

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

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Q Measurement Using Resonators

Compound Mode (2,1)

Wine Glass Disk Resonator

Input Output

Anchor

Support Beams

$R = 32 \mu\text{m}$

Unmatched Transmission [dB]

$f_o = 61.37 \text{ MHz}$
 $Q = 145,780$

Frequency [MHz]

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

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

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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_o (Port 3)

Shuttle

Tuning Electrode

Anchors

Folding Truss

Ground Plane

(Electrical) Port 1

(Electrical) Port 2

Amplitude [dB]

Frequency [kHz]

$f_o = 342.5 \text{ kHz}$
 $Q = 41,000$
 $Q = \frac{342,500}{8.3}$

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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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Measurement of Young's Modulus

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

$$\text{Resonance Frequency} = f_o = \left[\frac{\frac{1}{24} \left[\frac{4Eh(W/L)^3}{M_{eq}} \right]^{1/2}}{M_{eq}} \right]^{1/2}$$

h = thickness
W = width
L = length
M_{eq} = Equivalent mass

- 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

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Anisotropic Materials

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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

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

↑ Stresses Stiffness Coefficients ↑ Strains

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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:

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

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

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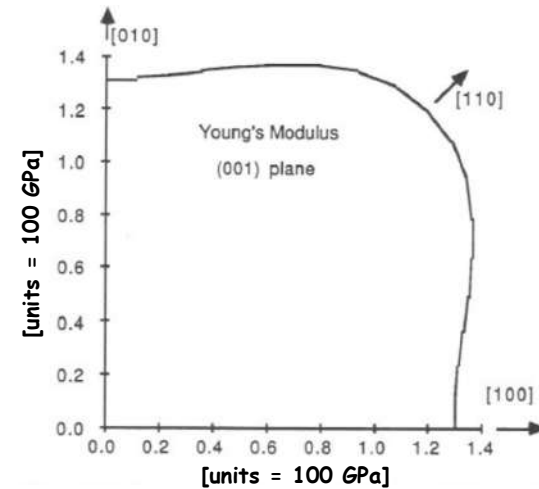
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Young's Modulus in the (001) Plane



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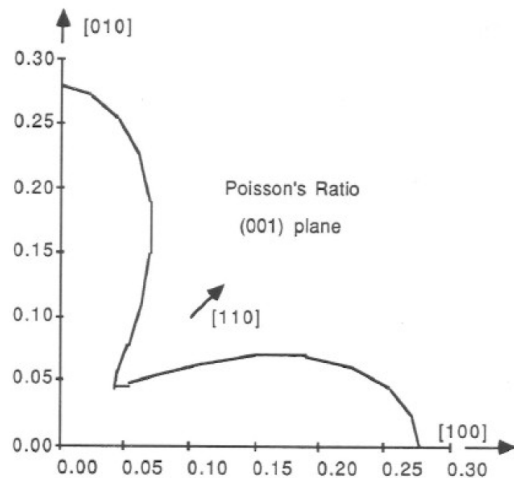
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Poisson Ratio in (001) Plane



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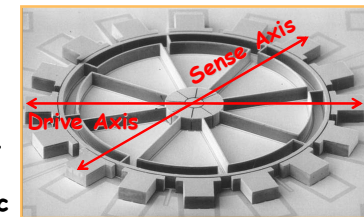
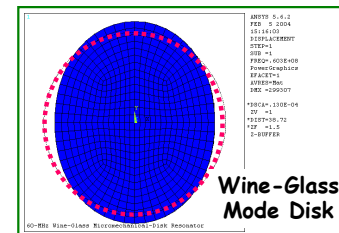
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Anisotropic Design Implications

- 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



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