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EE C247B – ME C218
Introduction to MEMS Design
Spring 2017

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Lecture Module 7: Mechanics of Materials

Outline

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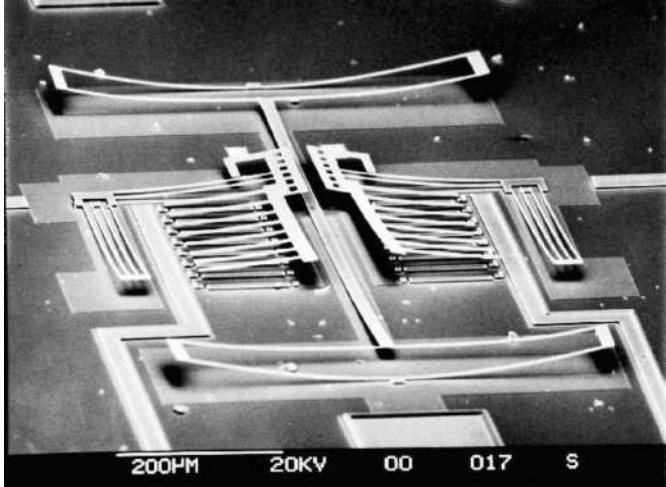
- Reading: Senturia, Chpt. 8
- Lecture Topics:
  - Stress, strain, etc., for isotropic materials
  - Thin films: thermal stress, residual stress, and stress gradients
  - Internal dissipation
  - MEMS material properties and performance metrics

Vertical Stress Gradients

- Variation of residual stress in the direction of film growth
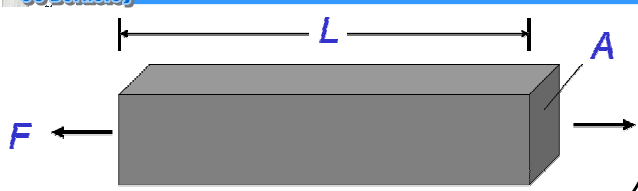- Can warp released structures in z-direction

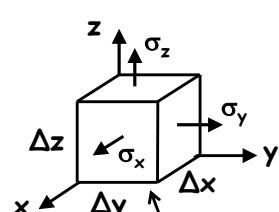## Elasticity

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

$$\text{Stress} = \left\{ \begin{array}{c} \text{Force per} \\ \text{unit area} \end{array} \right\} = \sigma = \frac{F}{A} \quad [\text{N/m}^2 : \text{Pa}]$$
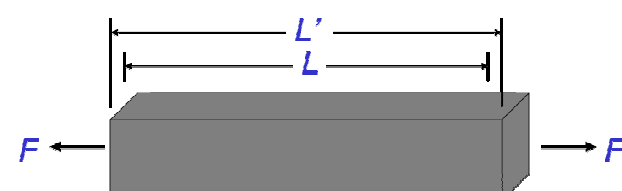
↙ standard mks unit

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

⇒ Note: assume stress acts uniformly across the entire surface of the element, not at just a point

Differential volume element
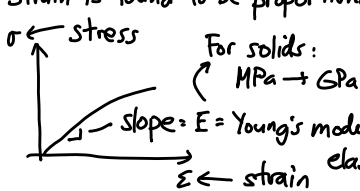
Strain (1D)

Sometimes a unit called the "microstrain" is used, where

$1 \mu\varepsilon = \frac{\Delta L}{L}$ of 1 part in 10^6

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

In the elastic regime (i.e., for "small" stresses at "low" temperatures), strain is found to be proportional to stress

σ ← stress

For solids:
MPa → GPa

slope = E = Young's modulus of elasticity

ε ← strain

$\sigma = \varepsilon E \rightarrow \boxed{\varepsilon = \frac{\sigma}{E} \quad [\text{unitless}]}$
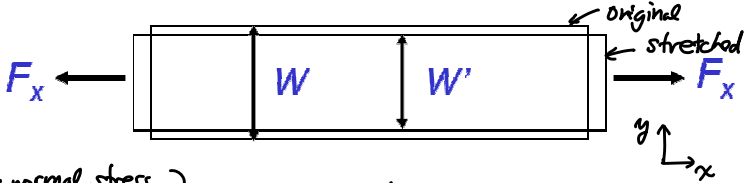
Thus, the units of E are the same as σ → Pa

The Poisson Ratio

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original
stretched

F_x ← | W | W' | → F_x

y ↑ → x

Apply normal stress to a free-standing object → uniaxial strain
→ but also get contraction in directions transverse to the uniaxial strain

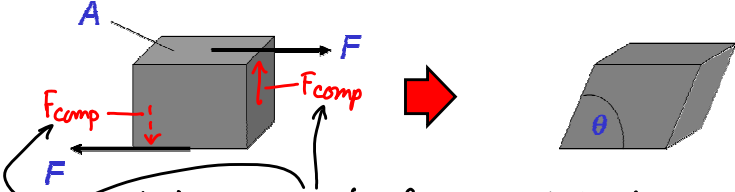⇒ contraction creates a (−) strain:

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

γ = Poisson ratio [unitless]
↳ typical values: $0 \rightarrow 0.5$
⇒ inorganic solids: $0.2 \rightarrow 0.3$
⇒ elastomers (e.g., rubber): ~0.5

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Shear Stress & Strain (1D)

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A

F

F_{comp} — F_{comp}

F

θ

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

$$\text{Shear Stress} = \left\{ \begin{array}{l} \text{Force Per Unit Area} \\ \text{Parallel to the Surfaces} \end{array} \right\} = \tau = \frac{F}{A} \quad [Pa]$$

↳ Generates a shear strain:

$$\text{Shear Strain} = \theta = \frac{\tau}{G} \leftarrow G \triangleq \text{shear modulus}$$

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

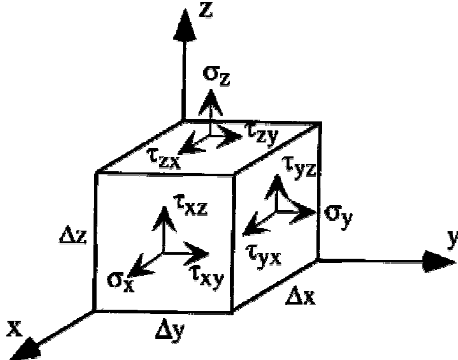EE C245: Introduction to MEMS Design   LecM 7   C. Nguyen   9/28/07   8

2D and 3D Considerations

- <u>**Important assumption**</u>: the differential volume element is in static equilibrium → no net forces or torques (i.e., rotational movements)
  - ⮡ Every σ must have an equal σ in the opposite direction on the other side of the element
  - ⮡ For no net torque, the shear forces on different faces must also be matched as follows:

$$\tau_{xy} = \tau_{yx} \qquad \tau_{xz} = \tau_{zx} \qquad \tau_{yz} = \tau_{zy}$$

Stresses acting on a differential volume element
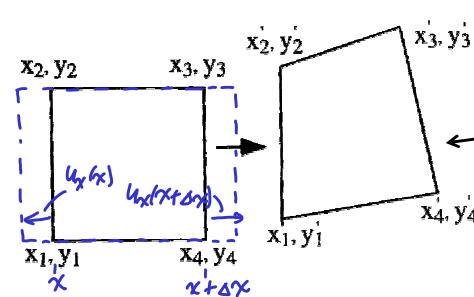
2D Strain

- In general, motion consists of
  - ⮡ rigid-body displacement (motion of the center of mass)
  - ⮡ rigid-body rotation (rotation about the center of mass)
  - ⮡ Deformation relative to displacement and rotation

Area element experiences both displacement and deformation

- Must work with displacement vectors
- Differential definition of axial strain: ⟶

$$\varepsilon_x = \frac{u_x(x + \Delta x) - u_x(x)}{\Delta x} = \frac{\partial u_x}{\partial x}$$

2D Shear Strain

⇒ For shear strains, must remove any rigid body rotation that accompanies the deformation
↳ use a symmetric definition of shear strain:

$$\gamma_{xy} = \theta_2 + \theta_1 \approx \left(\frac{\Delta u_x}{\Delta y} + \frac{\Delta u_y}{\Delta x}\right) = \left(\frac{\partial u_x}{\partial y} + \frac{\partial u_y}{\partial x}\right)$$

For small amplitude deformations.

Volume Change for a Uniaxial Stress

Stresses acting on a differential volume element

Given an x-directed uniaxial stress, σ_x:

$$\Delta x \rightarrow \Delta x (1 + \epsilon_x)$$
$$\Delta y \rightarrow \Delta y (1 - \gamma \epsilon_x)$$
$$\Delta z \rightarrow \Delta z (1 - \gamma \epsilon_x)$$

The resulting change in volume ΔV

$$\Delta V = \Delta x \Delta y \Delta z (1 + \epsilon_x)(1 - \gamma \epsilon_x)^2 - \Delta x \Delta y \Delta z$$
$$= \Delta x \Delta y \Delta z \left[(1 + \epsilon_x)(1 - \gamma \epsilon_x)^2 - 1\right]$$

{Assume small strains} ⇒ $\Delta V = \Delta x \Delta y \Delta z \left[(1 + \epsilon_x)(1 - 2\gamma \epsilon_x) - 1\right]$
$[(1 + mx)^n \approx 1 + nmx]$ ⇒ $\approx \Delta x \Delta y \Delta z [\cancel{1} + \epsilon_x - 2\gamma \epsilon_x - 2\gamma \cancel{\epsilon_x^2} - \cancel{1}]$ ← negl.

$$\boxed{\Delta V \approx \Delta x \Delta y \Delta z (1 - 2\gamma) \epsilon_x}$$

For $\gamma = 0.5$ (rubber) → no ΔV!
$\gamma < 0.5$ → finite ΔV

Isotropic Elasticity in 3D

• Isotropic = same in all directions
• The complete stress-strain relations for an isotropic elastic solid in 3D: (i.e., a generalized Hooke's Law)

$$\varepsilon_x = \frac{1}{E}\left[\sigma_x - v(\sigma_y + \sigma_z)\right] \qquad \gamma_{xy} = \frac{1}{G}\tau_{xy}$$

$$\varepsilon_y = \frac{1}{E}\left[\sigma_y - v(\sigma_z + \sigma_x)\right] \qquad \gamma_{yz} = \frac{1}{G}\tau_{yz}$$

$$\varepsilon_z = \frac{1}{E}\left[\sigma_z - \underbrace{v(\sigma_x + \sigma_y)}\right] \qquad \gamma_{zx} = \frac{1}{G}\tau_{zx}$$
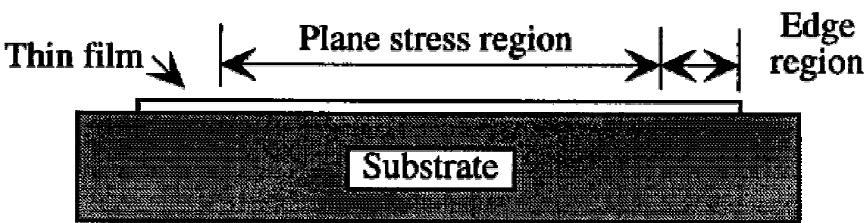
Basically, add in off-axis strains from normal stresses in other directions

Important Case: Plane Stress

• **Common case**: very thin film coating a thin, relatively rigid substrate (e.g., a silicon wafer)

• At regions more than 3 thicknesses from edges, the top surface is stress-free → $\sigma_z = 0$
• Get two components of in-plane stress:

$$\varepsilon_x = (1/E)[\sigma_x - v(\sigma_y + 0)]$$

$$\varepsilon_y = (1/E)[\sigma_y - v(\sigma_x + 0)]$$

Important Case: Plane Stress (cont.)

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- Symmetry in the xy-plane → $\sigma_x = \sigma_y = \sigma$
- Thus, the in-plane strain components are: $\varepsilon_x = \varepsilon_y = \varepsilon$
  where

$$\varepsilon_x = (1/E)[\sigma - \nu\sigma] = \frac{\sigma}{[E/(1-\nu)]} = \frac{\sigma}{E'}$$
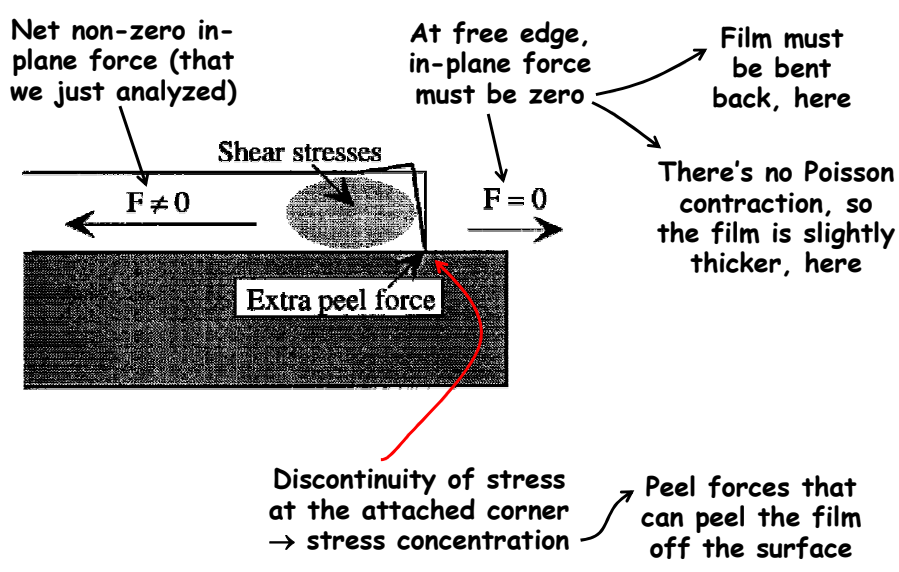
and where

$$\text{Biaxial Modulus} \triangleq E' = \frac{E}{1-\nu}$$

Edge Region of a Tensile (σ>0) Film

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Net non-zero in-plane force (that we just analyzed)

At free edge, in-plane force must be zero

Film must be bent back, here

Shear stresses

There's no Poisson contraction, so the film is slightly thicker, here

$F \neq 0$ $F = 0$

Extra peel force

Discontinuity of stress at the attached corner → stress concentration

Peel forces that can peel the film off the surface

Linear Thermal Expansion

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- As temperature increases, most solids expand in volume
- **Definition**: linear thermal expansion coefficient

$$\text{Linear thermal expansion coefficient} \Biggr\} \overset{\Delta}{=} \alpha_T = \frac{d\varepsilon_x}{dT} \quad [\text{Kelvin}^{-1}]$$

Remarks:
- α_T values tend to be in the 10^{-6} to 10^{-7} range
- Can capture the 10^{-6} by using dimensions of μstrain/K, where 10^{-6} K^{-1} = 1 μstrain/K
- In 3D, get volume thermal expansion coefficient $\longrightarrow$ $\dfrac{\Delta V}{V} = 3\alpha_T \Delta T$

- For moderate temperature excursions, α_T can be treated as a constant of the material, but in actuality, it is a function of temperature

α_T As a Function of Temperature

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[Madou, Fundamentals of Microfabrication, CRC Press, 1998]

- Cubic symmetry implies that α is independent of direction
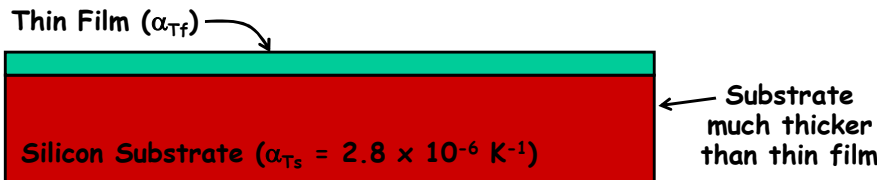
Thin-Film Thermal Stress

Thin Film (α_{Tf})

Silicon Substrate ($\alpha_{Ts} = 2.8 \times 10^{-6}$ K^{-1})

Substrate much thicker than thin film

- Assume film is deposited stress-free at a temperature T_r, then the whole thing is cooled to room temperature T_r
- Substrate much thicker than thin film → substrate dictates the amount of contraction for both it and the thin film
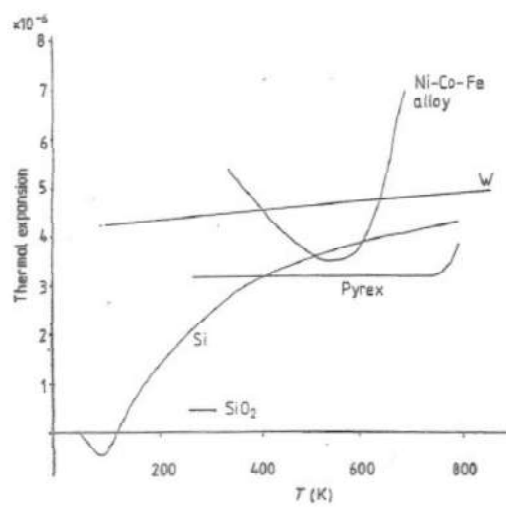
Thermal strain of the substrate: (in one in-plane dimension)

$$\epsilon_s = -\alpha_{Ts}\Delta T \quad , \quad \text{where} \quad \Delta T = T_d - T_r$$

If the film were not attached to the substrate: $\epsilon_{f,free} = -\alpha_{Tf}\Delta T$

⟳ over

Linear Thermal Expansion

But the film is attached to the substrate, so the actual strain in the film is the same as that in the substrate.

$$\epsilon_{f,attached} = -\alpha_{Ts}\Delta T$$

Thus:

$$\boxed{\text{Thermal Mismatch Strain} = \epsilon_{f,mismatch} = (\alpha_{Tf} - \alpha_{Ts})\Delta T}$$

↳ Note that this is biaxial strain
  ↳ it can only be developed by an in-plane biaxial stress:

$$\sigma_{f,mismatch} = \left(\frac{E}{1-\nu}\right)\epsilon_{f,mismatch}$$

Ex. Thin-film is polyimide → $\alpha_{Tf} = 70\times10^{-6}$ K^{-1}, $E' = 4$ GPa
    deposited @ 250°C, then cooled to RT = 25°C → $\Delta T = 225$ K   e.g., SiO₂

$$\epsilon_{f,mismatch} = (70-2.8)\mu(225) = 1.5\times10^{-2}$$
$$\sigma_{f,mismatch} = (4G)(1.5\times10^{-2}) = \underline{60.5\ MPa}$$

← stress is (+), ∴ tensile
[(-) would be compressive]

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MEMS Material Properties

Material Properties for MEMS

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Units: $(m/s)^2$

$\sqrt{(E/\rho)}$ is acoustic velocity

Material	Density, ρ, Kg/m^3	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

[Mark Spearing, MIT]

Young's Modulus Versus Density

Lines of constant acoustic velocity

[Ashby, Mechanics of Materials, Pergamon, 1992]

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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

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Yield Strength (cont.)

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

Stress

Tensile Strength

M

Fracture

Proportional Limit

(Si @ T=30°C)

Ductile (Mild Steel)

Brittle (Si)

Brittle (Si)

(or Si @ T>900°C)

[Maluf]

Strain

Young's Modulus and Useful Strength

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Stored mechanical energy

Material	Modulus, E, GPa	Useful Strength*, σ_f, MPa	$\dfrac{\sigma_f}{E}$ (-) x 10⁻³	$\dfrac{\sigma_f^2}{E}$ 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

Lines of constant maximum strain

[Ashby, Mechanics of Materials, Pergamon, 1992]

Quality Factor (or Q)

Clamped-Clamped Beam μResonator

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Resonator Beam

W_r L_r h

$Q \sim 10{,}000$

$\left|\dfrac{i_o}{v_i}\right|$

Electrode

v_i

V_P i_o

ω_o ω

Note: If $V_P = 0V$ ⇨ device off

Frequency:

Stiffness   **Young's Modulus**

$C(t)$

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

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

Density

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

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Quality Factor (or Q)

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

$|H(j\omega)|$

BW_{-3dB}

3dB

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

- **Example**: series LCR circuit

R C L

f_o f

⇨ $Q = \dfrac{\text{Im}(Z)}{\text{Re}(Z)} = \dfrac{\omega_o L}{R} = \dfrac{1}{\omega_o C R}$

- **Example**: parallel LCR circuit

G L C

⇨ $Q = \dfrac{\text{Im}(Y)}{\text{Re}(Y)} = \dfrac{\omega_o C}{G} = \dfrac{1}{\omega_o L G}$

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Selective Low-Loss Filters: Need Q

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| Resonator Tank | Coupler | Resonator Tank | Coupler | Resonator Tank |

General BPF Implementation

Typical LC implementation:

R_{x1} C_{x1} L_{x1} R_{x2} C_{x2} L_{x2} R_{x3} C_{x3} L_{x3}

C_{12} C_{23}

$\left|\frac{i_o}{v_i}\right|$ ω_o ω

- **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**

Increasing Insertion Loss

Tank Q
- 30,000
- 20,000
- 10,000
- 5,000
- 4,000

Transmission [dB]: 0, -5, -10, -15, -20, -25, -30, -35, -40

Frequency [MHz]: 998, 999, 1000, 1001, 1002

Oscillator: Need for High Q

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

Sustaining Amplifier

A v_o

Frequency-Selective Tank

$\left|\frac{i_o}{v_i}\right|$ ω_o ω

Ideal Sinusoid: $v_O(t) = V_O \sin(2\pi f_O t)$

$\leftarrow T_O \rightarrow$

$\omega_o = 2\pi/T_O$ ω

Higher Q

Real Sinusoid: $v_O(t) = (V_O + \varepsilon(t))\sin(2\pi f_O t + \theta(t))$

Tighter Spectrum

Zero-Crossing Point
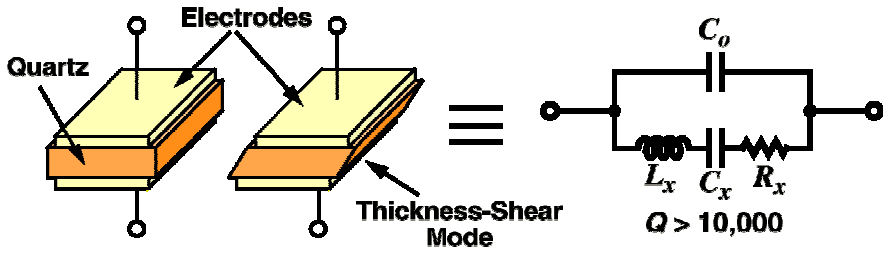
ω_o ω

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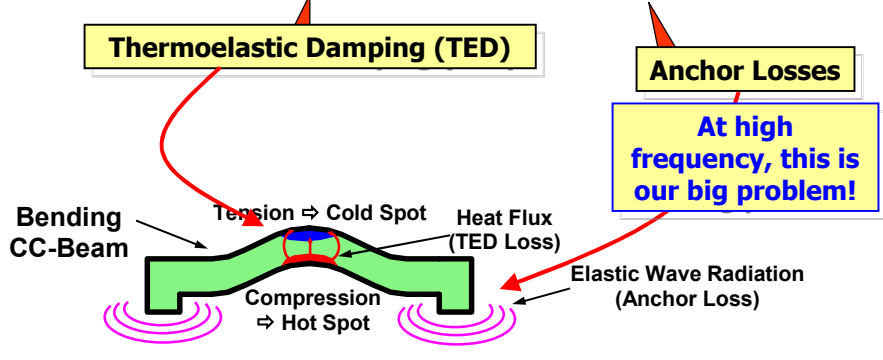
$$\frac{1}{Q} = \frac{1}{Q_{defects}} + \frac{1}{Q_{TED}} + \frac{1}{Q_{viscous}} + \frac{1}{Q_{support}}$$

Material Defect Losses

Gas Damping

Thermoelastic Damping (TED)

Anchor Losses

At high frequency, this is our big problem!

Bending CC-Beam

Tension ⇨ Cold Spot

Heat Flux (TED Loss)

Compression ⇨ Hot Spot

Elastic Wave Radiation (Anchor Loss)
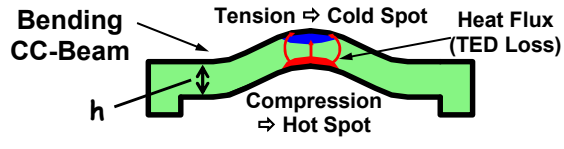
Thermoelastic Damping (TED)

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

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

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

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

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

Bending CC-Beam, Tension ⇨ Cold Spot, Heat Flux (TED Loss), h, Compression ⇨ Hot Spot

ς = 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
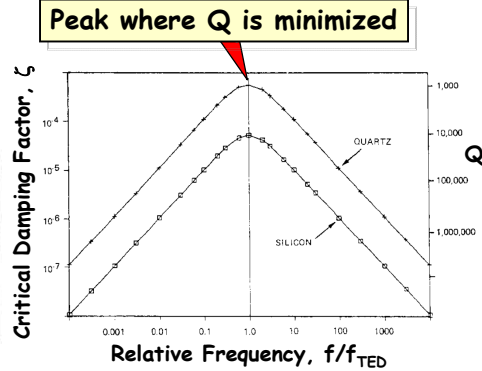
TED Characteristic Frequency

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

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

Peak where Q is minimized

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}

Critical Damping Factor, ς vs Relative Frequency, f/f_{TED} — QUARTZ, SILICON, Q

[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

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Polysilicon Wine-Glass Disk Resonator

Compound Mode (2,1)

Anchor

Input

Wine Glass Disk Resonator

Output

$R = 32\ \mu m$

Output

Support Beams

Input

Anchor

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

$f_o = 61.37$ MHz
$Q = 145,780$

Unmatched Transmission [dB]

-40
-60
-80
-100

61.325   61.375   61.425
Frequency [MHz]

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

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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

Polysilicon Stem (Impedance Mismatched to Diamond Disk)

Polysilicon Electrode

R

CVD Diamond μMechanical Disk Resonator

Ground Plane

f_o = 1.51 GHz
Q = 11,555 (vac)
Q = 10,100 (air)

Q = 10,100 (air)

Mixed Amplitude [dB]: -84, -86, -88, -90, -92, -94, -96, -98, -100

Frequency [MHz]: 1507.4, 1507.6, 1507.8, 1508, 1508.2

[Wang, Butler, Nguyen MEMS'04]

Disk Resonator Loss Mechanisms

(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-

λ/4 helps reduce loss, but not perfect

Disk   Stem   Stem Height

Hysteretic Motion of Defect

(Dwarfed By Substrate Loss)

Substrate

Substrate Loss Thru Anchors

(Dominates)

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]
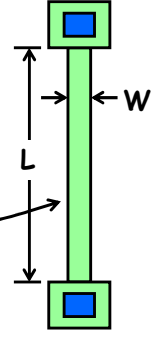
MEMS Stress Test Structure

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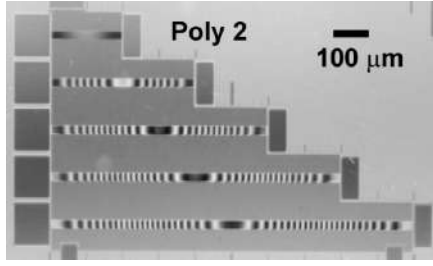
- **Simple Approach**: use a clamped-clamped beam
  - ↳ Compressive stress causes buckling
  - ↳ Arrays with increasing length are used to determine the critical buckling load, where

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

E = Young's modulus [Pa]
I = (1/12)Wh³ = moment of inertia
L, W, h indicated in the figure
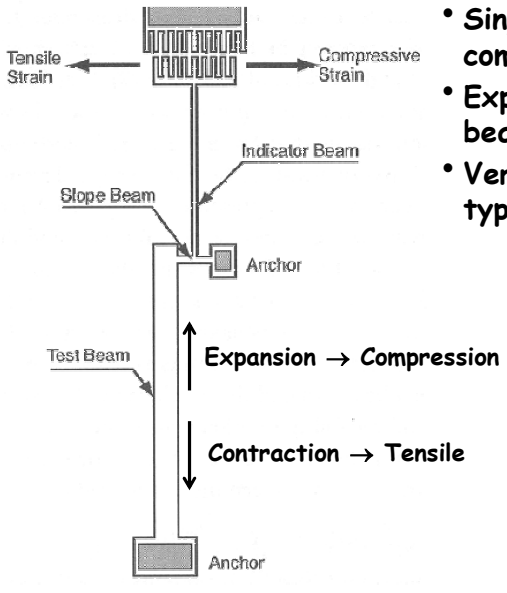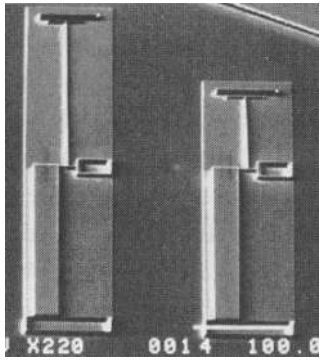
- ↳ **Limitation**: Only compressive stress is measurable

Poly 2   100 μm

More Effective Stress Diagnostic

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Tensile Strain   Compressive Strain

Indicator Beam

Slope Beam

Anchor

Test Beam

Expansion → Compression

Contraction → Tensile

Anchor

X220   0014   100.0

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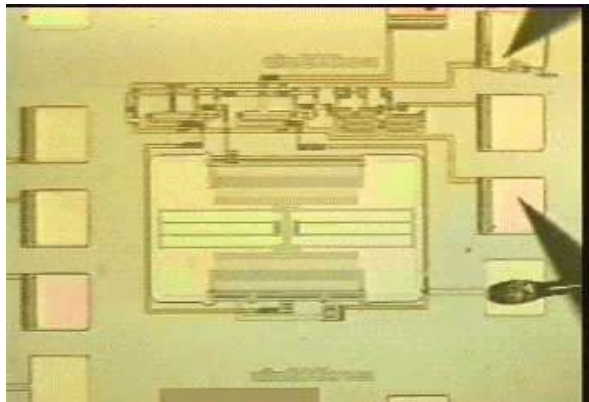- Vernier movement indicates type and magnitude of stress

Q Measurement Using Resonators

Compound Mode (2,1)

f_o = 61.37 MHz
Q = 145,780

Anchor

Input

Wine Glass Disk Resonator

R = 32 μm

Output

Output

Support Beams

Input

Anchor

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

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

Unmatched Transmission [dB]: -40, -60, -80, -100
Frequency [MHz]: 61.325, 61.375, 61.425

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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

Capacitive-Comb Transducer
Outer Beam
Inner Beam
Coupling Beam (not part of resonator)
Input Force, f_c (Port 3)
Ground Plane
Shuttle

(Electrical) Port 1
L_{bi}
L_{bo}
(Electrical) Port 2

i_1
i_2
v_1
w
v_2
V_1
V_P
Anchors
V_2

Folding Truss

Comb-Transducer
Anchors
Ratioed Folded-Beams
Shuttle
Tuning Electrode

f_o=342.5kHz
Q=41,000

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

8.3 Hz

Amplitude [dB]: -4, -8, -12, -16, -20, -24, -28, -32
Frequency [kHz]: 342.40, 342.45, 342.50, 342.55, 342.60

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Comb-Drive Resonator in Action
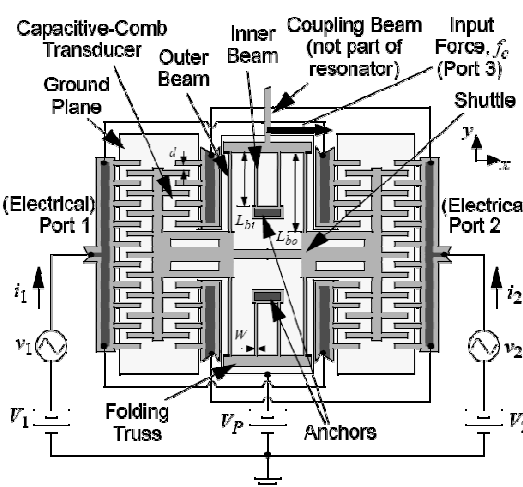
- **Below**: fully integrated micromechanical resonator oscillator using a MEMS-last integration approach

Folded-Beam Comb-Drive Resonator

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

f_o=342.5kHz
Q=41,000

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

← 8.3 Hz
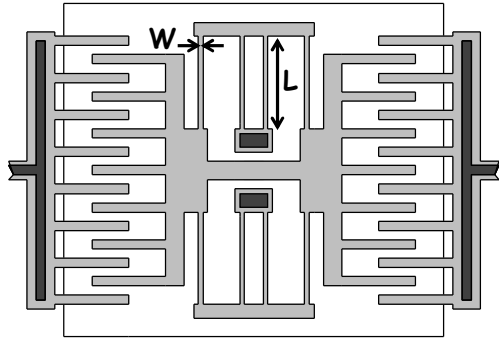
Measurement of Young's Modulus

- 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

W

L

- 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

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- 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

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

Stresses   **Stiffness Coefficients**   **Strains**

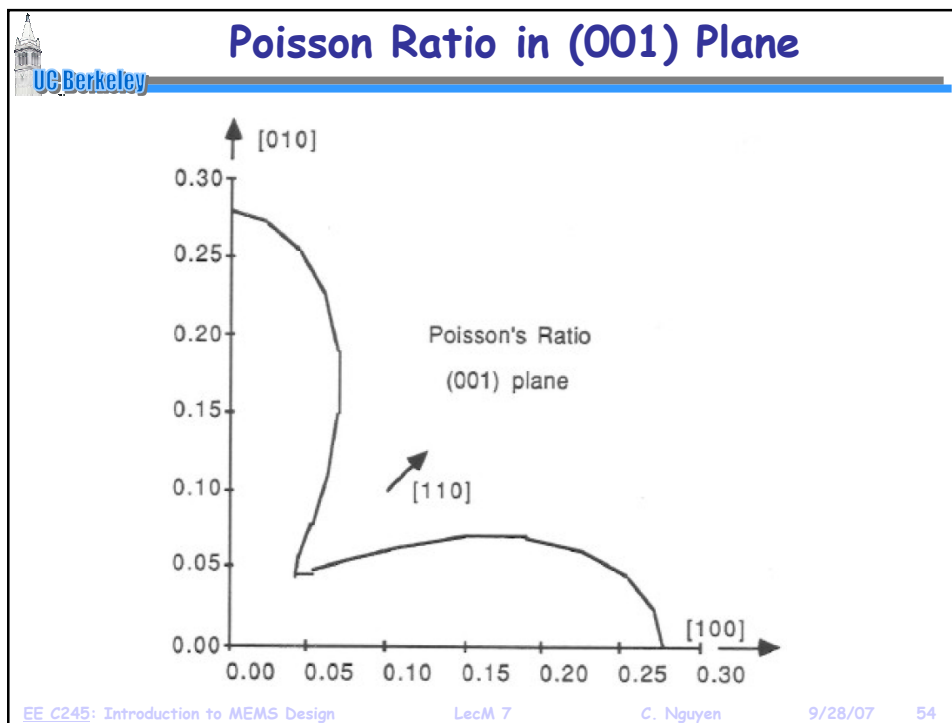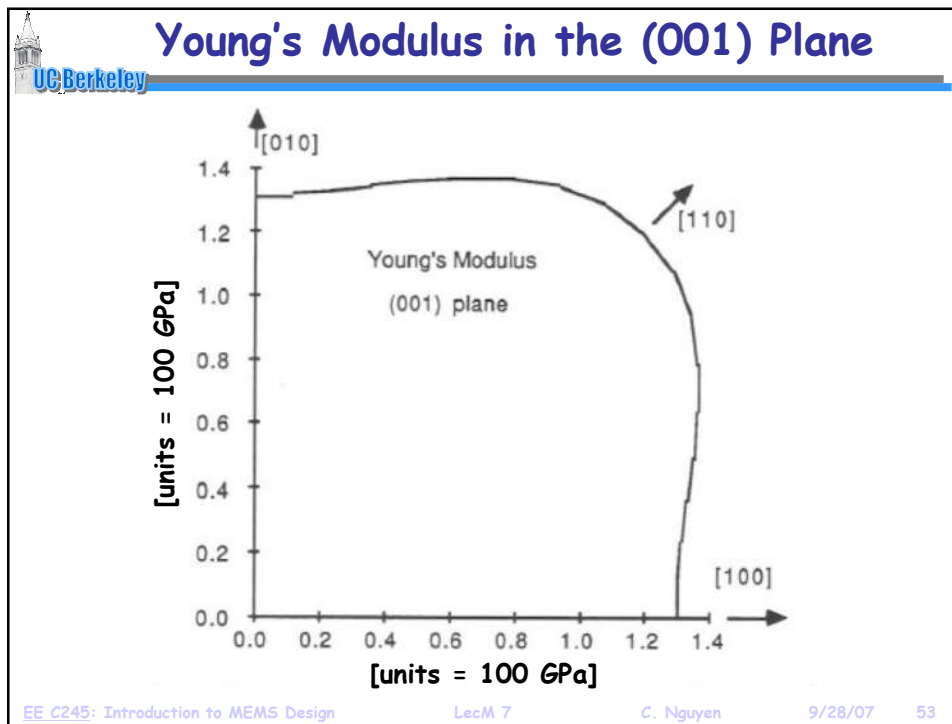## Stiffness Coefficients of Silicon

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- 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:

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

where
$$\begin{cases} C_{11} = 165.7 \text{ GPa} \\ C_{12} = 63.9 \text{ GPa} \\ C_{44} = 79.6 \text{ GPa} \end{cases}$$

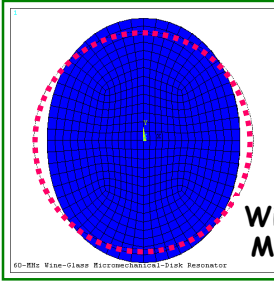## Young's Modulus in the (001) Plane

Poisson Ratio in (001) Plane

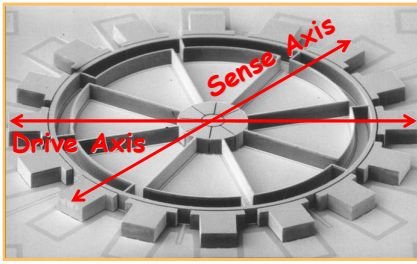## Anisotropic Design Implications

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- 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

Sense Axis
Drive Axis

Ring Gyroscope

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