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Understanding the Materials Behavior of Tetrahedral Amorphous Carbon Using MEMS Resonators

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Acknowledgments:
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Overview

Primary work here at Sandia

- Background information on carbon and ta-C films
- Realization and measurement of MEMS oscillators
- Results
- Future work

Other Research activities (w/ primary collaborators)

- RF Switch mechanics (C. Dyck)
- Microfluidic MEMS pressure transducer (T. Michalske)
- Low-force contacting metal surfaces (M. Baker)

Motivation

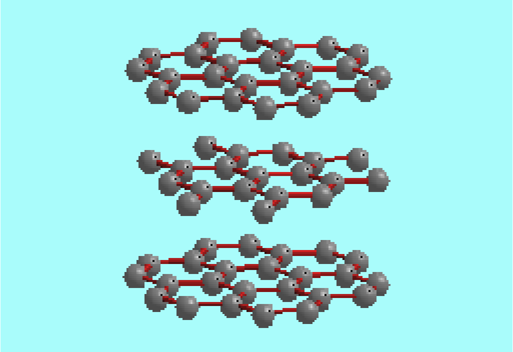
MEMS structures can be applied in:

- Sensors (corrosion, biological)
- Frequency standard (LM shared vision proposal)
- Accelerometers (D. Carr)
- RF MEMS switches (C. Dyck)

Carbon

graphite

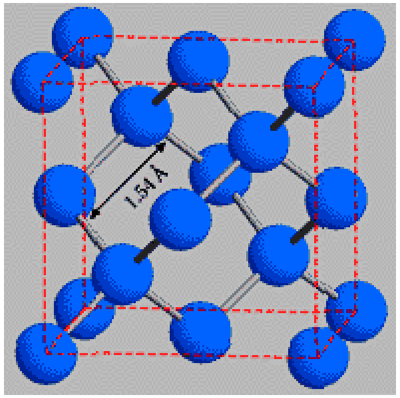
http://www.phy.mtu.edu/~jaszczak/graphiteover.html



100% 3-fold carbon, delocalized π electrons

diamond

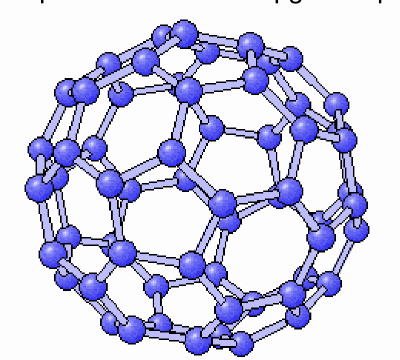
http://www.amnh.org/exhibitions/diamonds/structure.html



100% 4-fold carbon, wide gap semiconductor

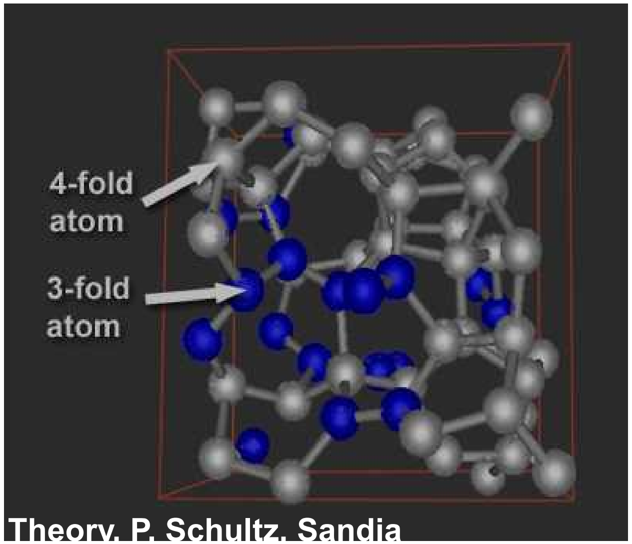
C_{60}

http://www.fhi-berlin.mpg.de/th/personal/hermann/Cnclusters.gif

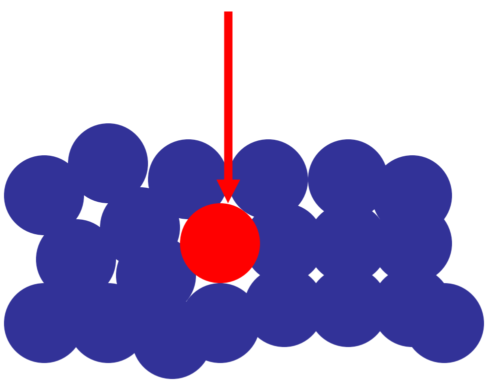


100% 3-fold carbon, molecular solid

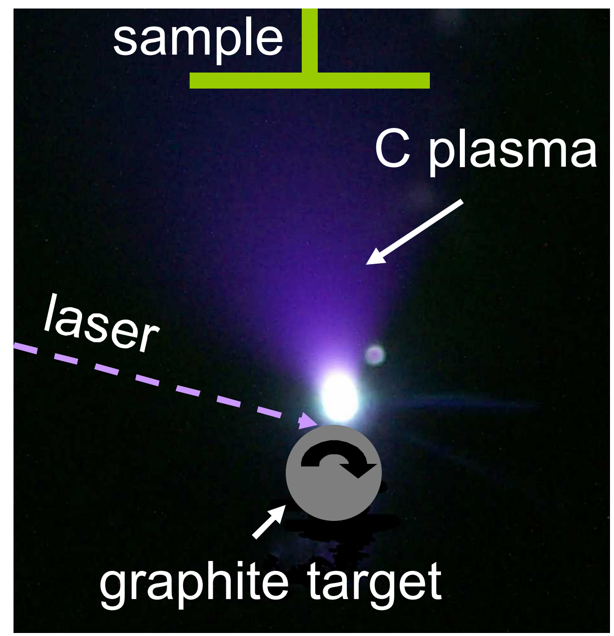
Tetrahedrally-coordinated amorphous carbon films



- ~ 80% 4-fold, 20% 3-fold
- 3-fold atoms cluster into chain-like structures (limited by kinetics)



"growth by subplantation"



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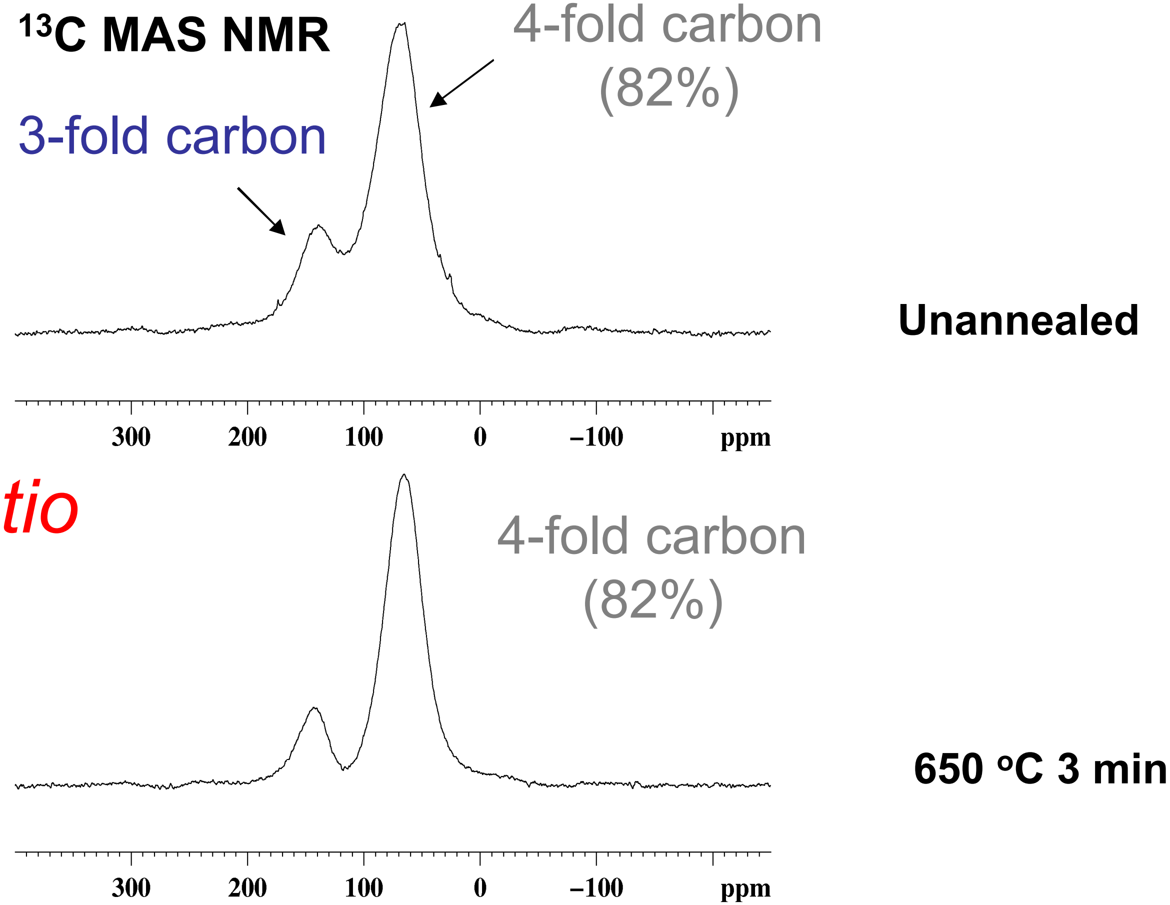
Compositionally stable after stress relief

- *peaks narrow*
- *no change in ratio*



*Alam et al., PRB **67**, '03.*

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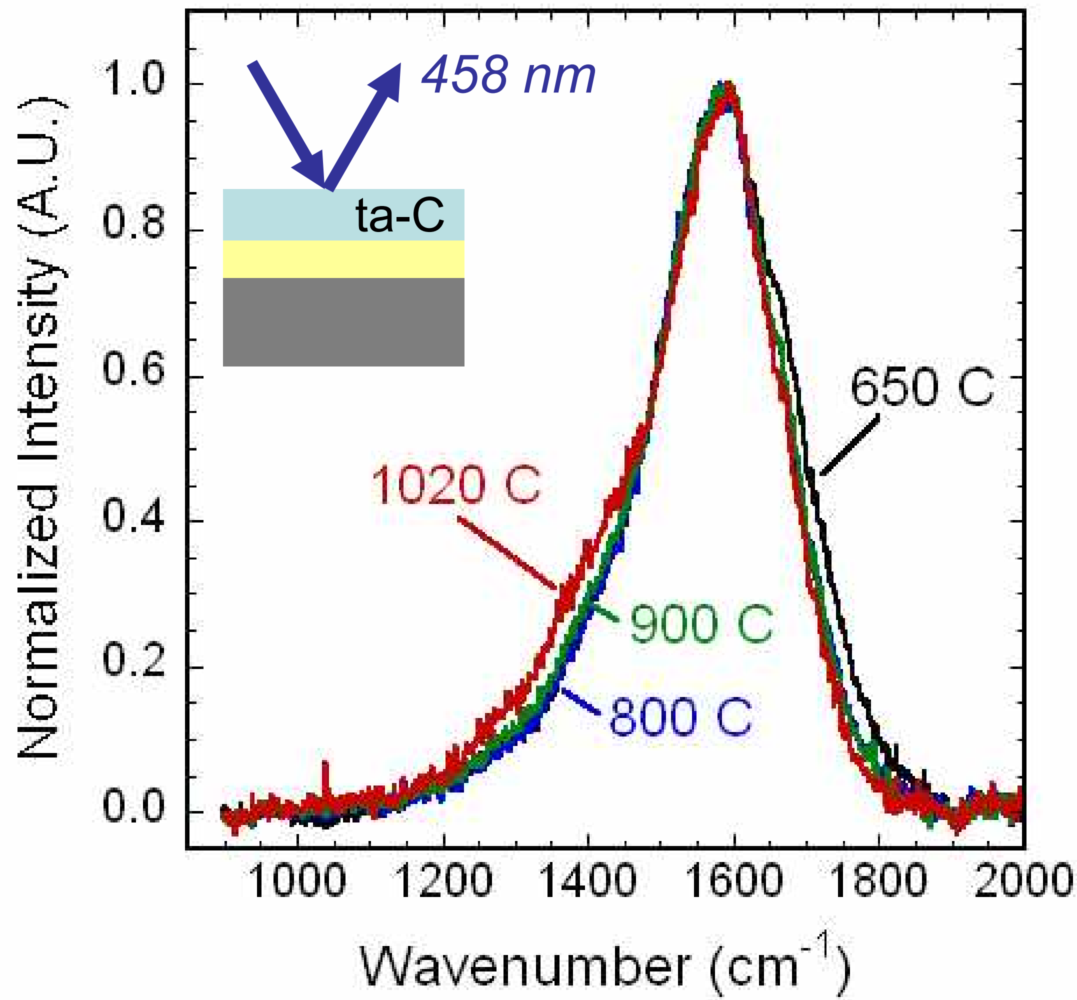
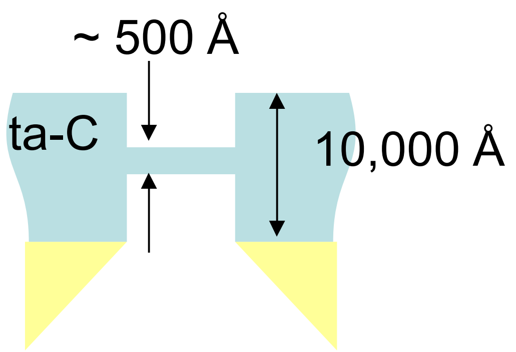
Compositionally stable after high temperature annealing

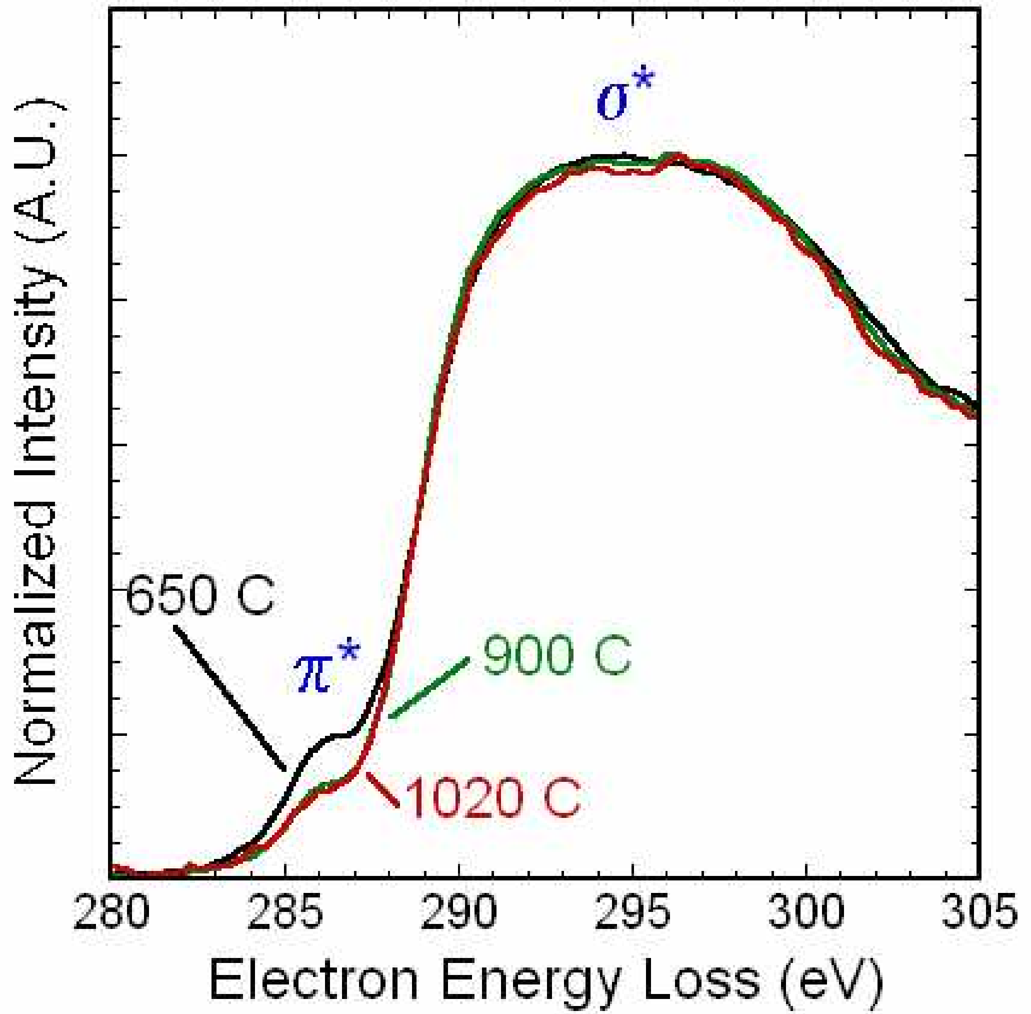
visible Raman shows only very minor structural changes in ta-C with annealing
⇒ 4-fold/3-fold ratio is not changed



Compositionally stable after high temperature annealing

transmission EELS shows no increase in 3-fold carbon with annealing up to 1020ºC

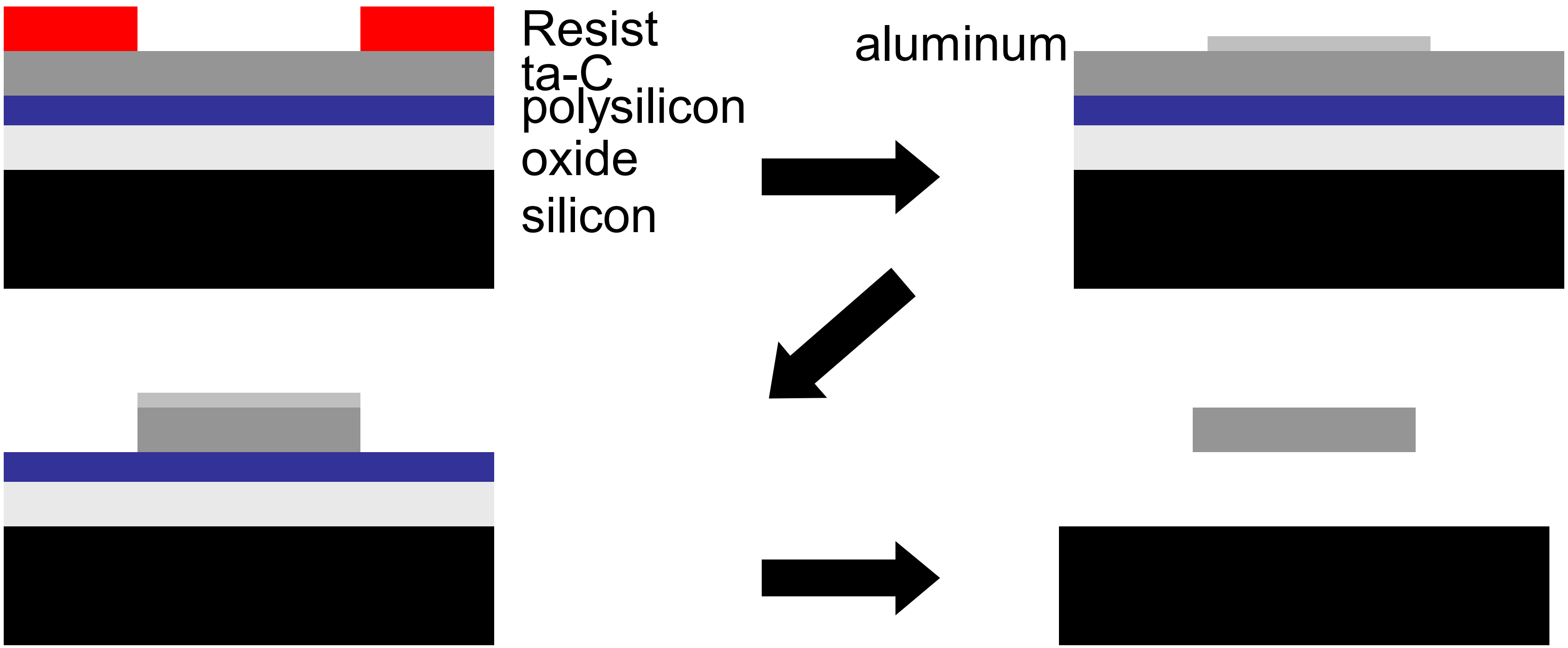


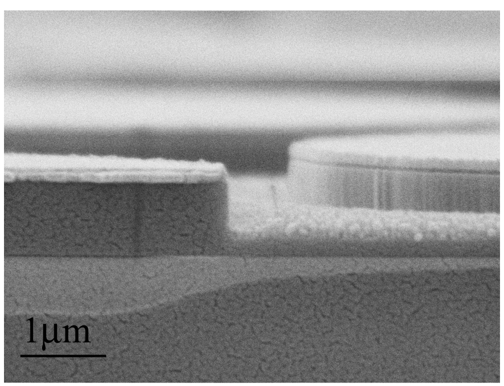


Thermal properties of ta-C films

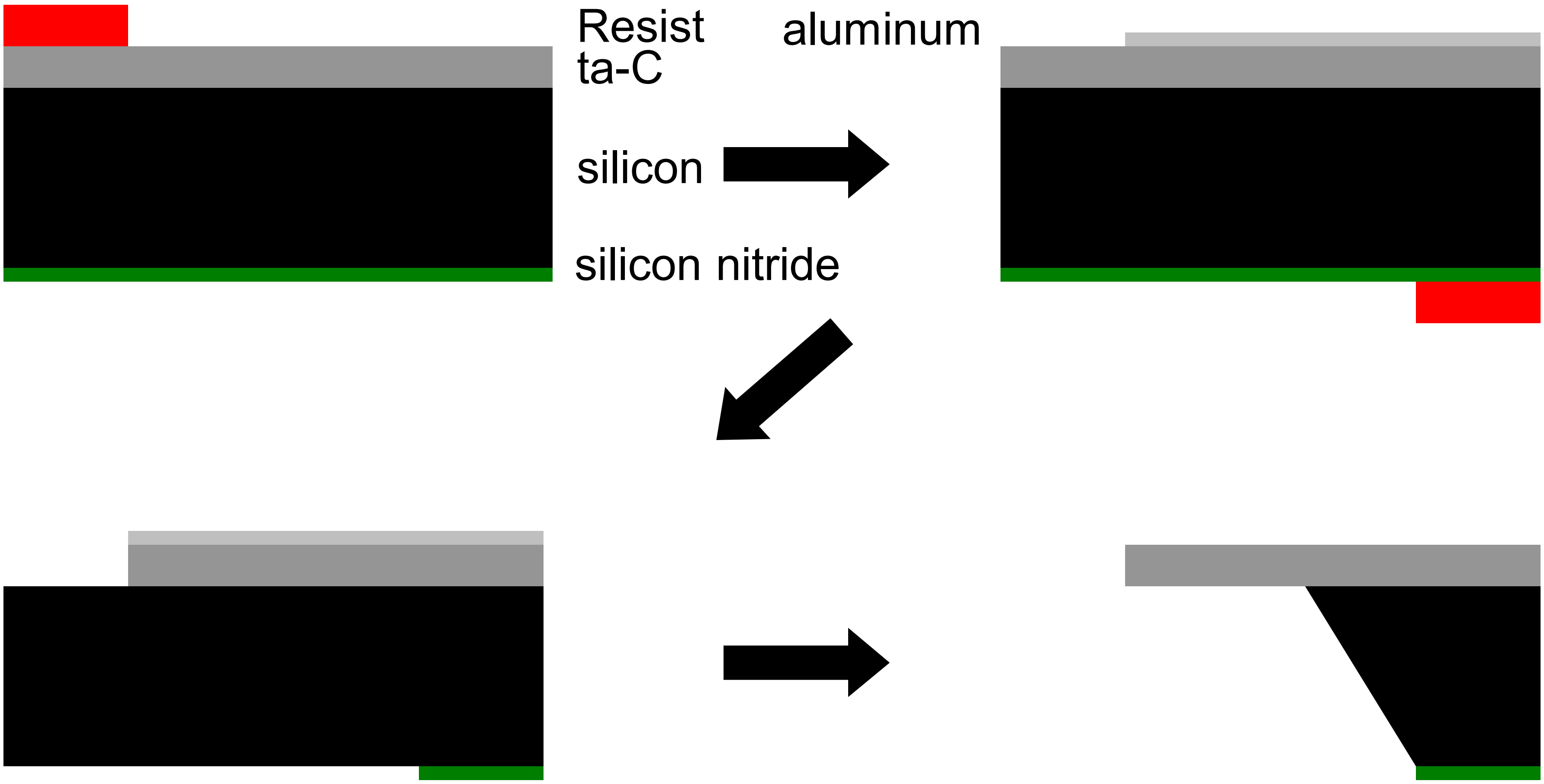
Material Property	Value	Units
Heat Capacity per unit Volume (C)	1.83×10^6	$(J/m^3\ K)$
Thermal Conductivity (κ)	3	(W/m K)
Density (ρ)	3050	(kg/m^3)
Young's Modulus (E)	631	(GPa)
Specific Heat Capacity (Cp)	600	(J/kg K)
Gruneisen's Constant (g)	1.37	none
Thermal Expansion Coeffecient (α)	1.67×10^{-6}	K^{-1}

Device realization : surface micromachining

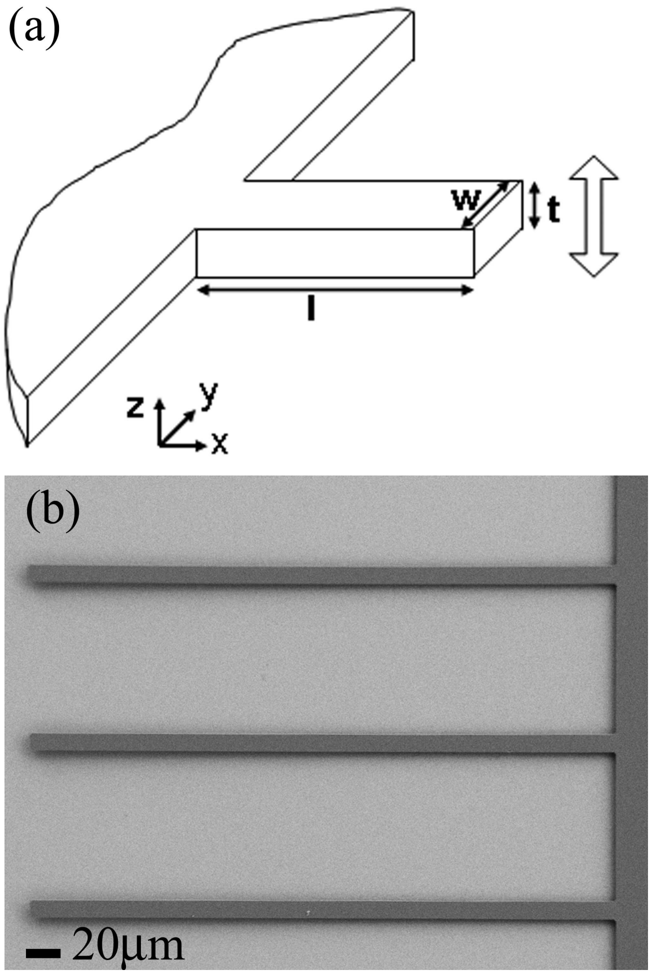


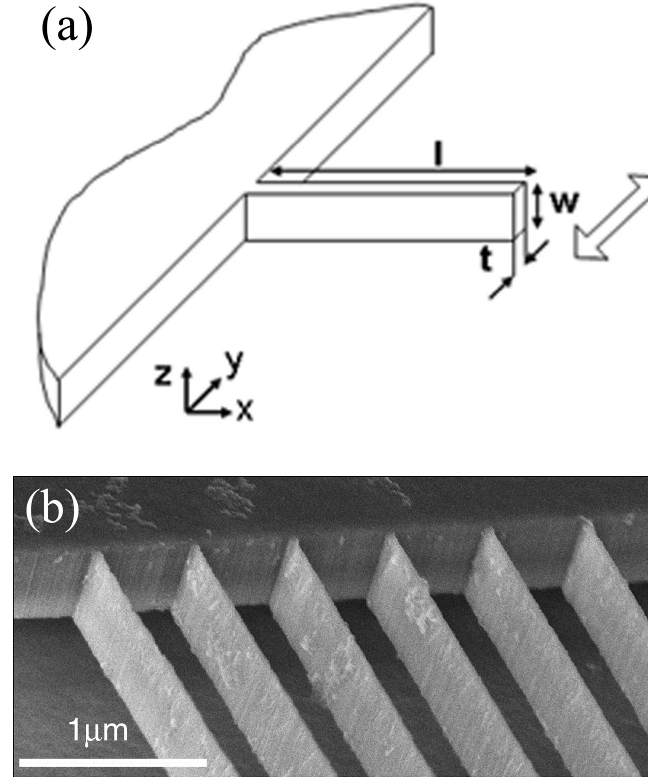


Device realization : bulk micromachining



Cantilevers

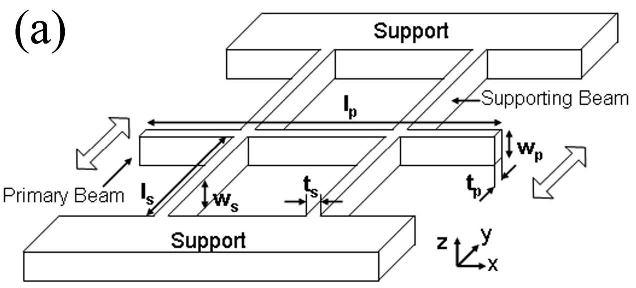




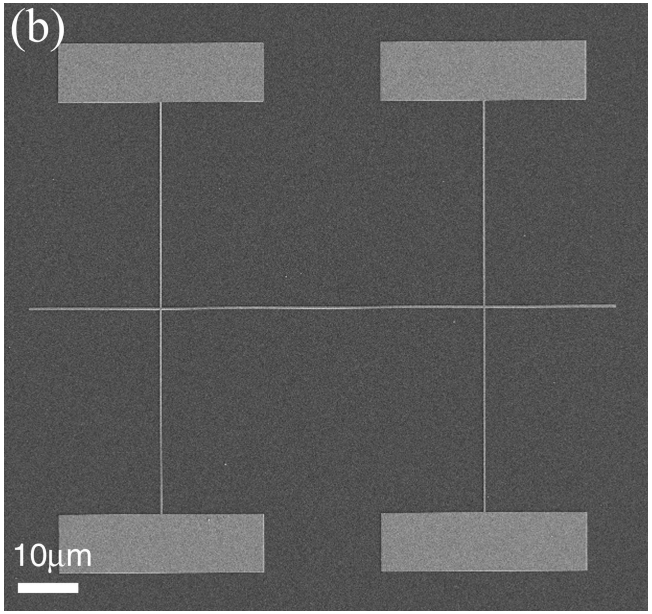
D. Carr, B.E.N. Keeler (1769)

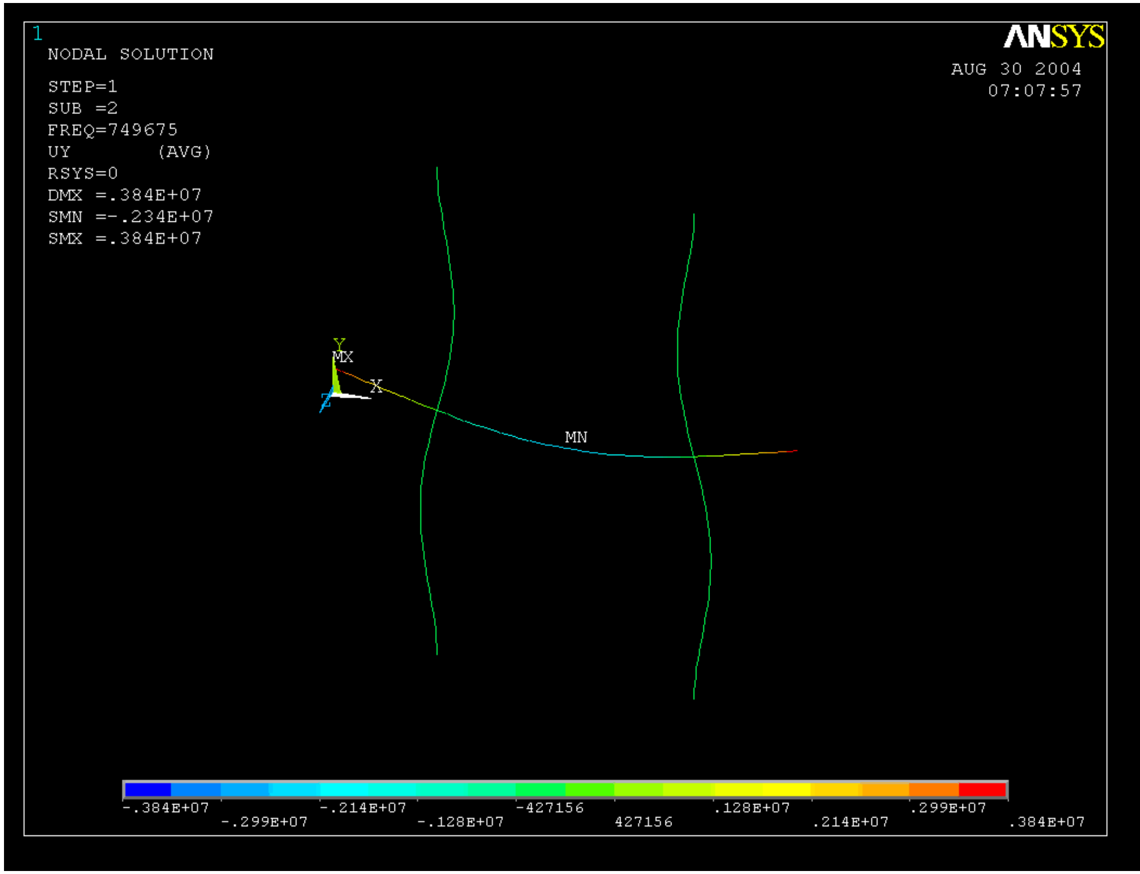
$$f_o = \frac{(1.875)^2}{2\pi} \frac{t}{l^2} \sqrt{\frac{E}{12\rho}}$$

Free-Free beams



$$f_o = \frac{(4.730)^2}{2\pi}\frac{t}{l^2}\sqrt{\frac{E}{12\rho}}$$





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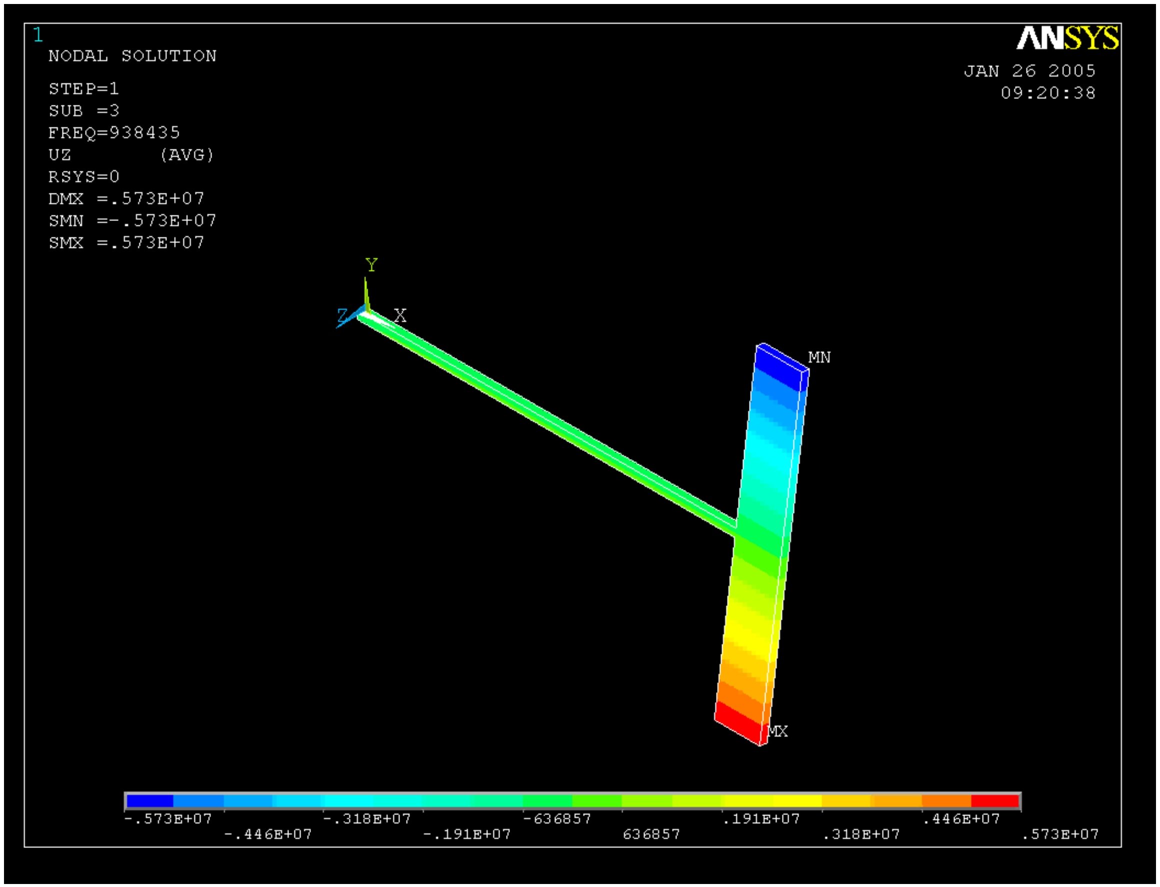
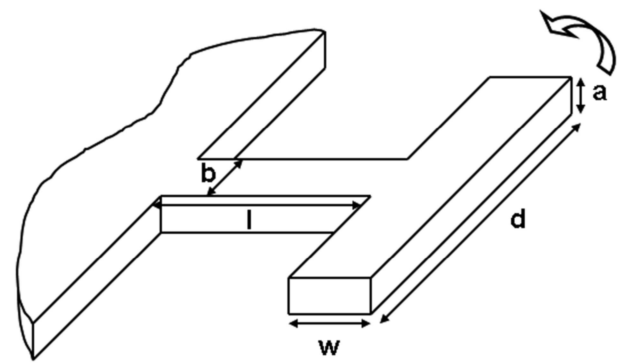
Torsional oscillators

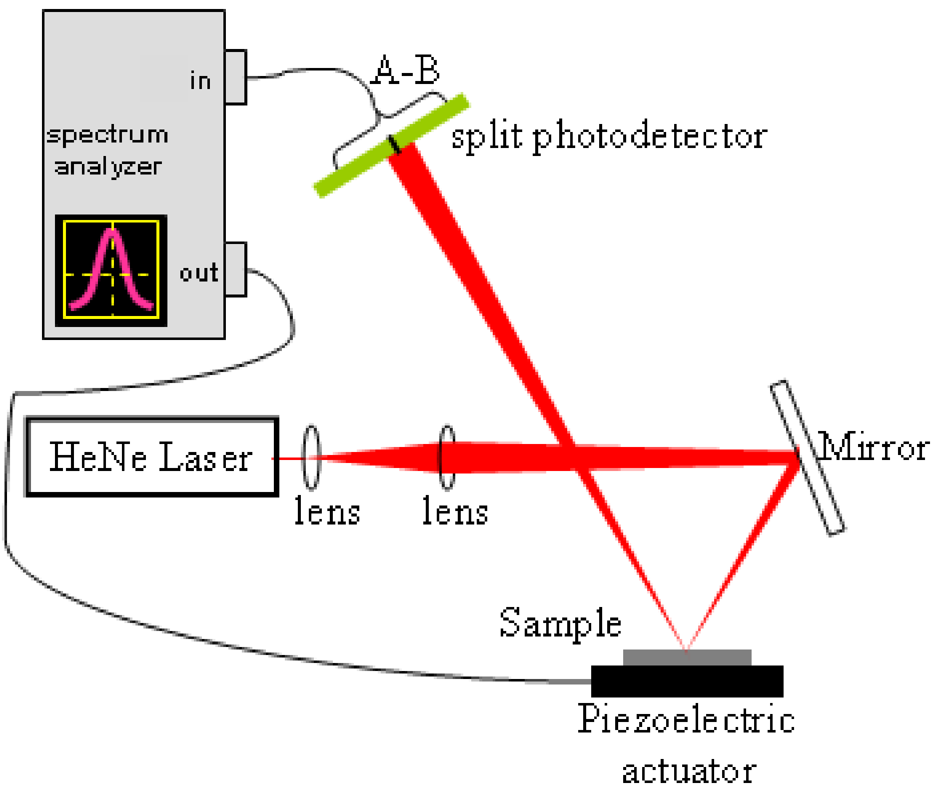




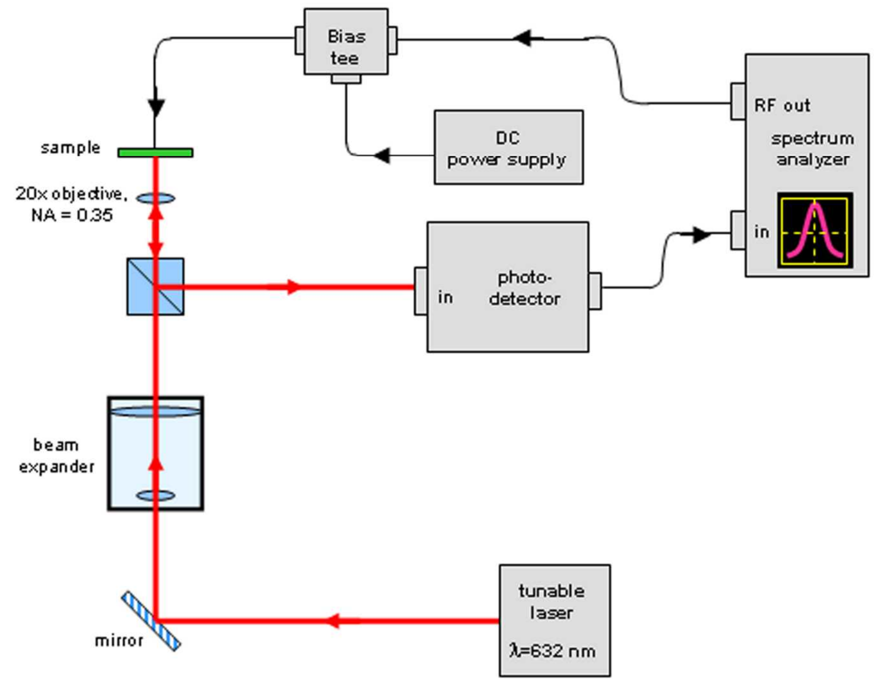
$$f_o = (0.216)\sqrt{\frac{G}{\rho}\frac{b^3}{wld^3}}$$

Measurement

Laser Deflection

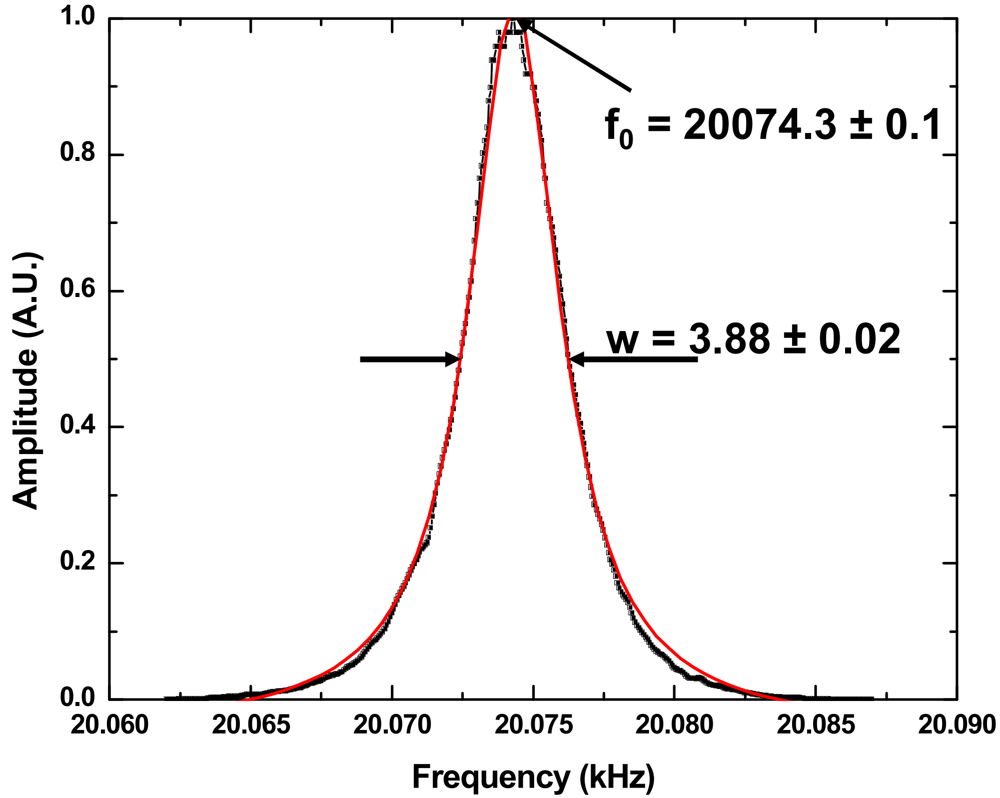


Laser Interference



D. Carr, B.E.N. Keeler (1769)

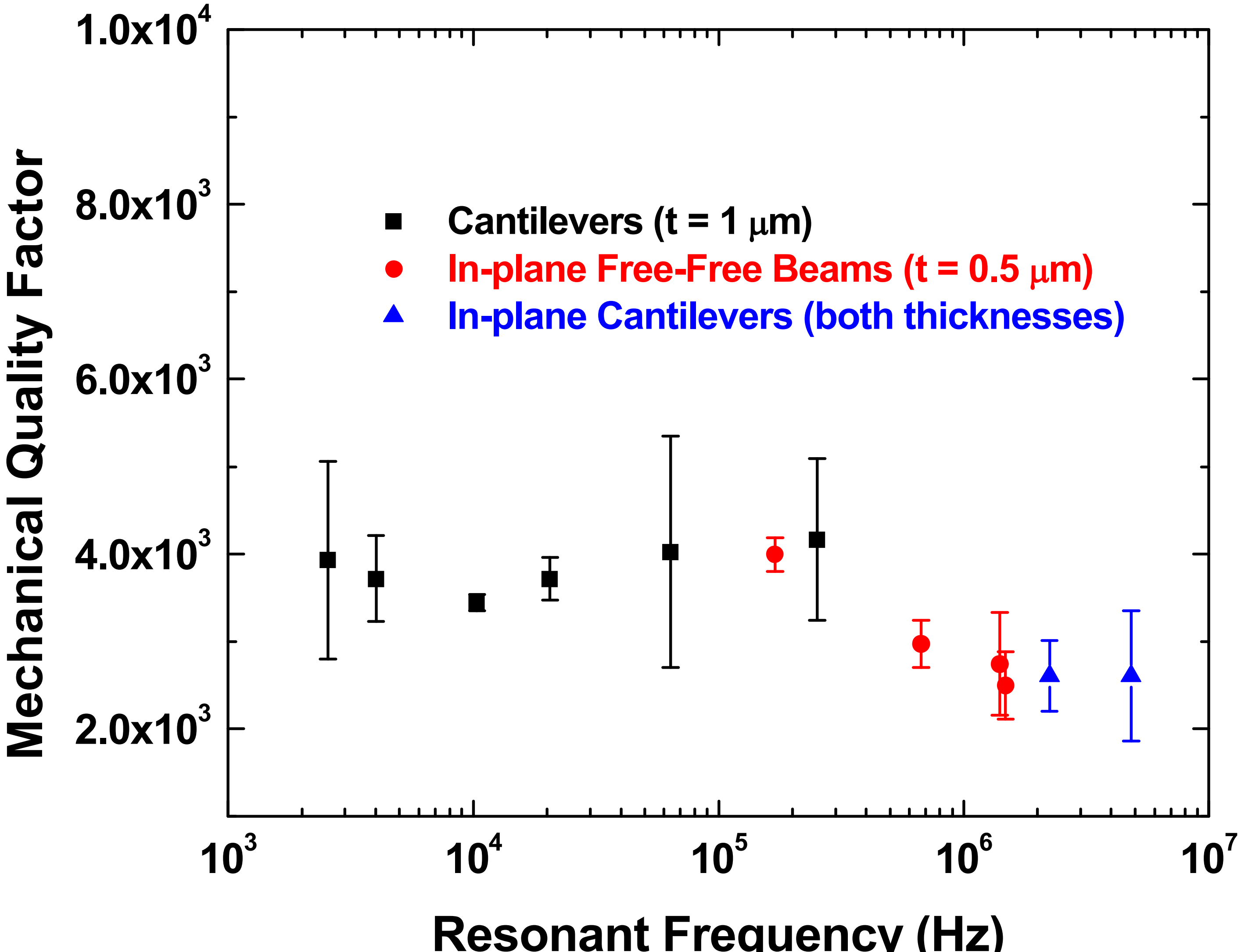
Typical spectral response and curve fitting



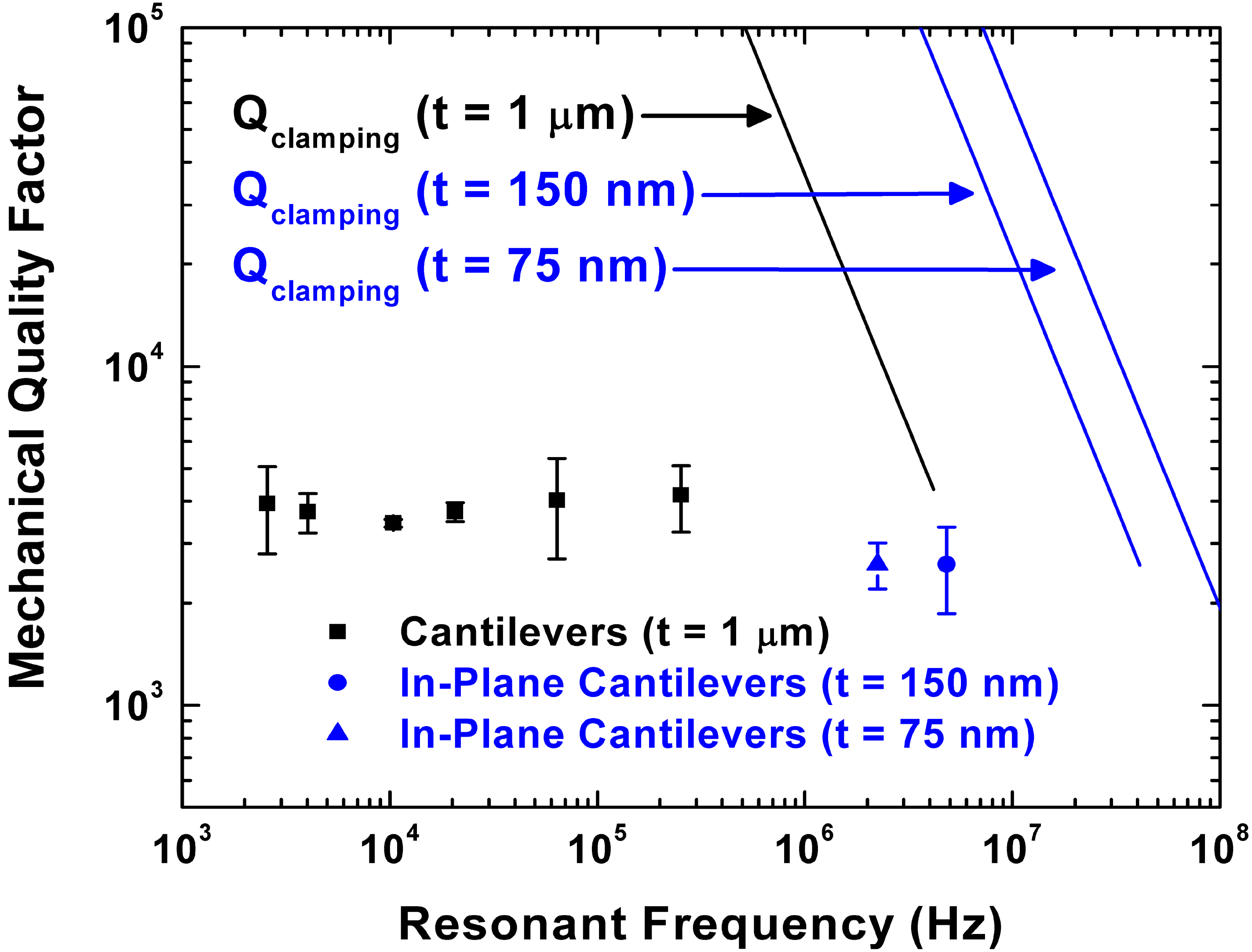
Q = 5172 ± 437

$$y = y_0 + \left(\frac{2A}{\pi}\right)\frac{w}{\left(4(f - f_0)^2 + w^2\right)}$$

Typical quality factors



Clamping loss limited?



$$Q_{clamping} \approx 0.34 \frac{l^3}{t^3}$$

H. Hosaka, K. Itao, and S. Kuroda, Sens. Actuators A 49, 87 (1995).

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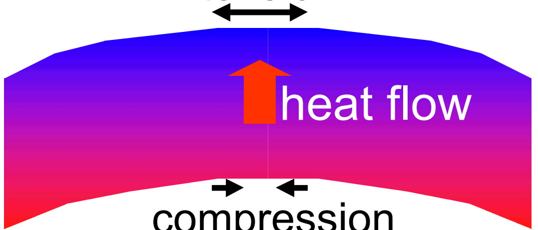
Limited by thermoelastic dissipation?

transverse mode:



$$Q_{TED} = \frac{1}{2\Gamma(T)\Omega(f)},$$

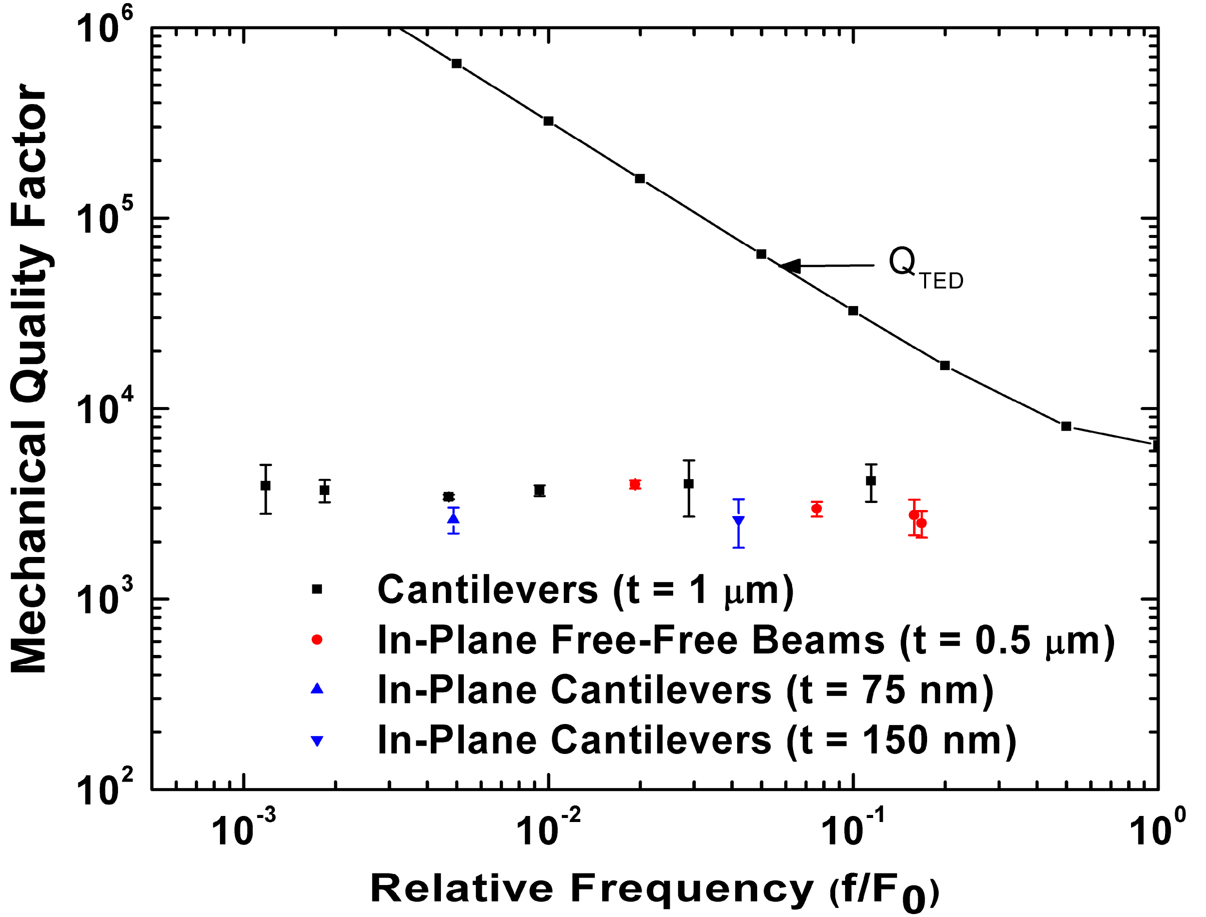
$$\Gamma(T) = \frac{\alpha^2 TE}{4\rho C_p},$$

$$\Omega(f) = \frac{2f/F_0}{1+(f/F_0)^2},$$

$$F_0 = \frac{\pi\kappa}{2\rho C_p t^2}.$$

T. V. Roszhart, in *Tech. Dig. Solid-State Sens. Actuator Workshop*, Hilton Head, SC 1990, pp. 13-16.

Limited by thermoelastic dissipation?



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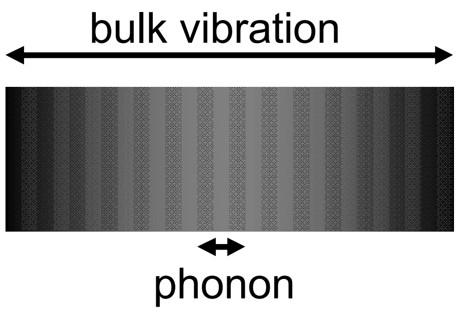
Limited by phonon phonon interactions?

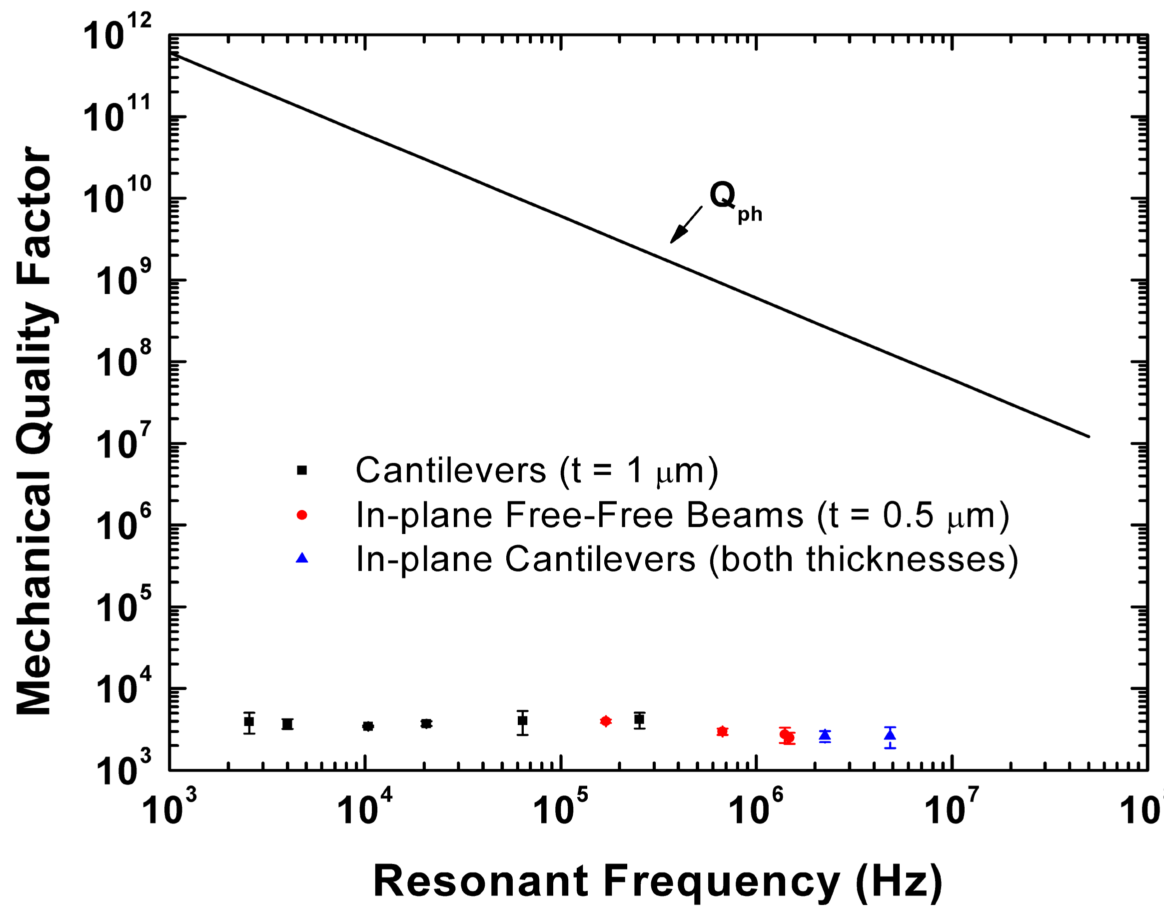


$$Q_{ph} \approx \frac{\rho v^2}{C T \gamma^2}\left[\frac{\omega \tau_{ph}}{1+(\omega \tau_{ph})^2}\right]^{-1},$$

$$\tau_{ph} = \frac{3\kappa}{\rho C_p v_D^2},$$

$$\frac{3}{\upsilon_D^3} = \frac{1}{\upsilon_l^3} + \frac{2}{\upsilon_t^3},$$

$$\upsilon_l = \left(\frac{E}{\rho}\right)^{\frac{1}{2}} \qquad v_l = 1.65\ v_t$$



B. Braginsky, V. P. Mitrofanov, V. I. Panov, <u>Systems with Small Dissipation</u>

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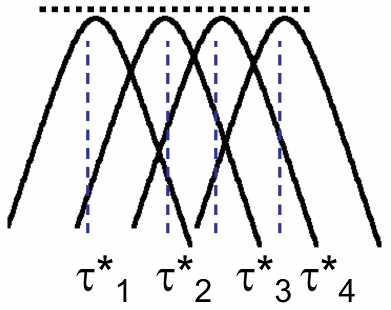
Plausible explanation

spectrum of defects

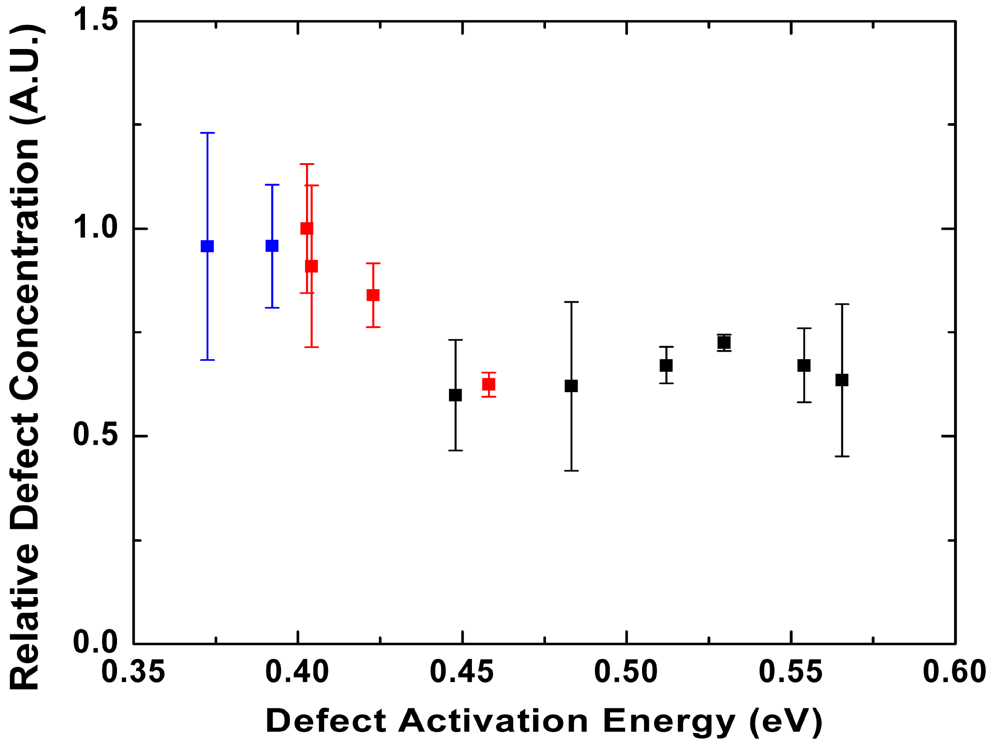


$$Q_{defect} = A\left[\frac{\omega\tau^*}{1+(\omega\tau^*)^2}\right]^{-1}$$

$$\frac{1}{\tau^*} = \frac{1}{\tau_0}\exp\left(\frac{-E_A}{k_B T}\right)$$

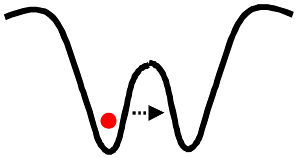
Atomic attempt frequency

$\tau_o = 10^{-13}$ s



Similar to other amorphous materials

- near universal behavior in dissipation in amorphous materials at low temperature
- described by a flat distribution of “tunneling states”

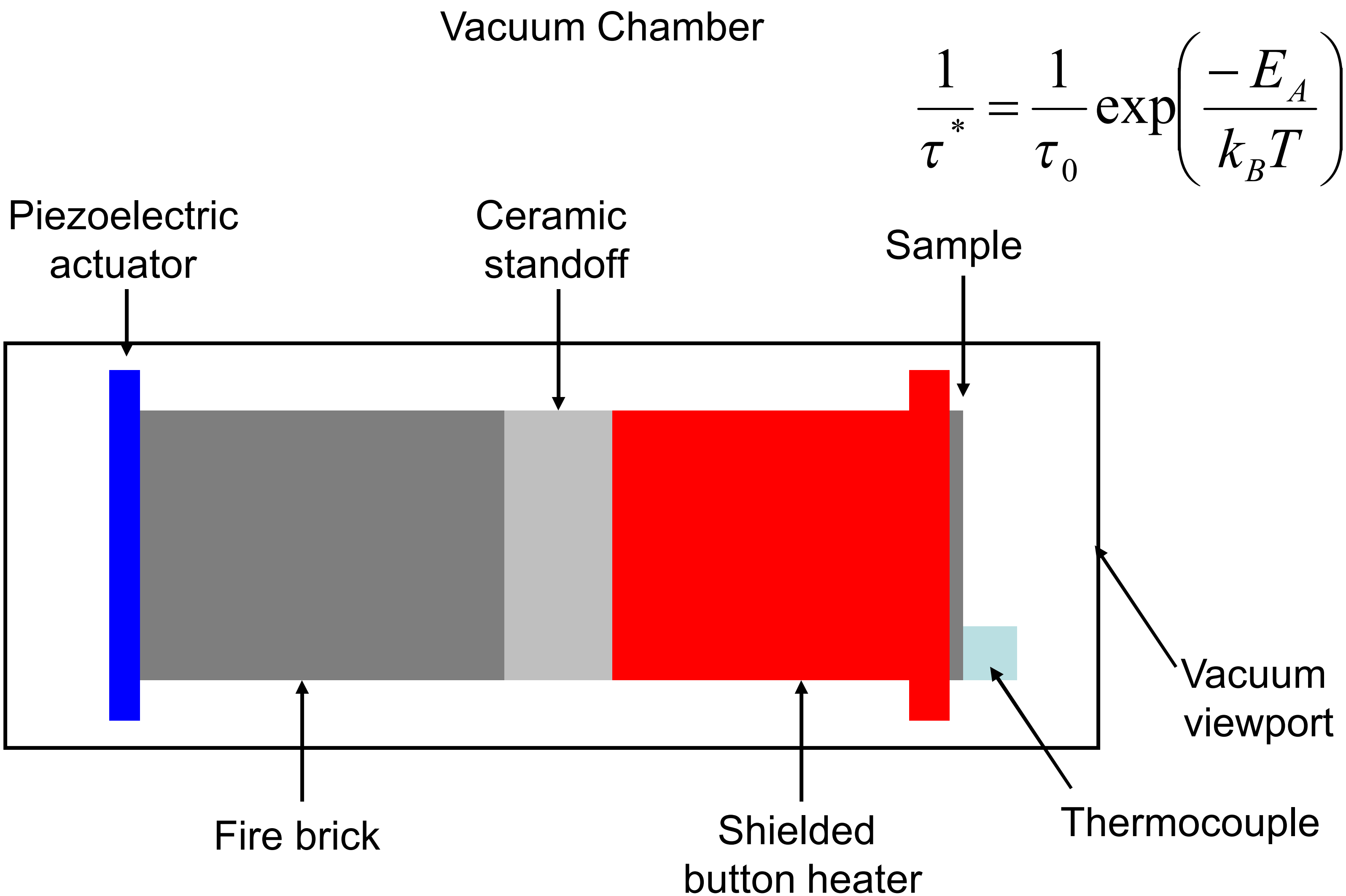


Material	Q
ta-C	**3.3×10^3 (high T)**
SiO_2	1.9×10^3
GeO_2	2.8×10^3
B_2O_3	1.6×10^3
Se	1.8×10^3
As_2S_3	4.5×10^3
$CdGeAs_2$	5.3×10^3
Polycarbonate	2.1×10^3
Polymethylmethacrylate	1.1×10^3
Polystyrene	0.8×10^3

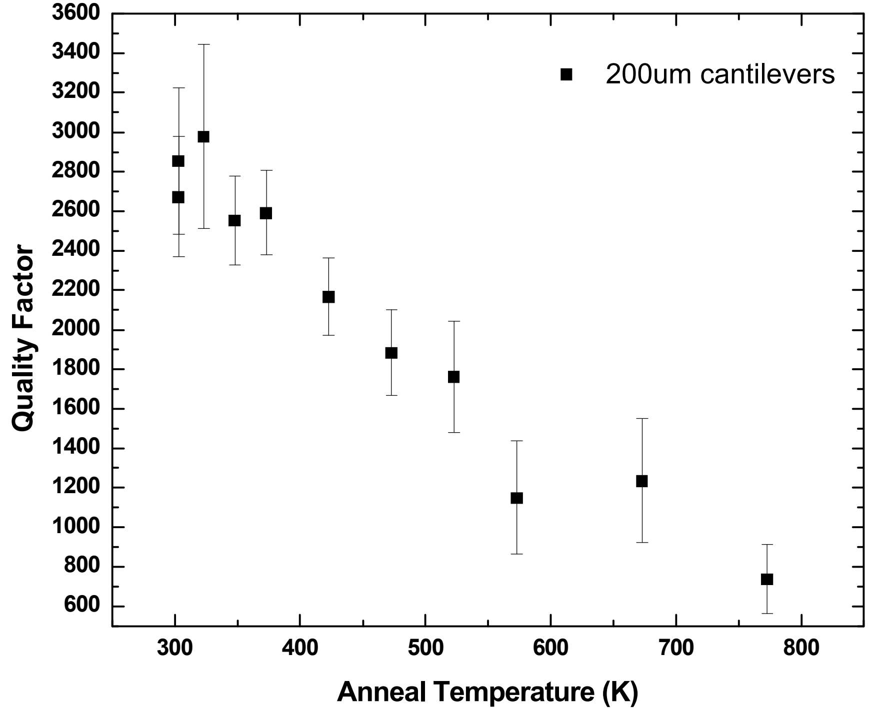
*Topp & Cahill, Z. Phys. B **101**, ’96; Braginsky et al., Systems with Small Dissipation (1985).*

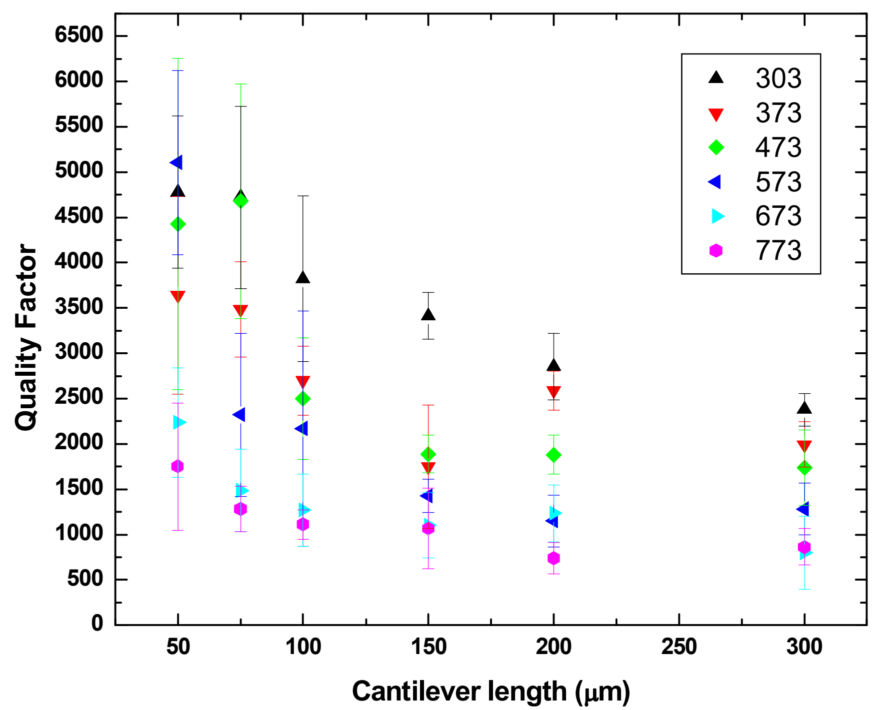
Explore higher E_a by measuring at higher T

$$\frac{1}{\tau^*} = \frac{1}{\tau_0}\exp\left(\frac{-E_A}{k_B T}\right)$$

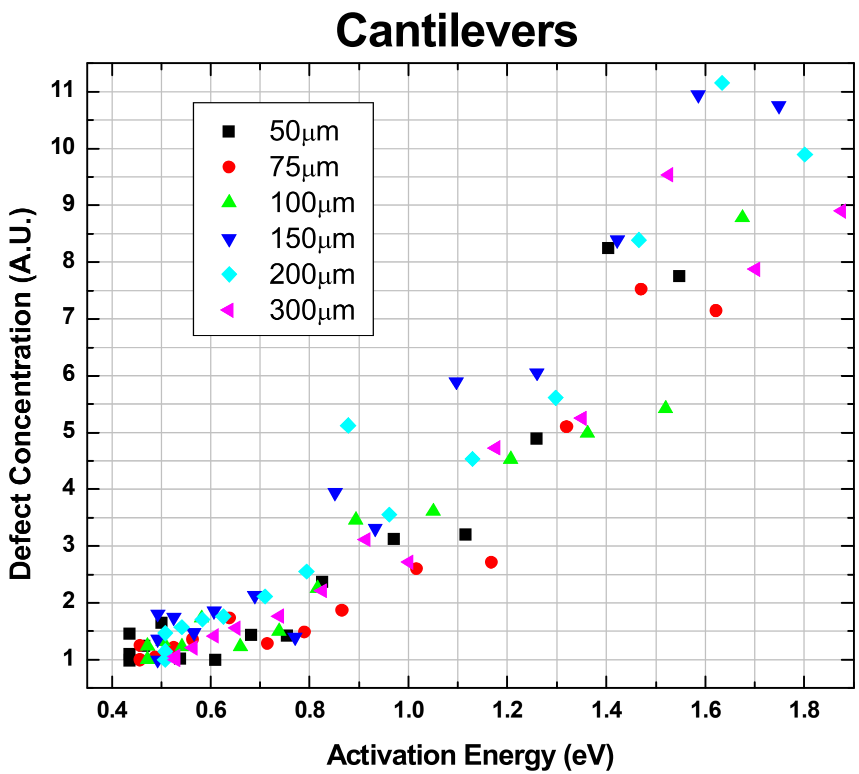


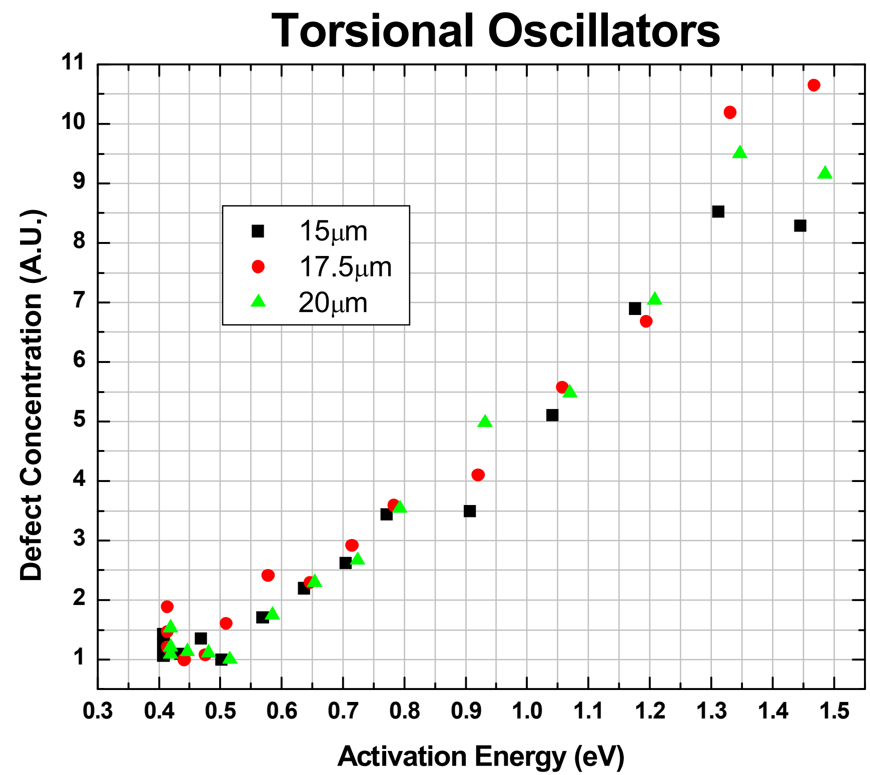
Data at elevated temperature





More defects with larger activation energies





vacancy self-diffusion in crystalline diamond: 2.3 eV
self-interstitial diffusion in crystalline diamond: 1.3 eV

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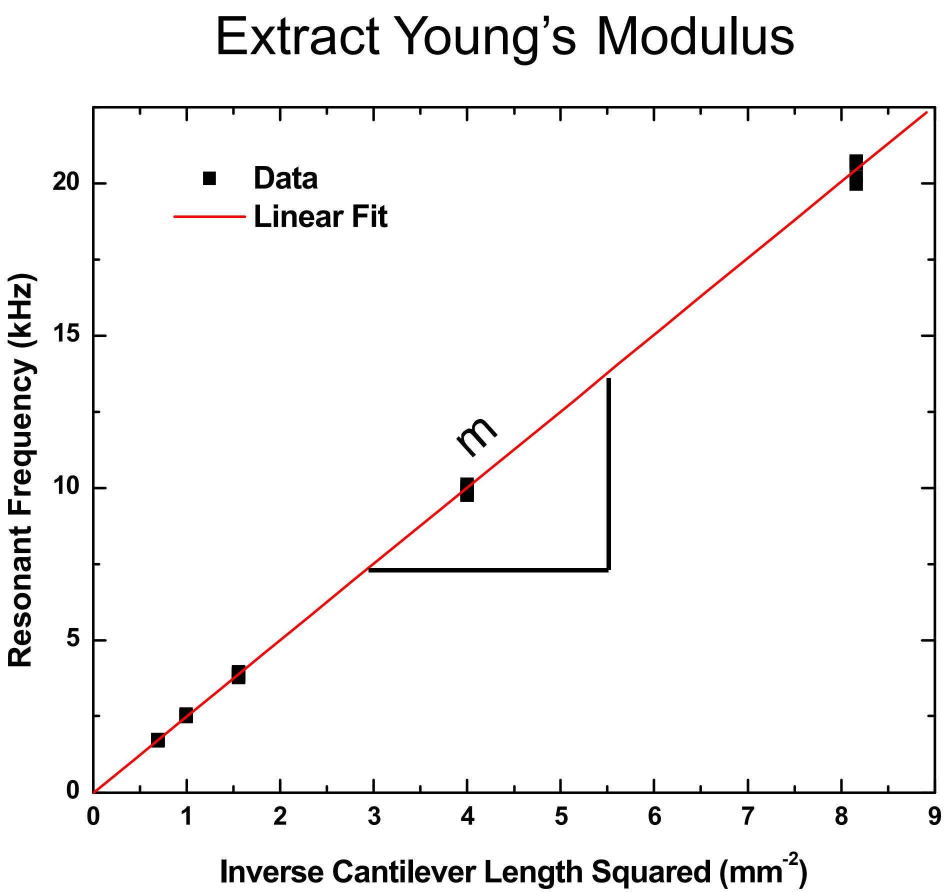
Summary of dissipation

- At room temperature, similar Qs over large frequency range
- Oscillators don't appear to be limited by:
    - Clamping losses
    - Thermoelastic Dissipation
    - Phonon-phonon interactions
- Possible broad spectrum of defects limiting Q
- Behave similar to other amorphous materials at lower temperature
- Higher concentrations of defects, limiting Q, at higher activation energies

Extract Young's modulus

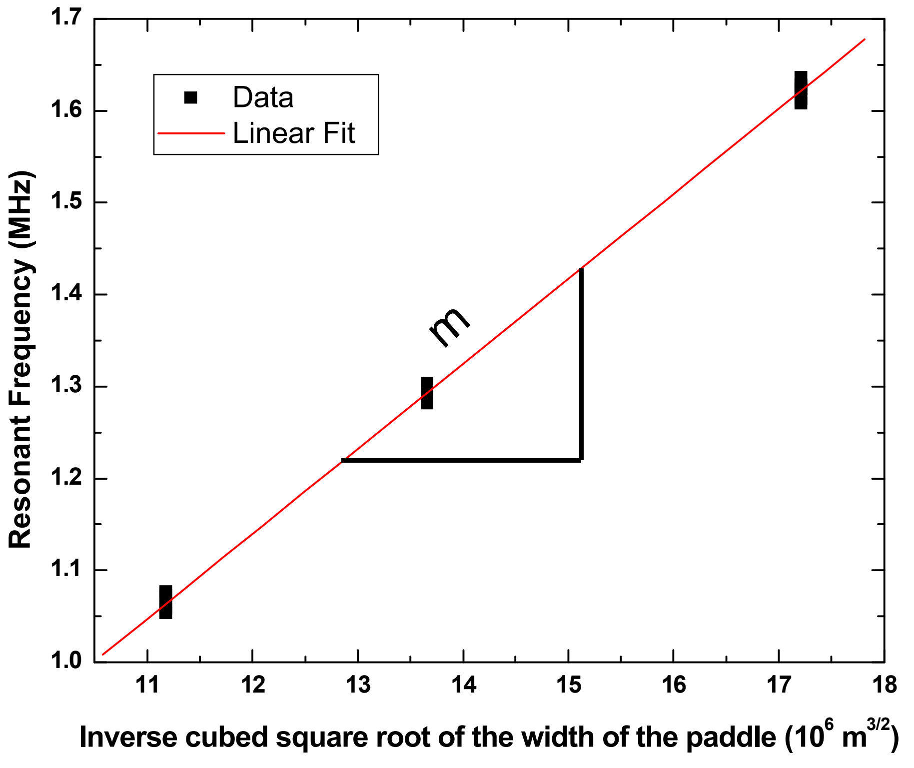


$$f_o = \frac{(1.875)^2}{2\pi}\frac{t}{l^2}\sqrt{\frac{E}{12\rho}}$$

$$E = 12\rho\left(\frac{2\pi\times10^{-6}}{(1.875)^2}\frac{m}{t}\right)^2$$

$$E = 655 \pm 1\,GPa$$

Extract shear modulus

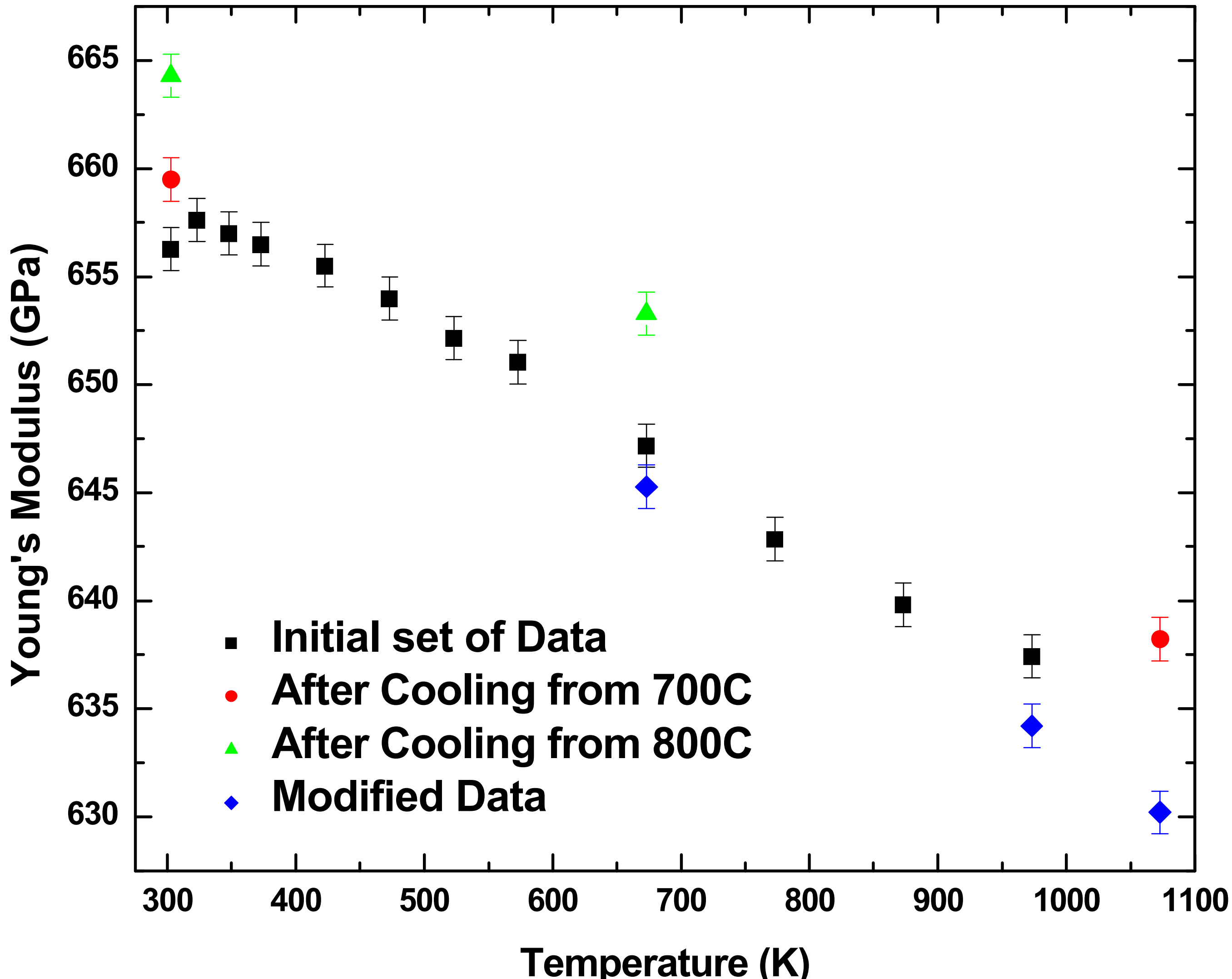


$$f_o = (0.216)\sqrt{\frac{G}{\rho}\frac{b^3}{wld^3}}$$

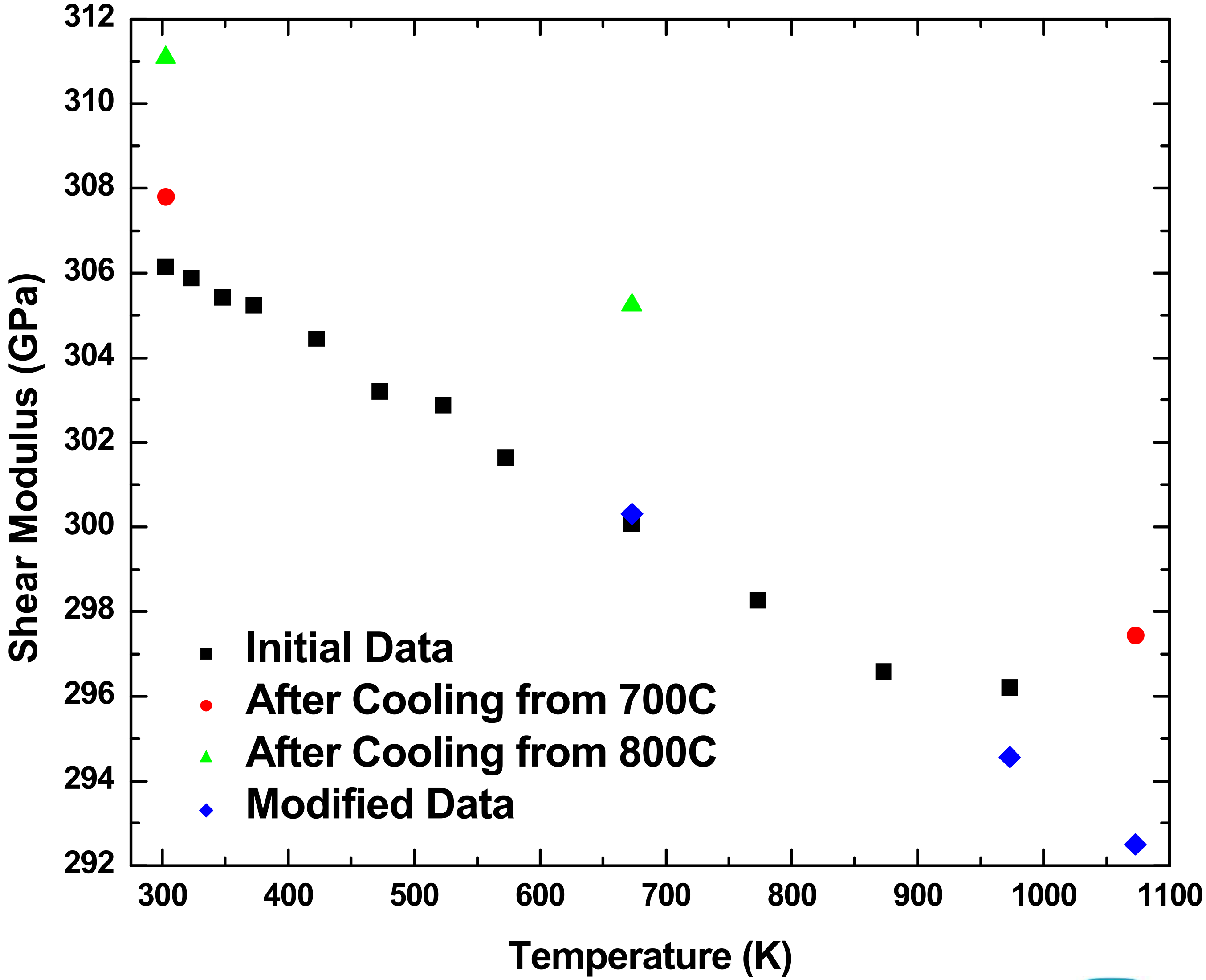
$$G = \frac{m^2 \rho\, w l}{(0.0467) b^3}$$

$$G = 306 \pm 2\, GPa$$

Temperature dependence of Young's modulus



Temperature dependence of the shear modulus



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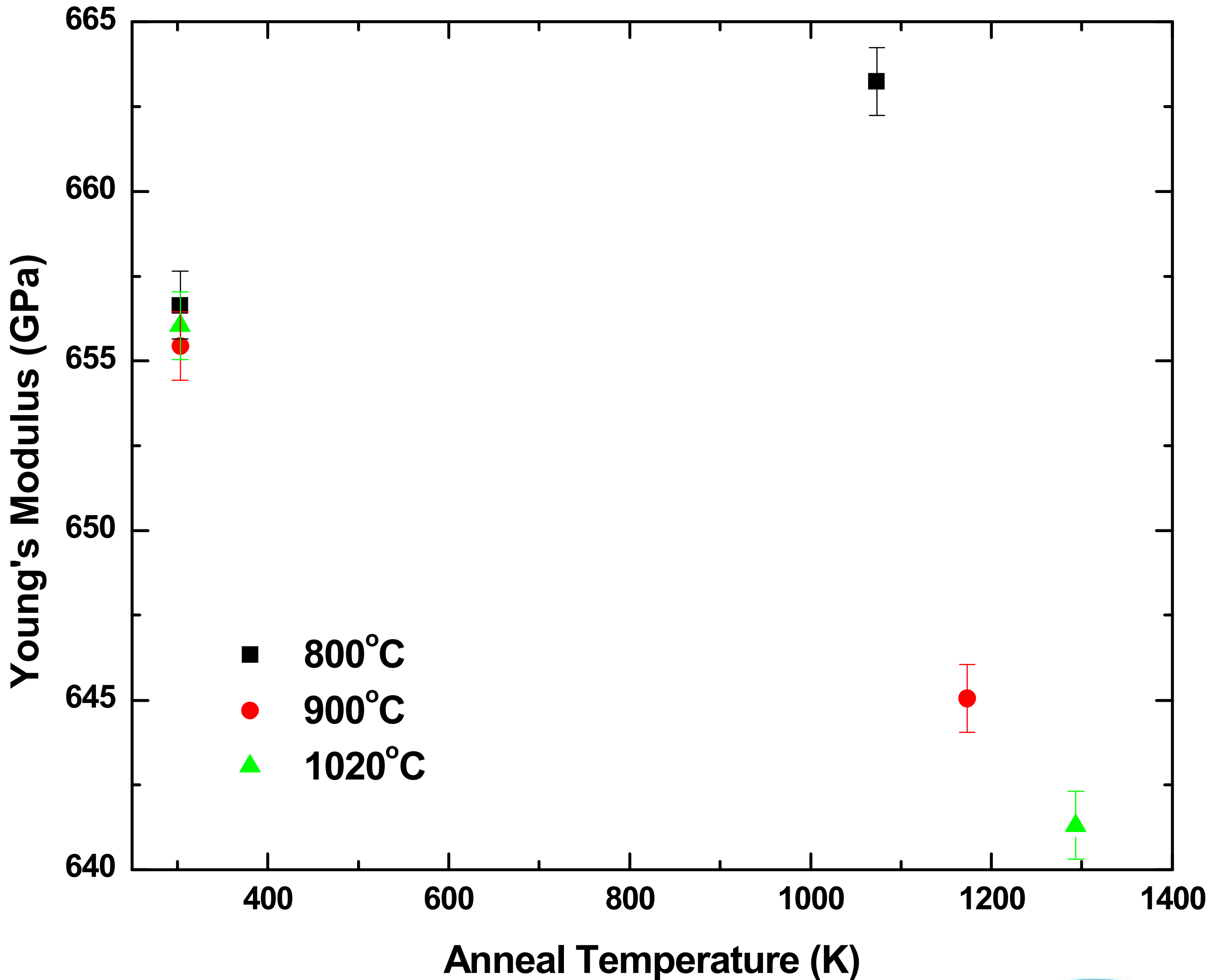
Young's Modulus after higher temperature annealing



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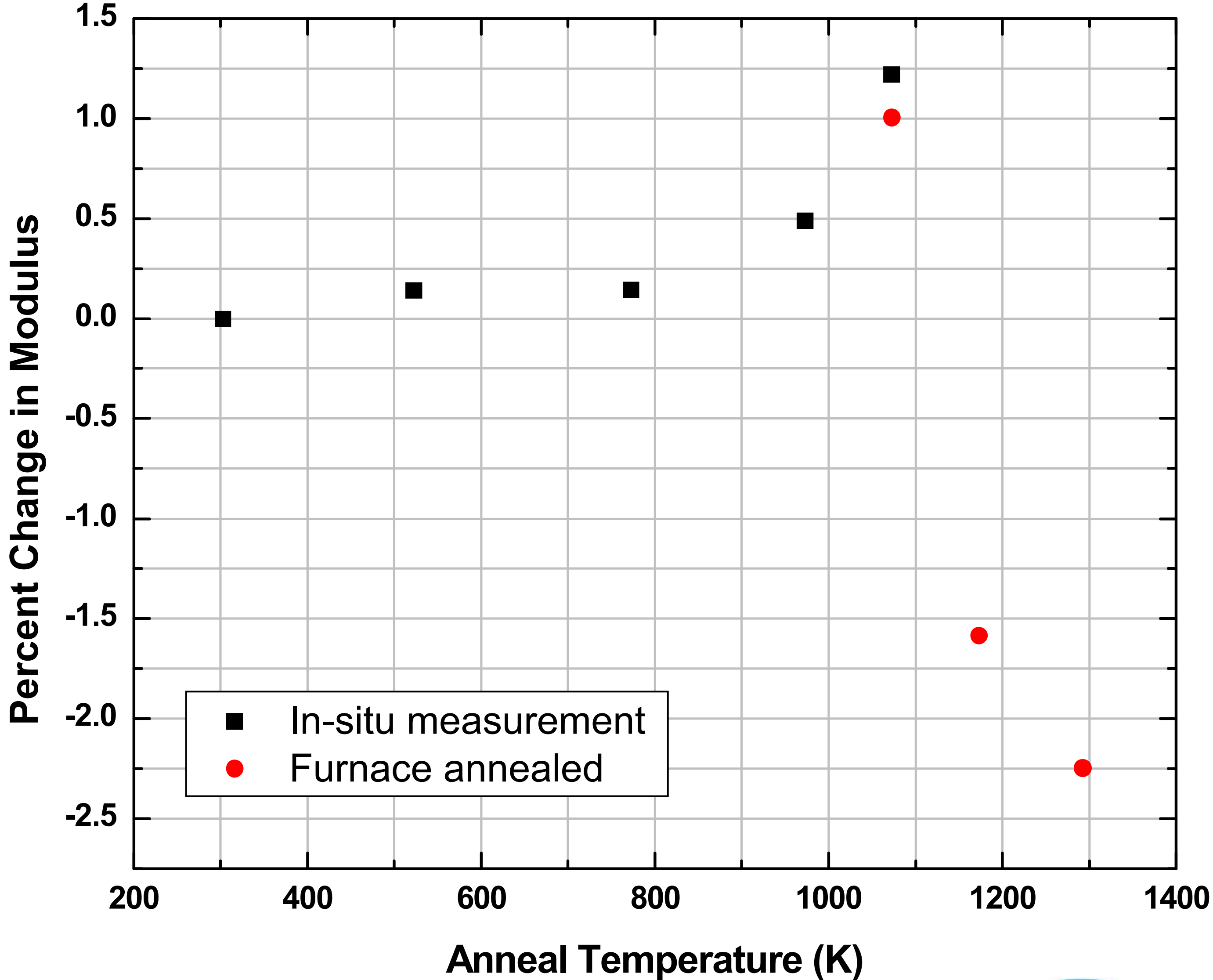
Young’s modulus after higher temperature annealing

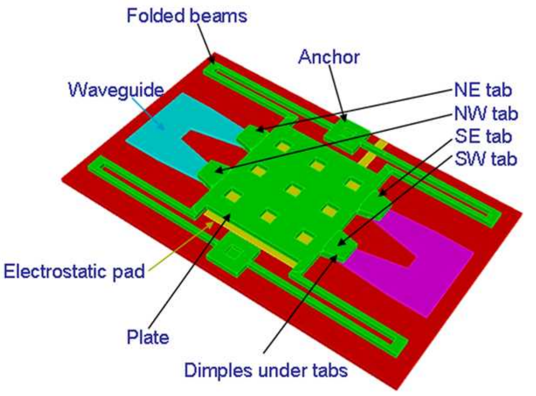


Summary of mechanical properties

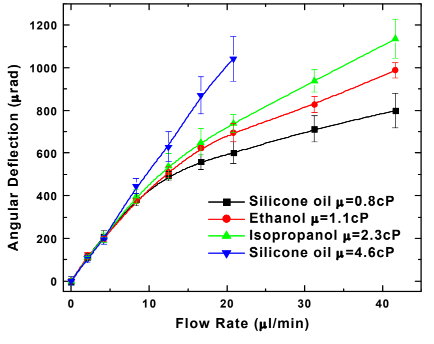
- Extracted both Young's and Shear Moduli
- Determined the temperature dependence of both E and G
- The film experiences a permanent mechanical change above 700C

Other Research Activities

•RF Switch mechanics (C. Dyck)

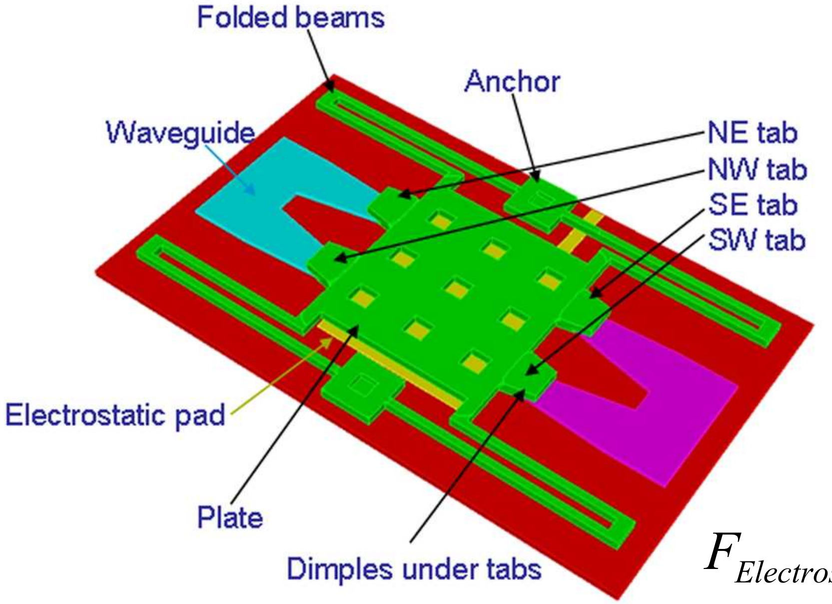


•Microfluidic MEMS pressure transducer (T. Michalske)



•Low-force contacting metal surfaces (M. Baker)

RF Switch mechanics

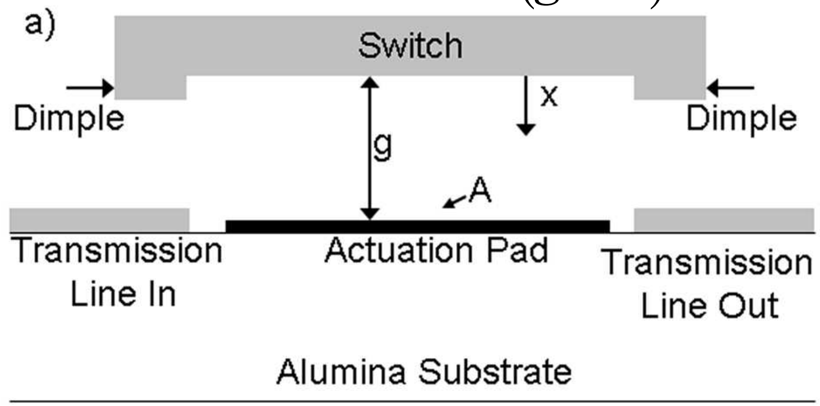


$$m_{eff}\ddot{x} = F_{Electrostatic} - F_{Spring}$$

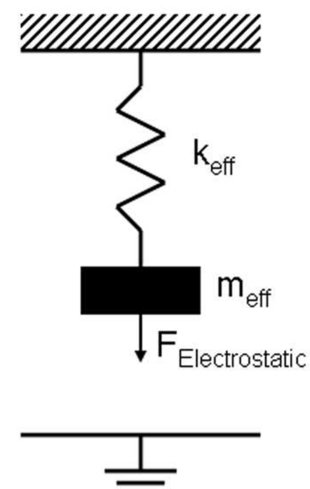
$$F_{Electrostatic} = \frac{\varepsilon_o A V^2}{2(g-x)^2}$$

$$F_{Spring} = k_{eff}x$$

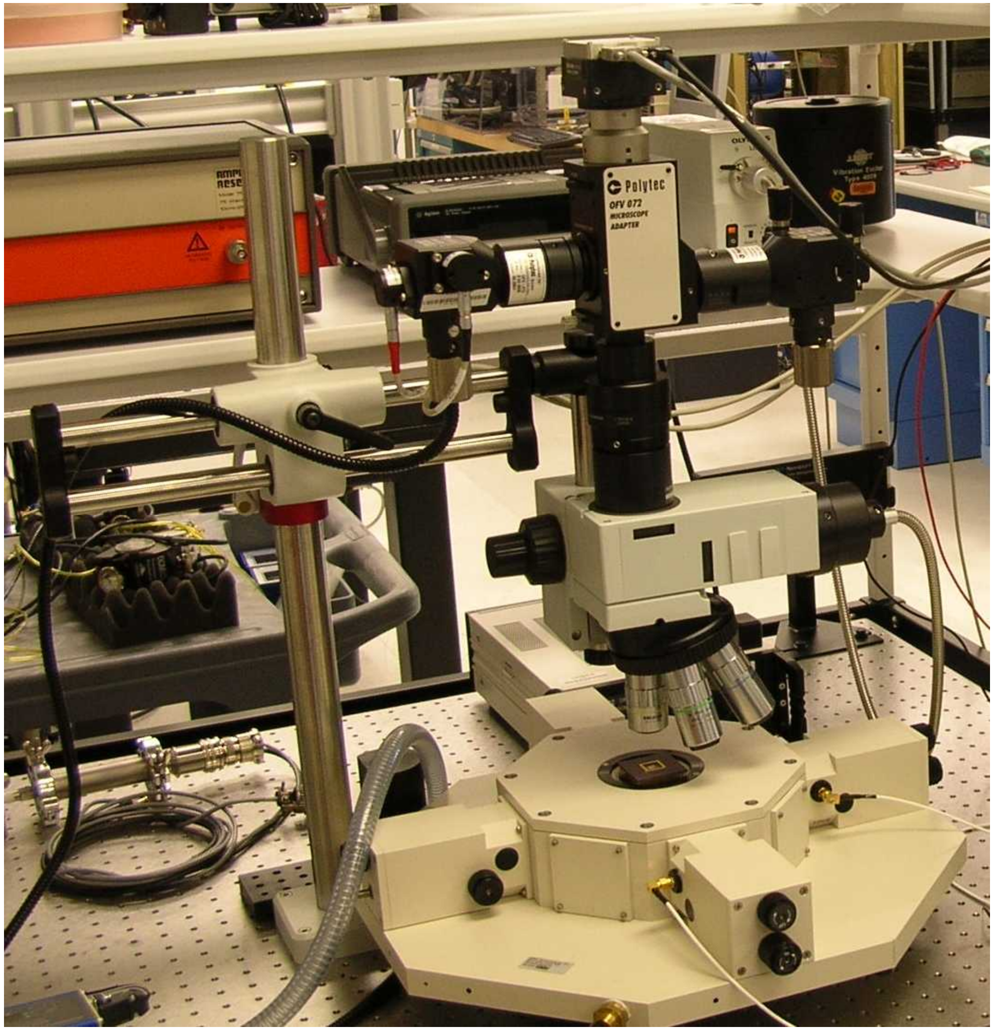
a)



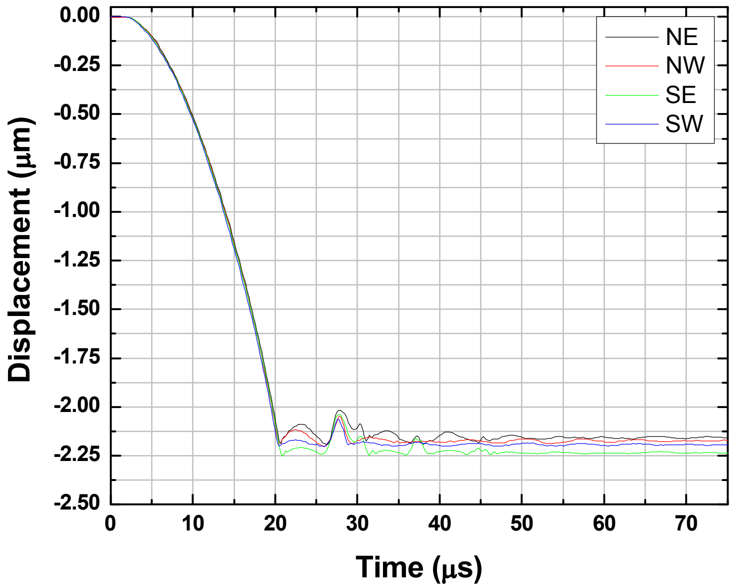
b)

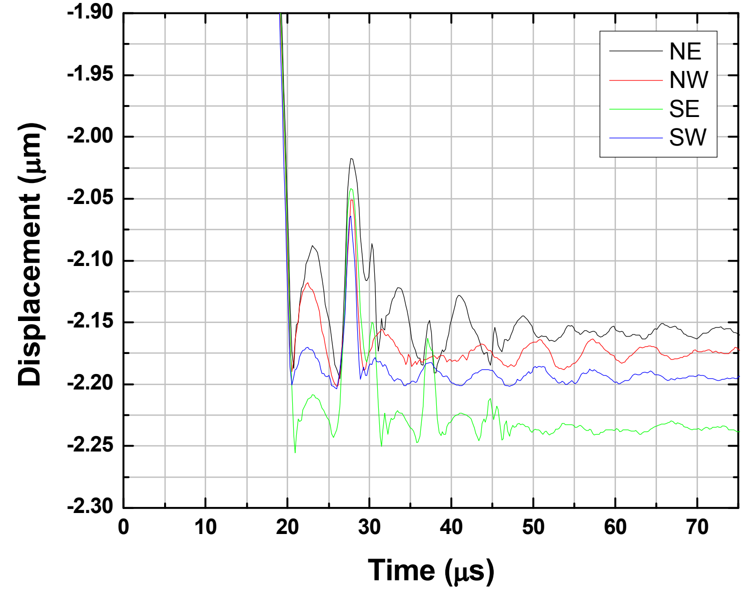


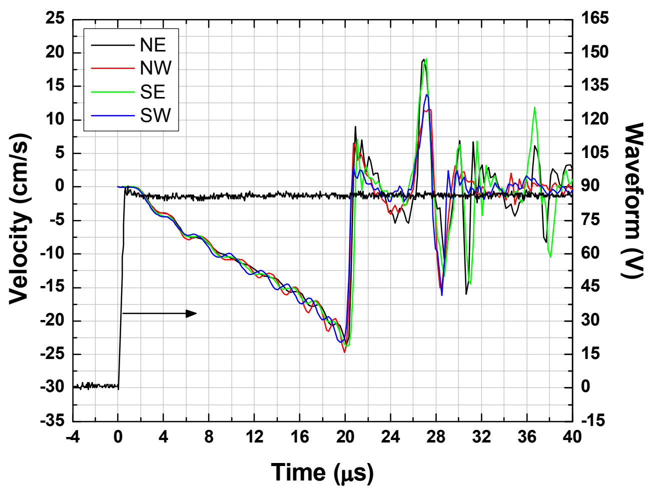
RF Switch mechanics



RF Switch mechanics







Step Voltage

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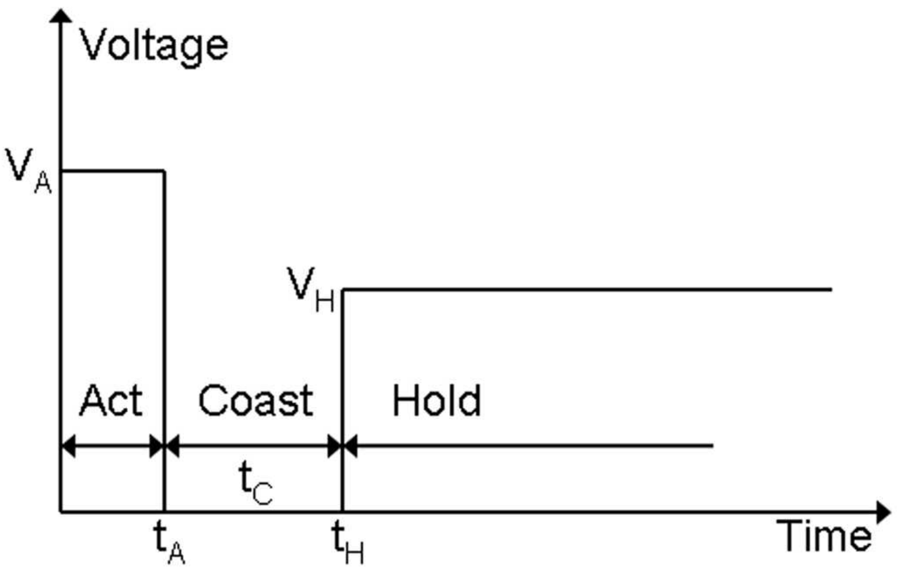
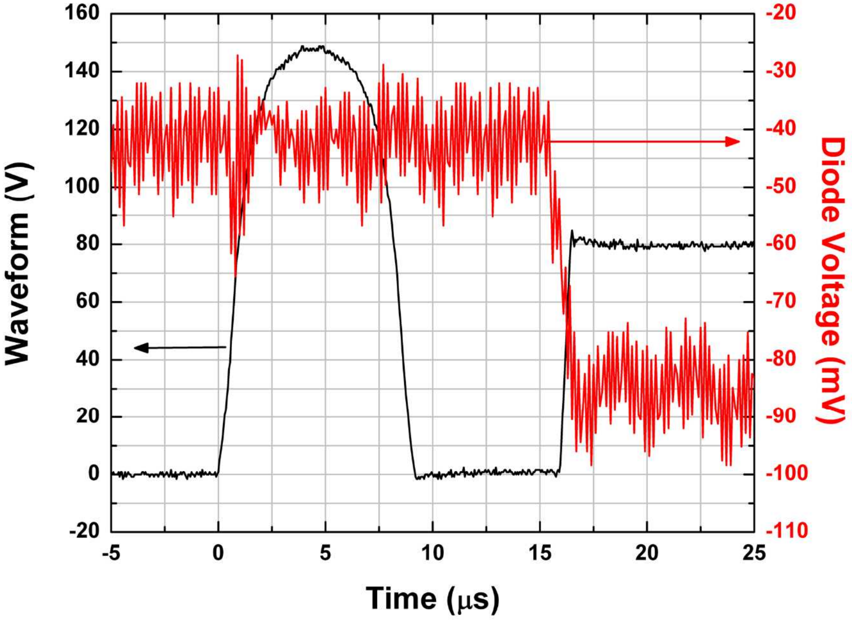
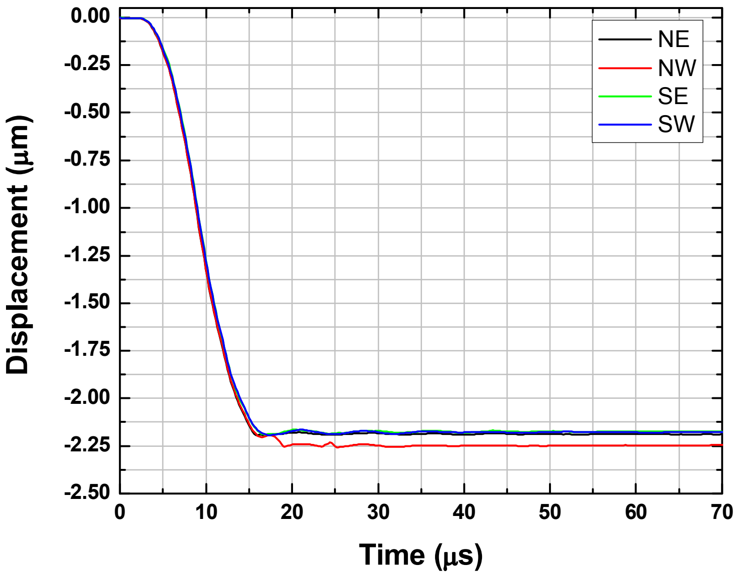
RF Switch mechanics

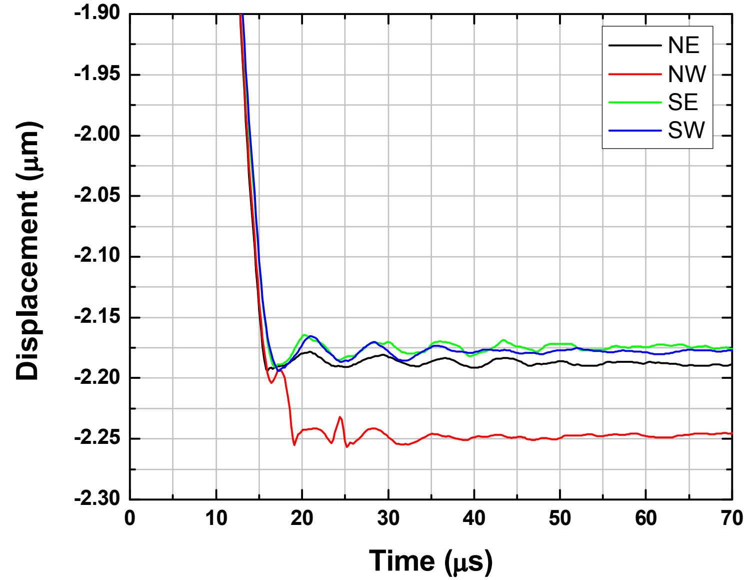


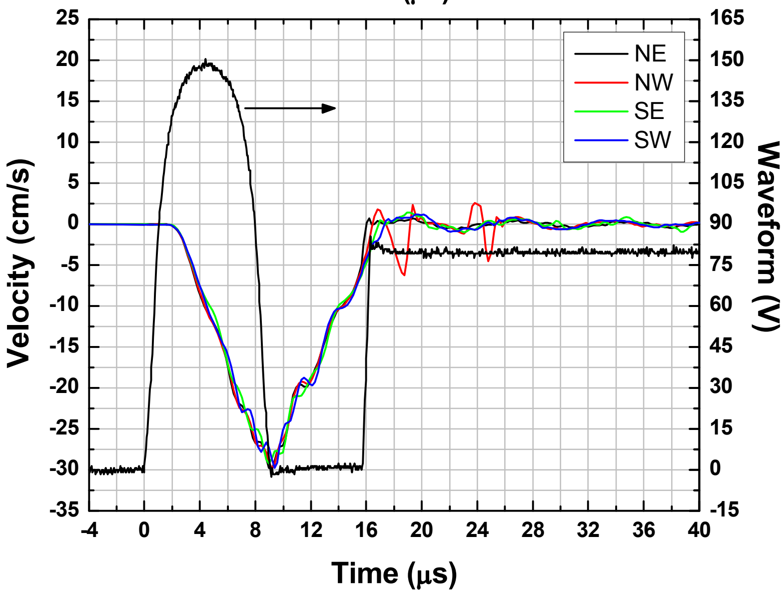


$$\frac{k_{eff} x_f^{\;2}}{2} = \int_0^{x_A} F_{Electrostatic}\, dx$$

RF Switch mechanics







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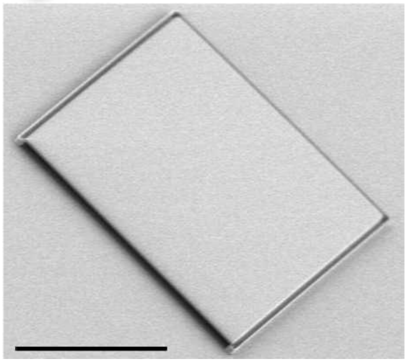
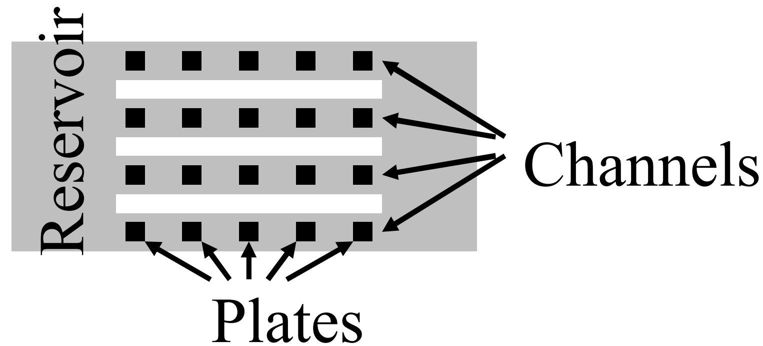
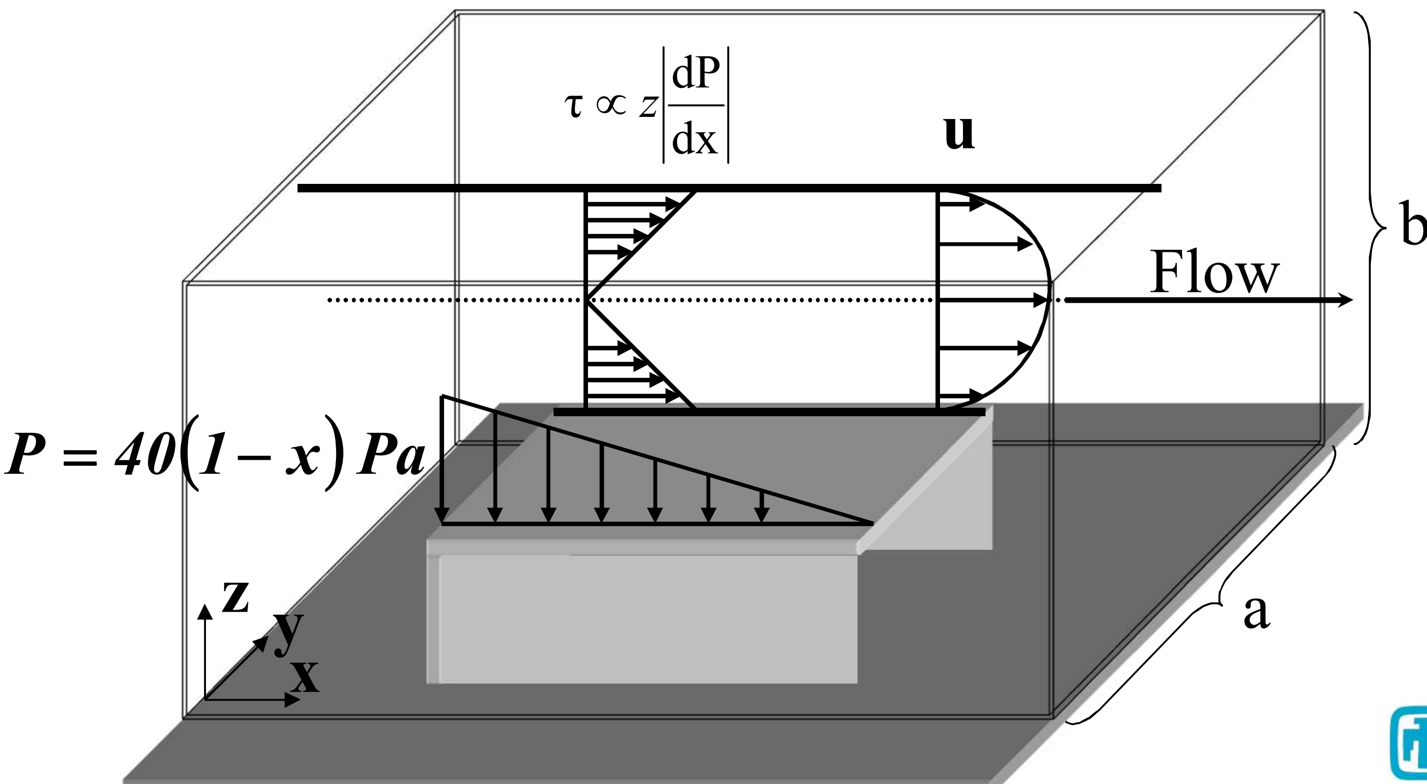
Microfluidic MEMS pressure transducer

Terry Michalske (1040/CINT/etc)

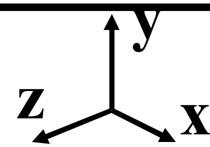




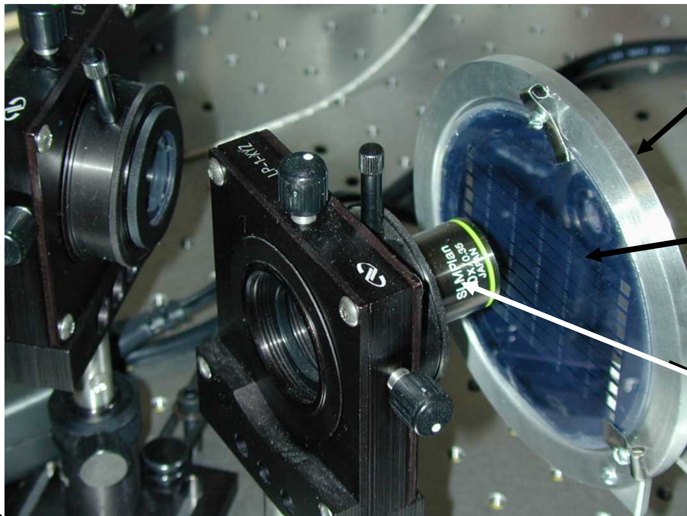
Surface Shear = 9 Pa



Microfluidic MEMS pressure transducer

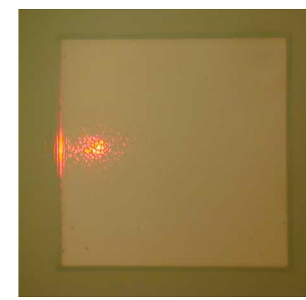


Holder for device wafer

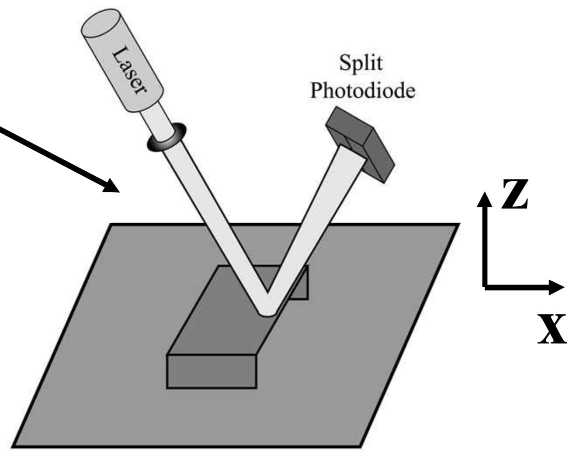


Bonded Silicon and glass wafer stack with devices in microfluidic channels

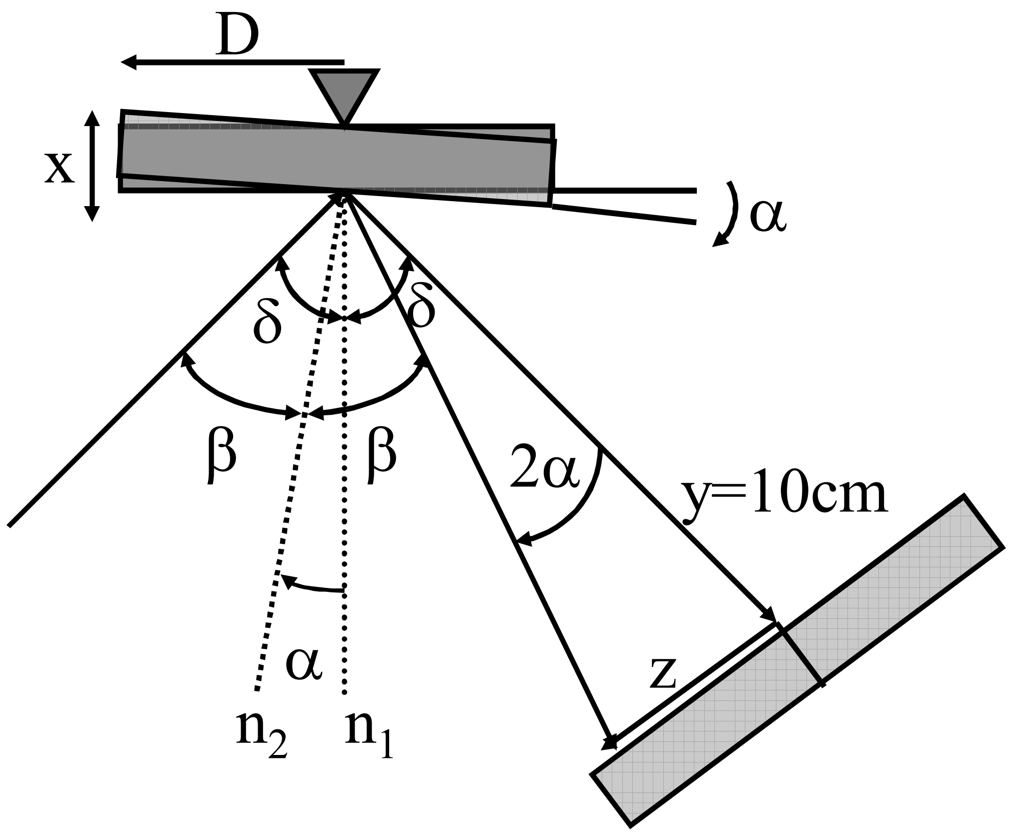
Optical Interrogation of the plate

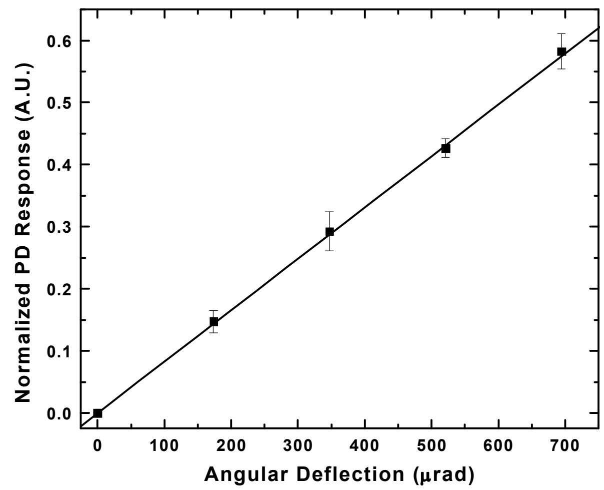


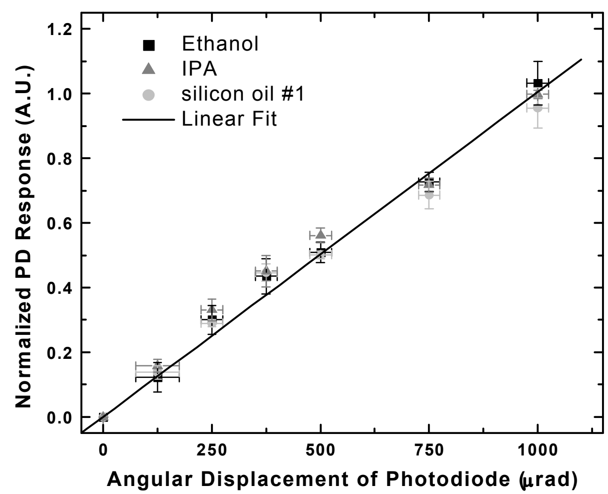
Laser Deflection



Microfluidic MEMS pressure transducer







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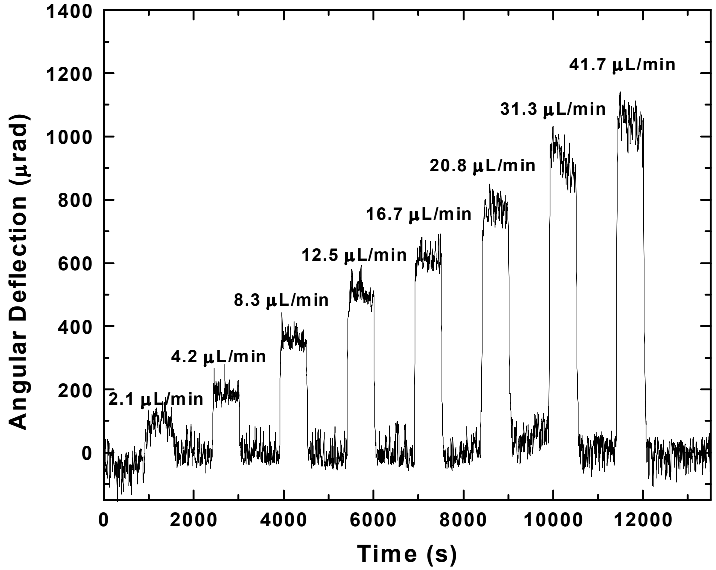
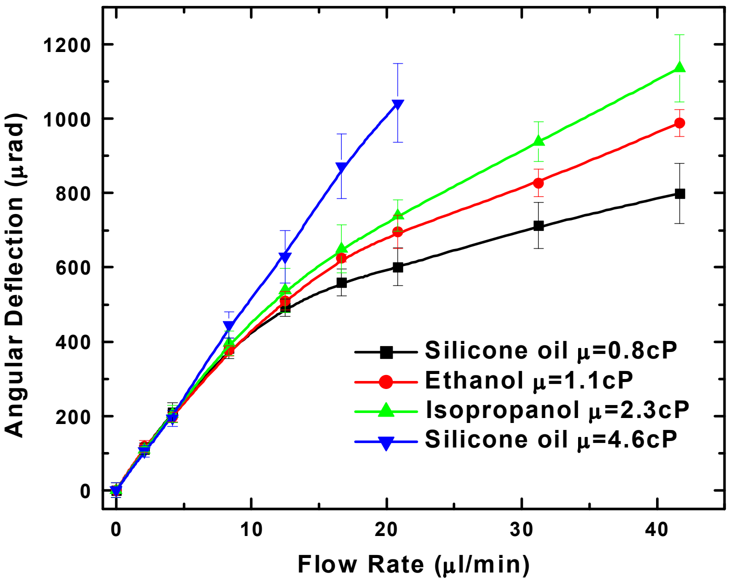
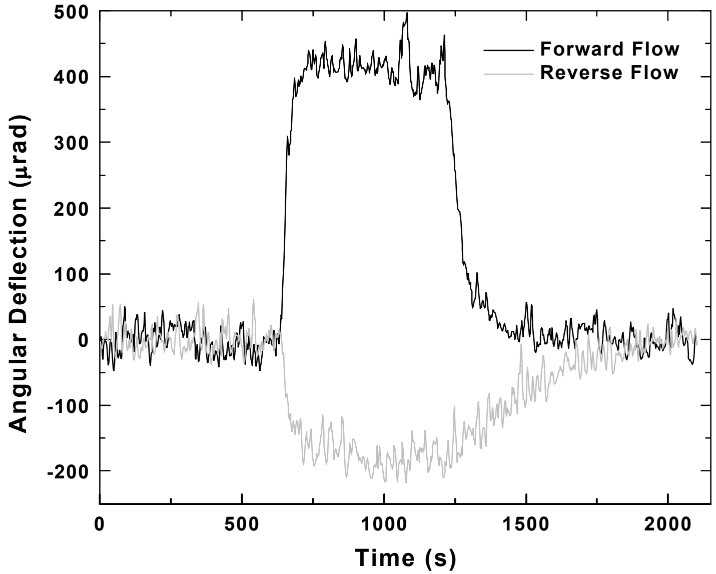
Microfluidic MEMS pressure transducer







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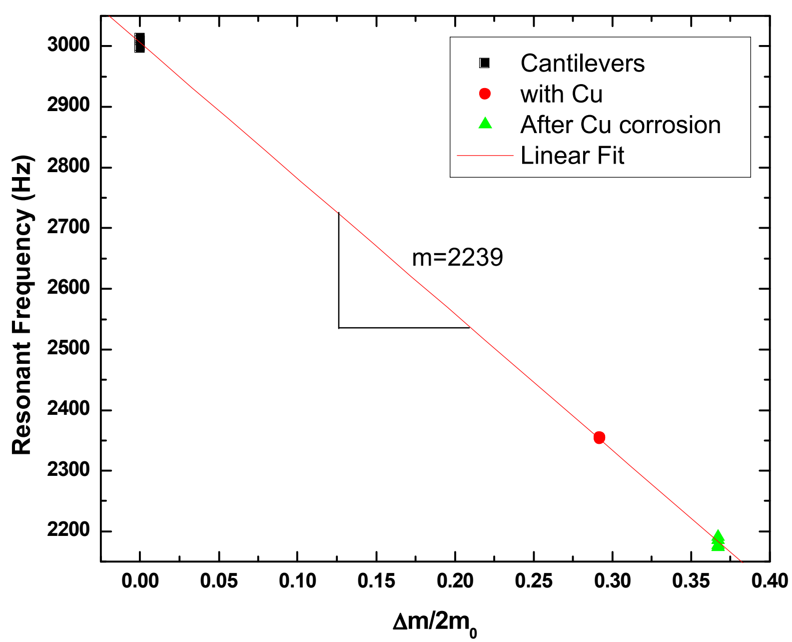
Cantilevers as Sensors

Resonant Frequency of Cantilever

$$f_o = \frac{(1.875)^2}{2\pi}\frac{t}{l^2}\sqrt{\frac{E}{12\rho}} = c\sqrt{\frac{Et^3w}{l^3}}m_o^{-1/2}$$

Resonant Frequency of Cantilever with added mass Δm

$$f = c\sqrt{\frac{Et^3w}{l^3}}m_o^{-1/2}\left(1+\frac{\Delta m}{m_o}\right)^{-1/2} = f_o\left(1-\frac{\Delta m}{2m_o}\right)$$



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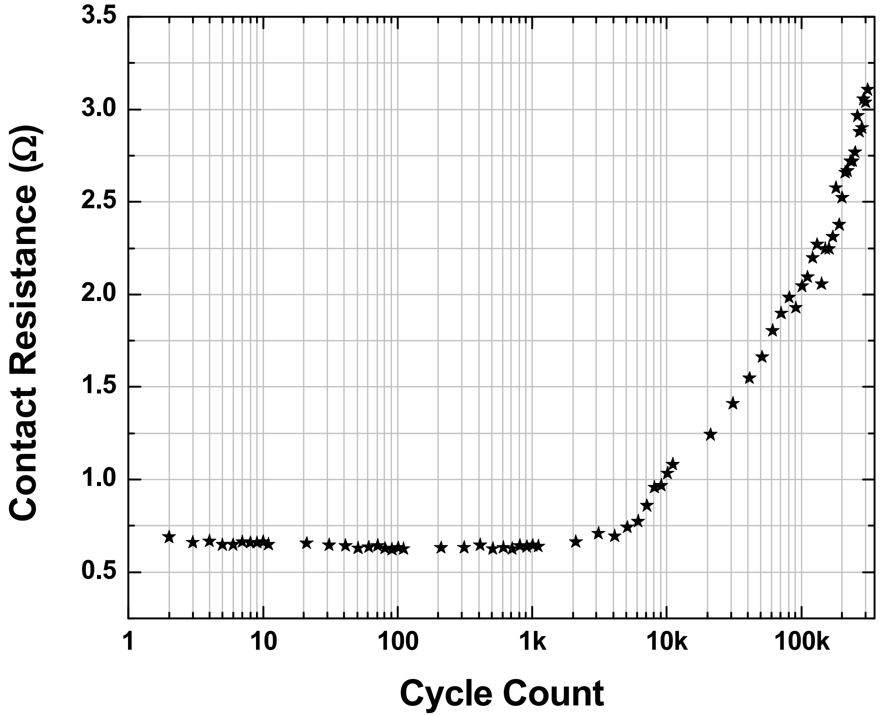
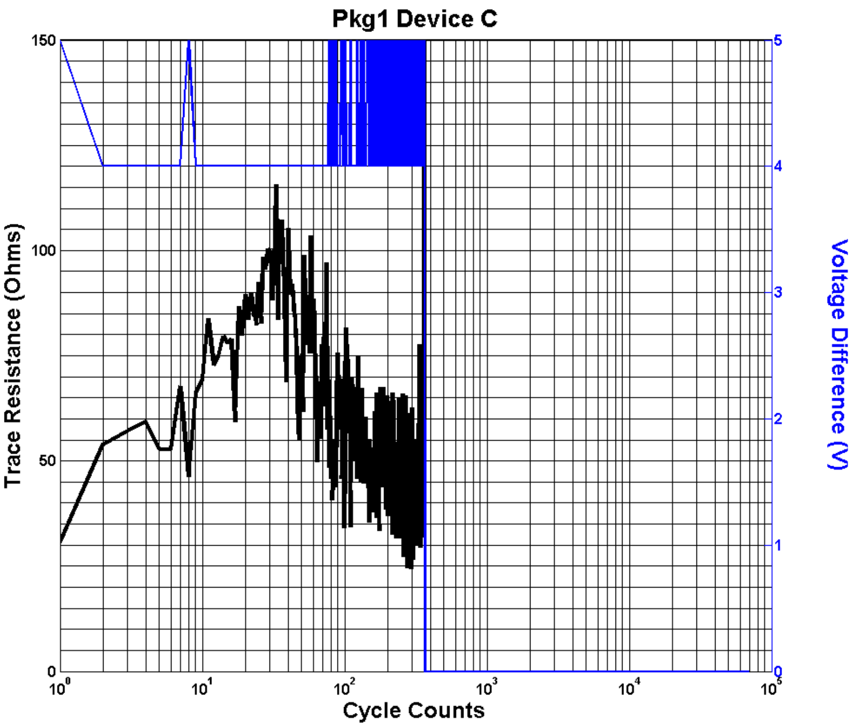
Low-force contacting metal surfaces

Used primarily in relays

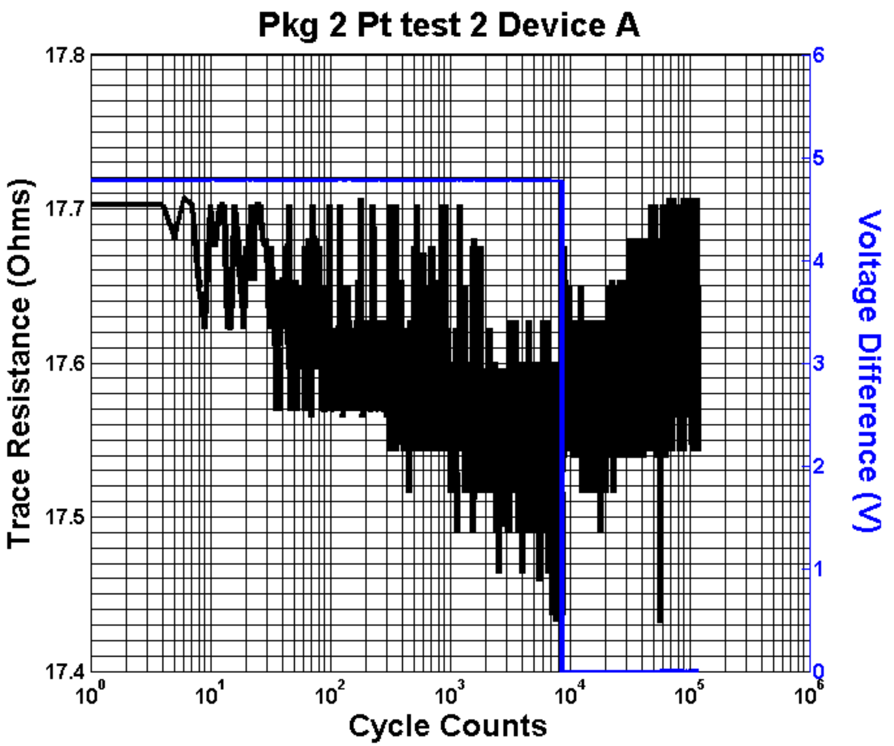


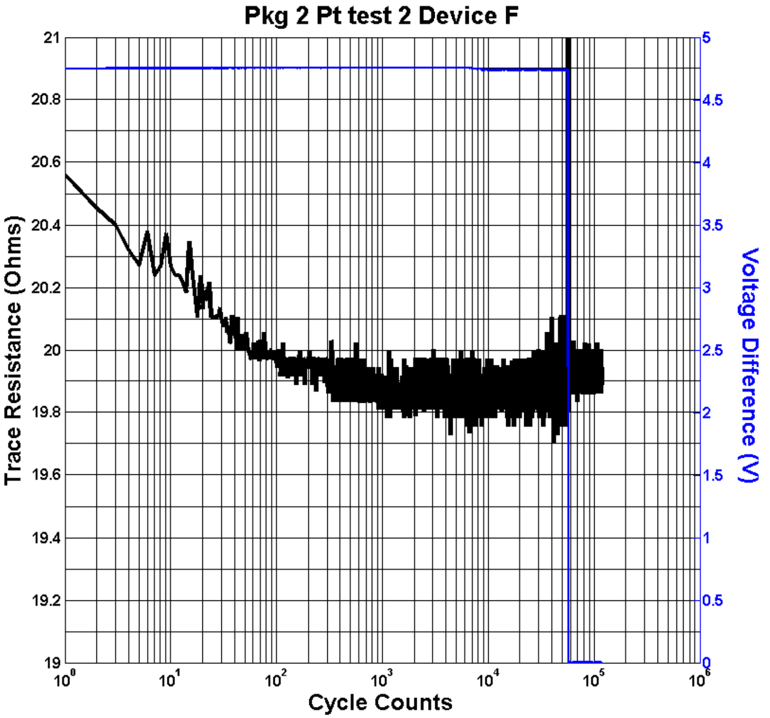


Cycled relay in Nitrogen

Low-force contacting metal surfaces

Cycled in Vacuum



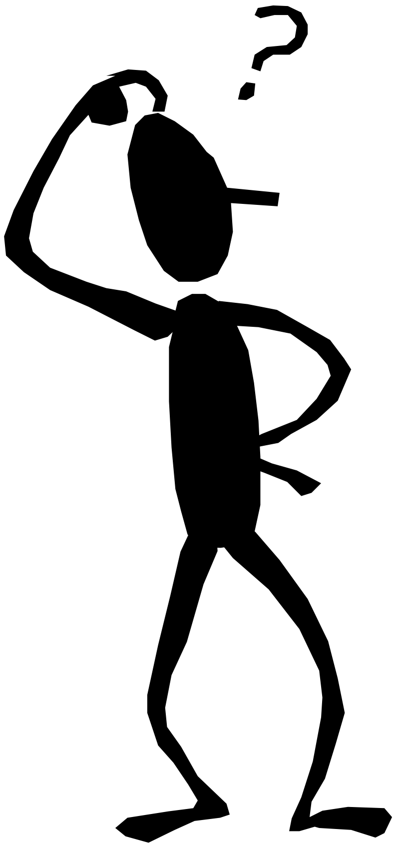


Low-force contacting metal surfaces

Acknowledgments

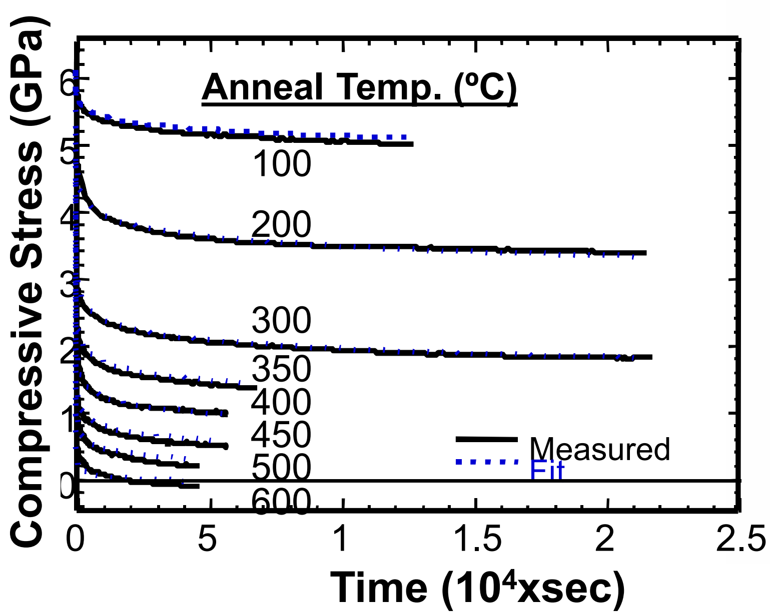
- Ta-C (J. Sullivan, T. Friedmann, R. Doty, S. Hearne, N. Modine, W. Pan, P. Kotula, D. Tallant, R. Ellis, & J. Wendt)
- T. Michalske & T. Sounart
- D. Carr, B. Keeler, and D. Sandison
- C. Dyck & J. Webster
- D. Epp & Anton Sumali
- M. Baker & D. Sandison

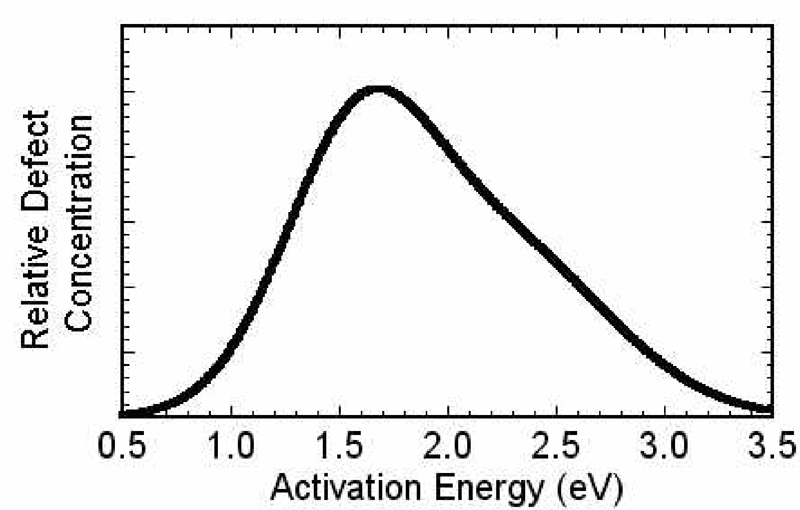
Questions?



Film deposition

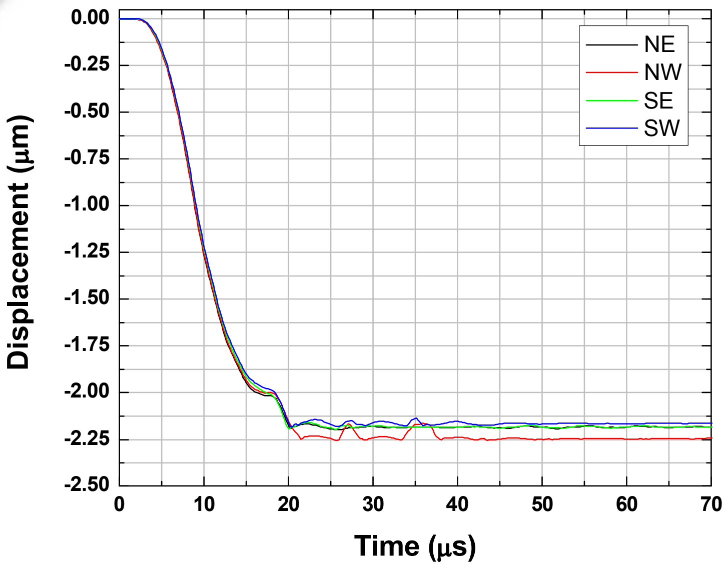
- **Room temperature deposition**
- **Stress relief can be achieved by furnace annealing or room temperature laser annealing**
- **Very pure films (contaminants of H, O, N < ppm levels)**

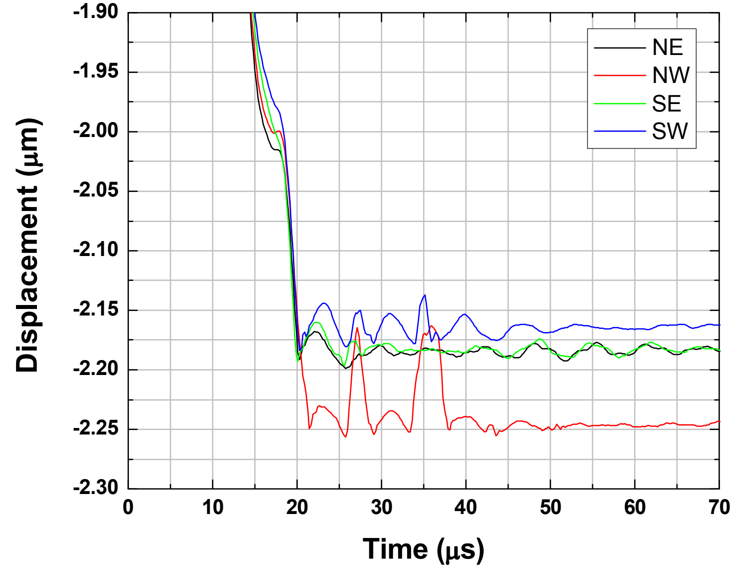


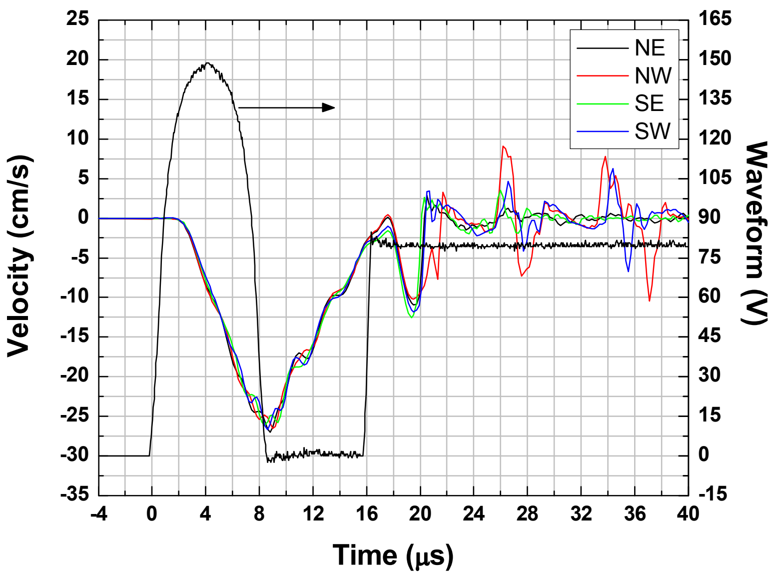


Sullivan, et al., J. Electron. Mater. ***26****, '97; Alam, et al., Phys. Rev. B* ***67****, '03*

RF Switch mechanics







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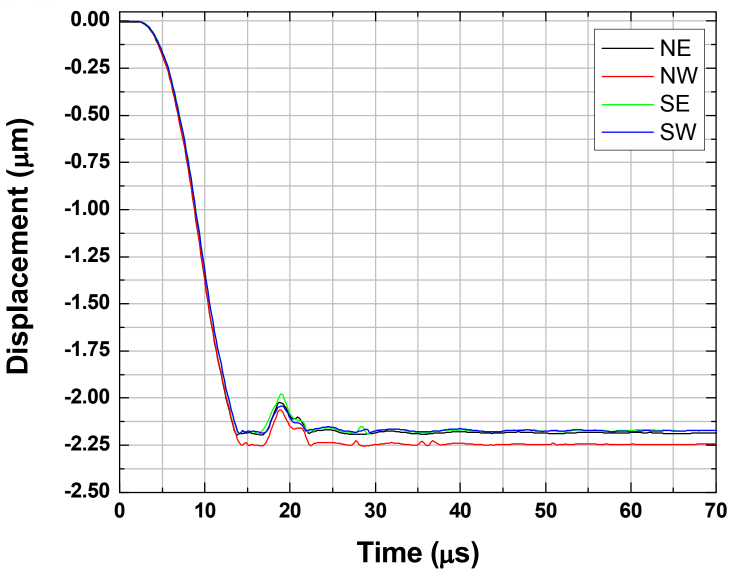
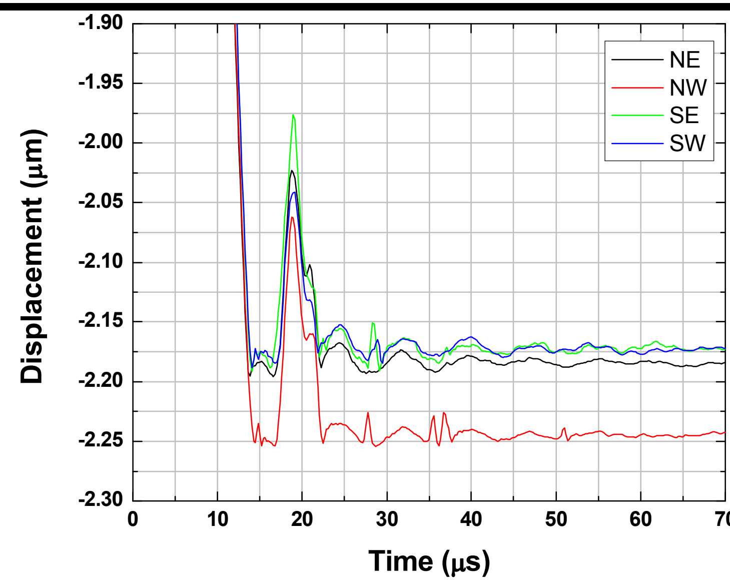
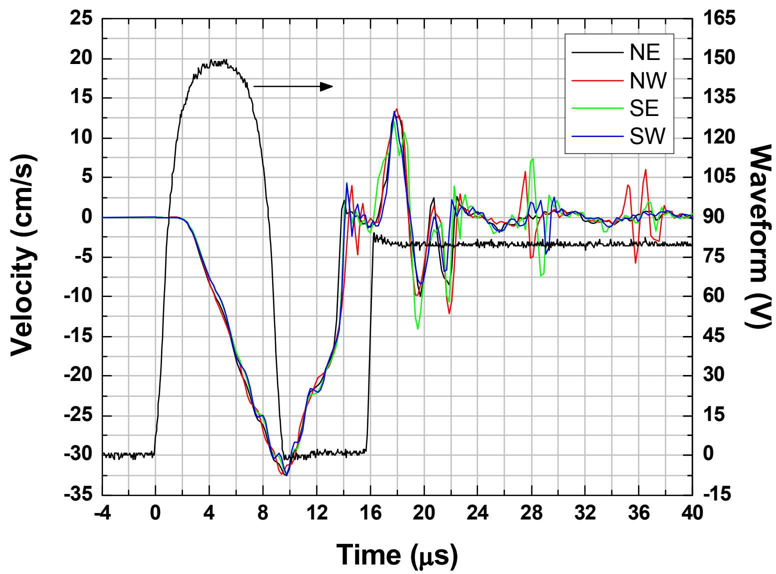
RF Switch mechanics







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