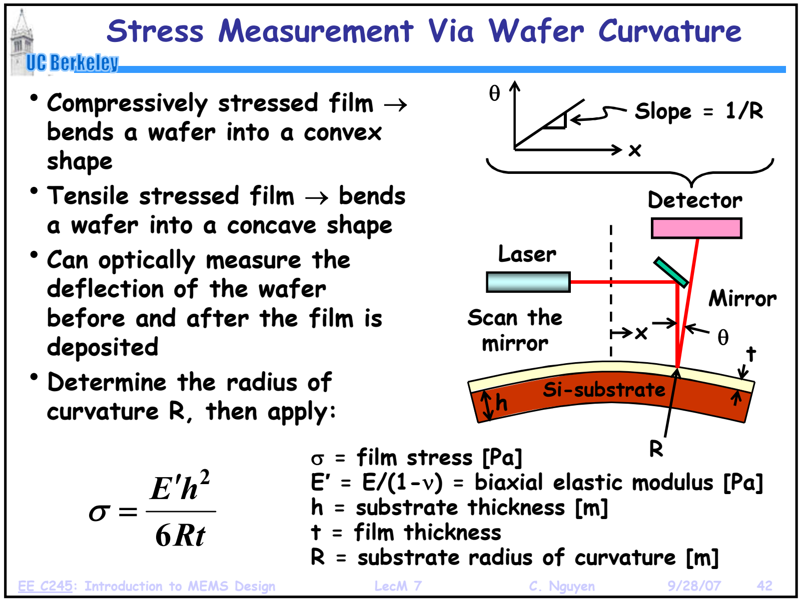
[Wang, Butler, Nguyen MEMS'04]



Disk Resonator Loss Mechanisms



MEMS Material Property Test Structures

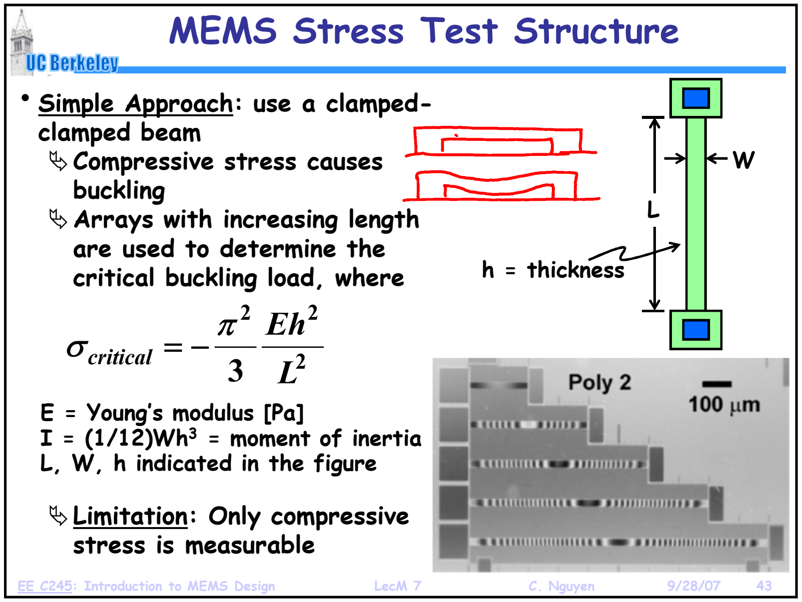


Stress Measurement Via Wafer Curvature

- 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]



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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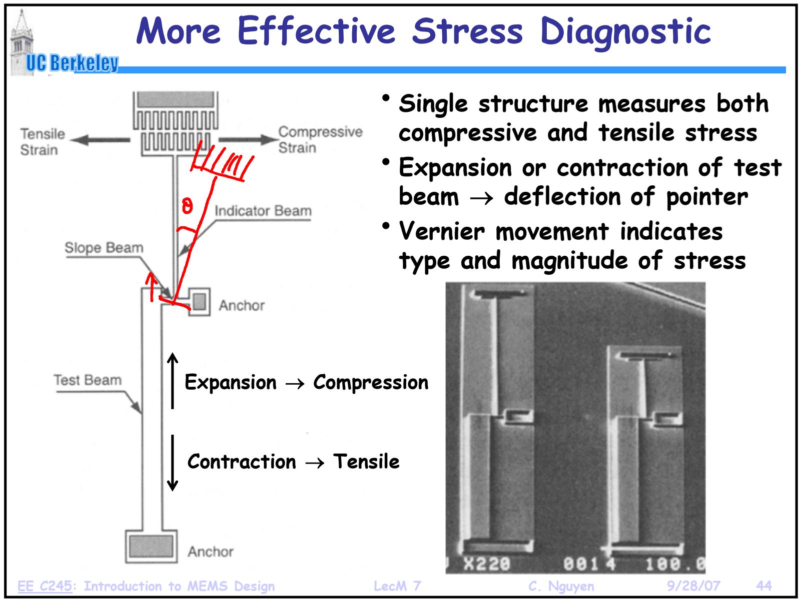

More Effective Stress Diagnostic

- 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

Expansion → Compression

Contraction → Tensile

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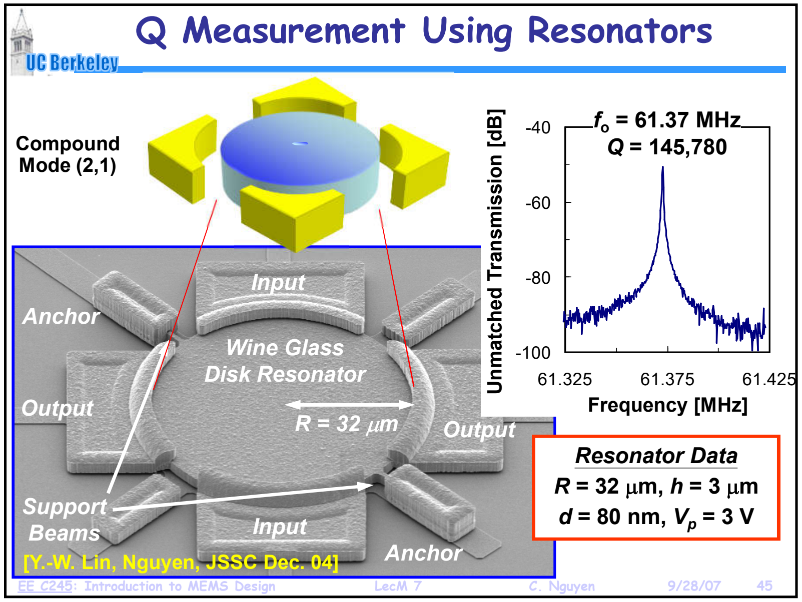

Q Measurement Using Resonators

[Y.-W. Lin, Nguyen, JSSC Dec. 04]

Resonator Data
$R = 32\ \mu m$, $h = 3\ \mu m$
$d = 80\ nm$, $V_p = 3\ V$

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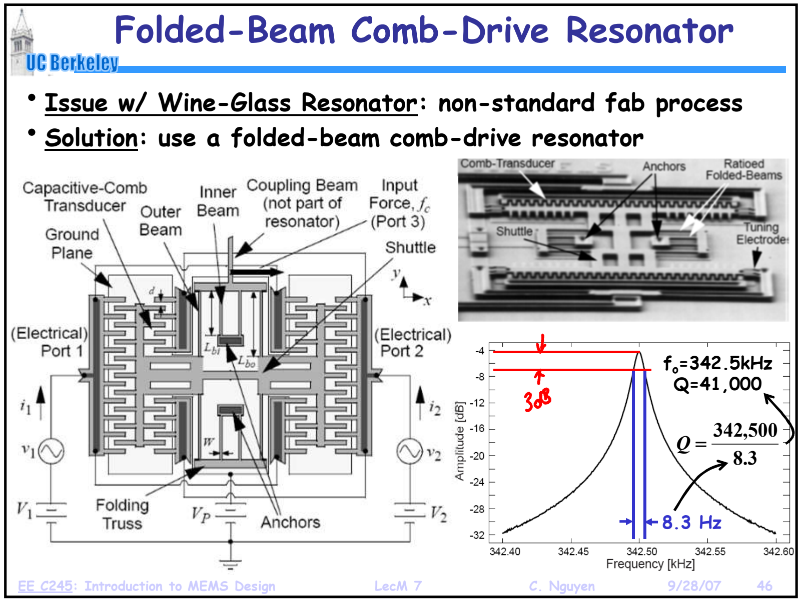

Folded-Beam Comb-Drive Resonator

- **Issue w/ Wine-Glass Resonator**: non-standard fab process
- **Solution**: use a folded-beam comb-drive resonator

$$Q = \frac{342{,}500}{8.3}$$

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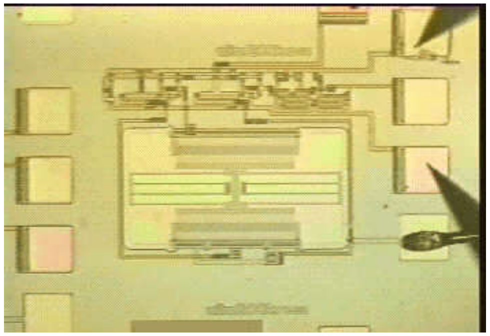
Comb-Drive Resonator in Action

- **Below**: fully integrated micromechanical resonator oscillator using a MEMS-last integration approach



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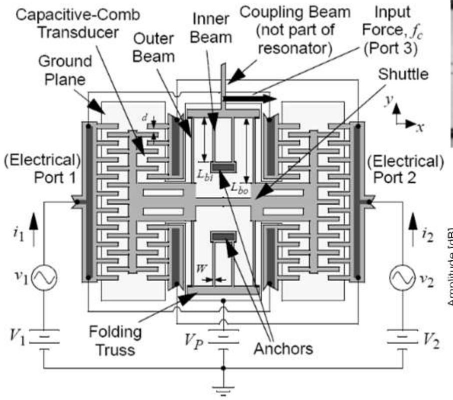
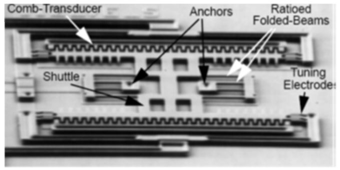
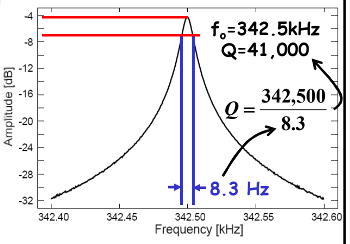






f_o=342.5kHz
Q=41,000

$$Q = \frac{342{,}500}{8.3}$$

Measurement of Young's Modulus

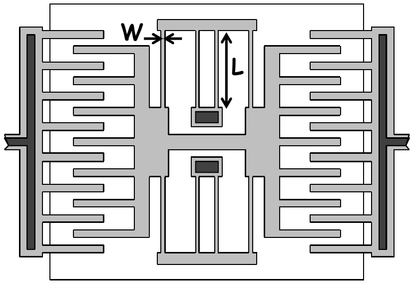
- Use micromechanical resonators
  - ↳ Resonance frequency depends on E
  - ↳ For a folded-beam resonator:

Young's modulus

$$\text{Resonance Frequency} = f_o = \left[\frac{4Eh(W/L)^3}{M_{eq}}\right]^{1/2}$$

Equivalent mass

h = thickness



- Extract E from measured frequency f_o
- Measure f_o for several resonators with varying dimensions
- Use multiple data points to remove uncertainty in some parameters

Anisotropic Materials

Elastic Constants in Crystalline Materials

- Get different elastic constants in different crystallographic directions → 81 of them in all
  - Cubic symmetries make 60 of these terms zero, leaving 21 of them remaining that need be accounted for
- Thus, describe stress-strain relations using a 6x6 matrix

$$\underbrace{\begin{bmatrix}\sigma_x\\ \sigma_y\\ \sigma_z\\ \tau_{yz}\\ \tau_{zx}\\ \tau_{xy}\end{bmatrix}}_{\text{Stresses}}=\underbrace{\begin{bmatrix}C_{11}&C_{12}&C_{13}&C_{14}&C_{15}&C_{16}\\ C_{12}&C_{22}&C_{23}&C_{24}&C_{25}&C_{26}\\ C_{13}&C_{23}&C_{33}&C_{34}&C_{35}&C_{36}\\ C_{14}&C_{24}&C_{34}&C_{44}&C_{45}&C_{46}\\ C_{15}&C_{25}&C_{35}&C_{45}&C_{55}&C_{56}\\ C_{16}&C_{26}&C_{36}&C_{46}&C_{56}&C_{66}\end{bmatrix}}_{\text{Stiffness Coefficients}}\underbrace{\begin{bmatrix}\varepsilon_x\\ \varepsilon_y\\ \varepsilon_z\\ \gamma_{yz}\\ \gamma_{zx}\\ \gamma_{xy}\end{bmatrix}}_{\text{Strains}}$$

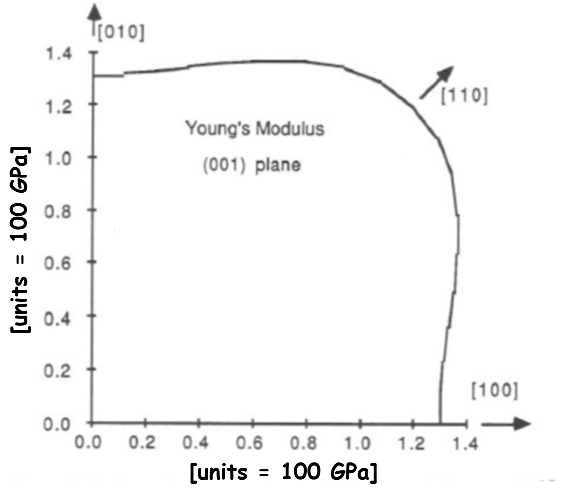
Stiffness Coefficients of Silicon

- Due to symmetry, only a few of the 21 coefficients are non-zero
- With cubic symmetry, silicon has only 3 independent components, and its stiffness matrix can be written as:

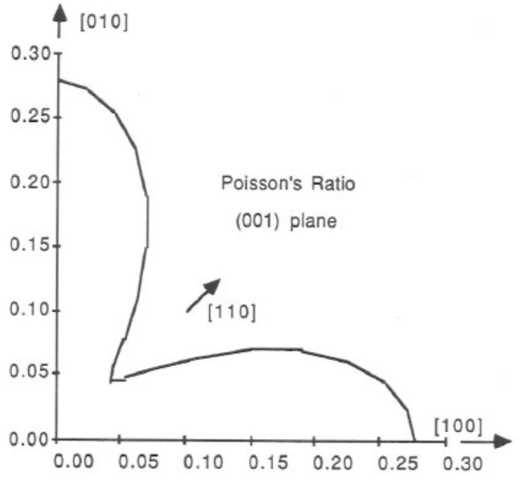
$$\begin{bmatrix}\sigma_x\\ \sigma_y\\ \sigma_z\\ \tau_{yz}\\ \tau_{zx}\\ \tau_{xy}\end{bmatrix}=\begin{bmatrix}C_{11}&C_{12}&C_{13}&0&0&0\\ C_{12}&C_{22}&C_{23}&0&0&0\\ C_{13}&C_{23}&C_{33}&0&0&0\\ 0&0&0&C_{44}&0&0\\ 0&0&0&0&C_{55}&0\\ 0&0&0&0&0&C_{66}\end{bmatrix}\begin{bmatrix}\varepsilon_x\\ \varepsilon_y\\ \varepsilon_z\\ \gamma_{yz}\\ \gamma_{zx}\\ \gamma_{xy}\end{bmatrix}$$

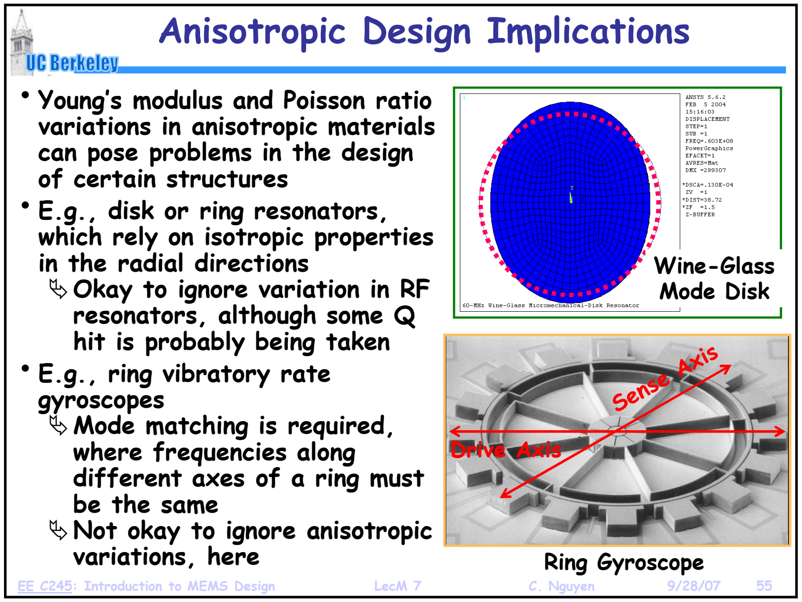
$$\text{where}\left\{\begin{aligned}C_{11}&=165.7\text{ GPa}\\ C_{12}&=63.9\text{ GPa}\\ C_{44}&=79.6\text{ GPa}\end{aligned}\right.$$

Young's Modulus in the (001) Plane



Poisson Ratio in (001) Plane





Anisotropic Design Implications

- Young's modulus and Poisson ratio variations in anisotropic materials can pose problems in the design of certain structures
- E.g., disk or ring resonators, which rely on isotropic properties in the radial directions
  - Okay to ignore variation in RF resonators, although some Q hit is probably being taken
- E.g., ring vibratory rate gyroscopes
  - Mode matching is required, where frequencies along different axes of a ring must be the same
  - Not okay to ignore anisotropic variations, here

Wine-Glass Mode Disk

Ring Gyroscope