Ultimate (Resonant) MEMS Sensors

IEEE Sensors 2013 Tutorial Session 1: Novel Trends in Sensing

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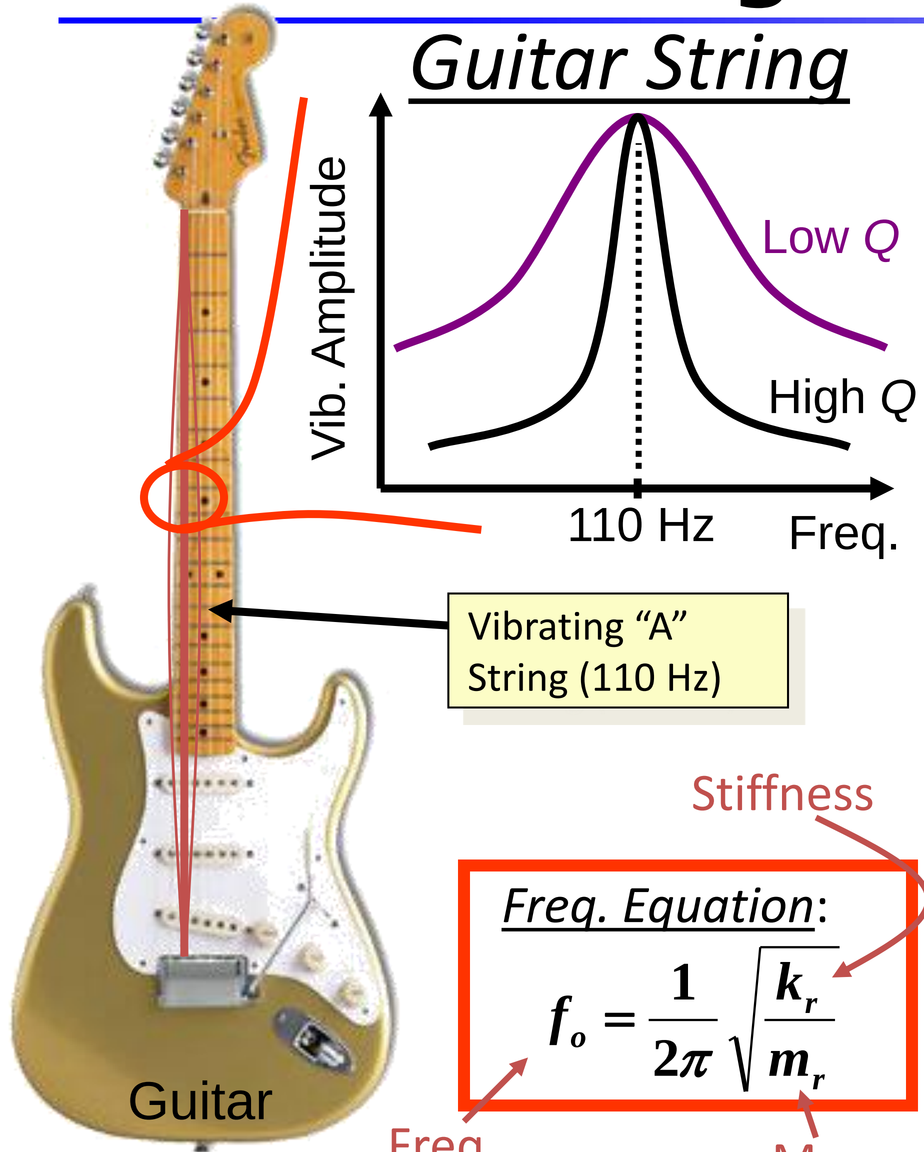
What is a MEMS Resonator?
Scaling Guitar Strings



Vibrating "A" String (110 Hz)

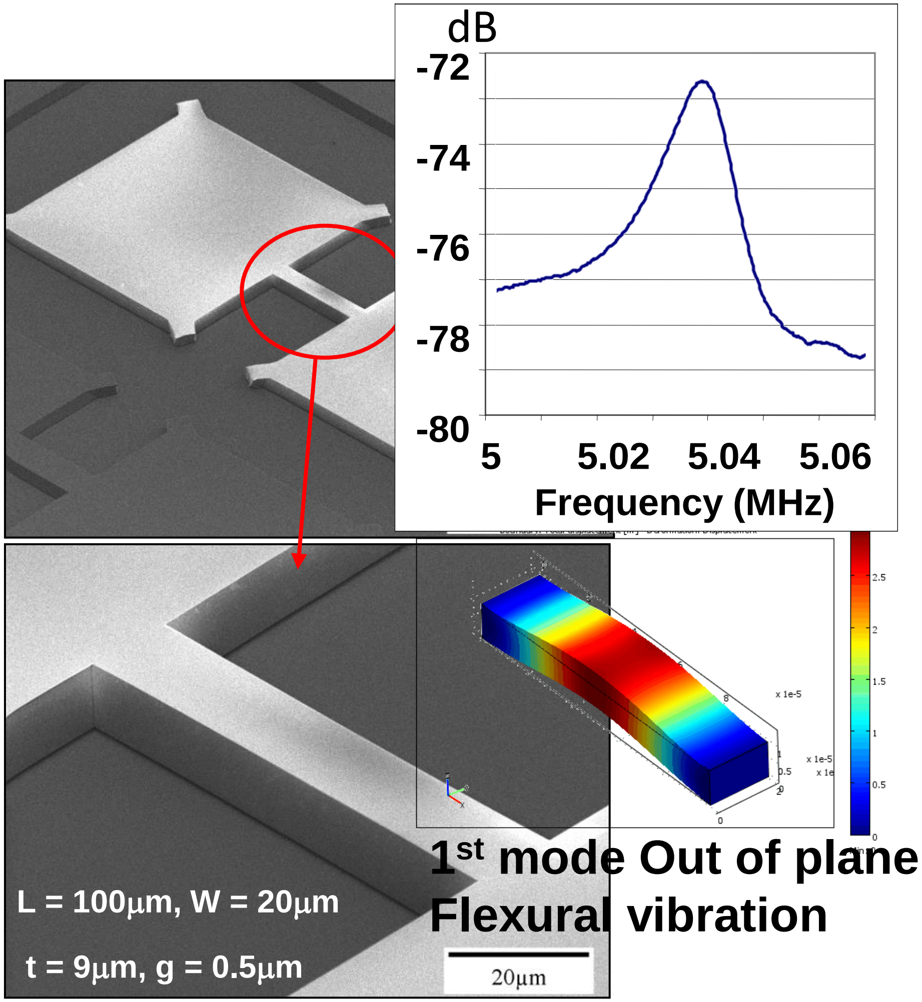
Stiffness

Freq. Equation:

$$f_o = \frac{1}{2\pi}\sqrt{\frac{k_r}{m_r}}$$

Freq.

Mass



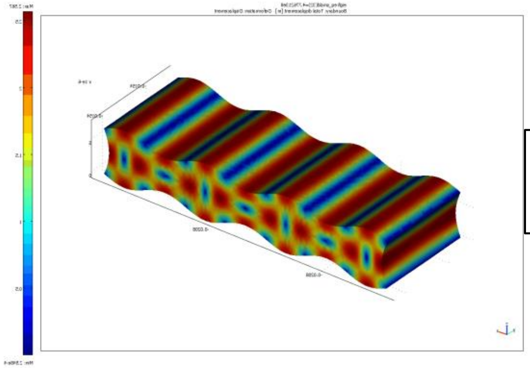
1^{st} mode Out of plane Flexural vibration

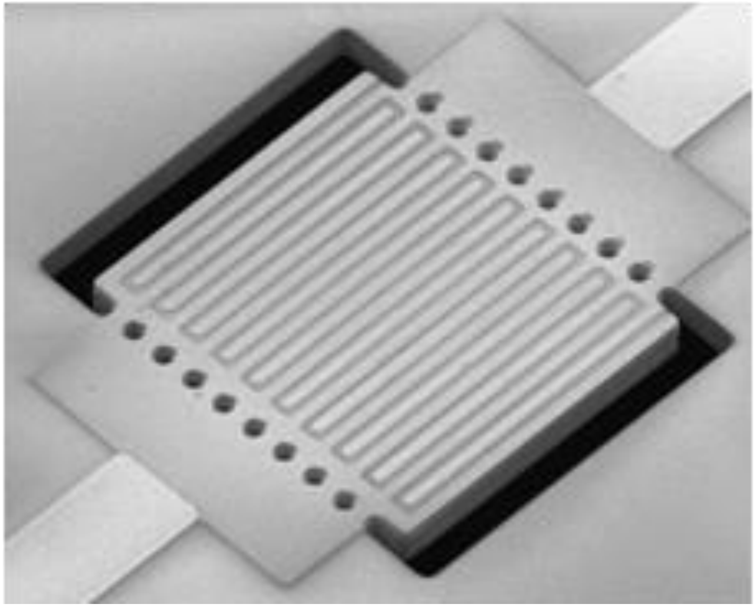
Piezoelectric MEMS Resonators

☐ Piezoelectric Actuation

Applied electrical field

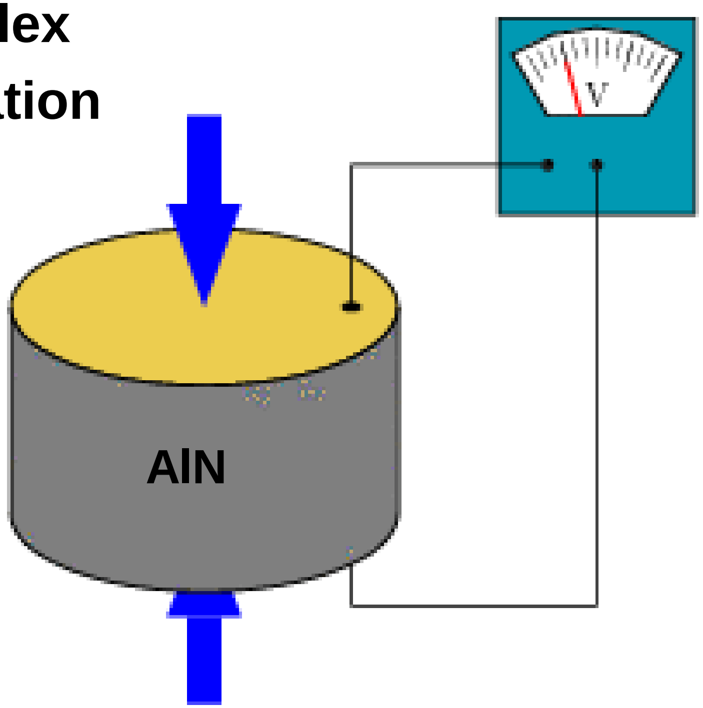
Internal generation of
a mechanical force


Finite Element Modal Analysis of a Piezo-Electric Resonator

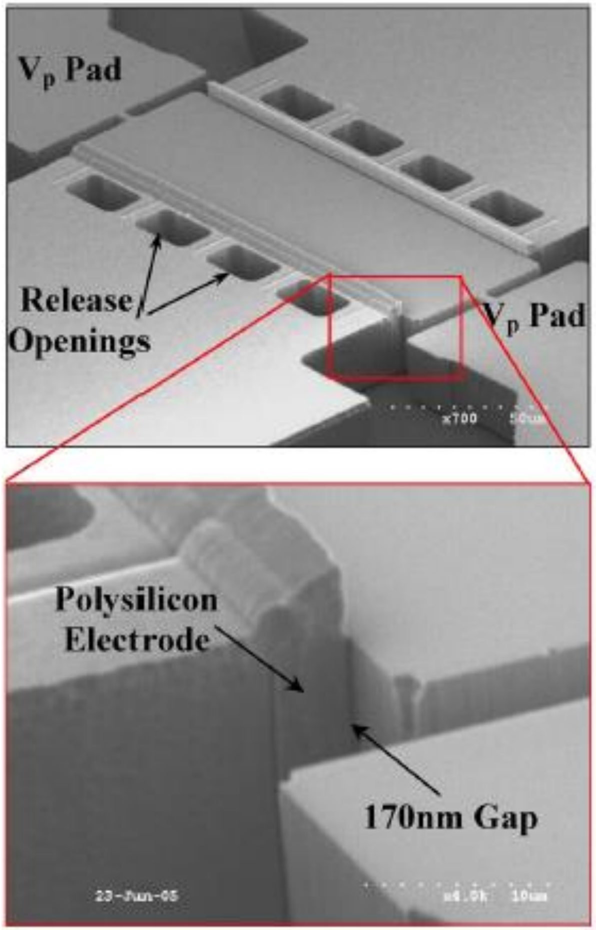


B. Harrington, M. Shahmohammadi, and R. Abdolvand, “Toward Ultimate Performance in GHz MEMS Resonators: Low Impedance and High Q,” IEEE MEMS 2010

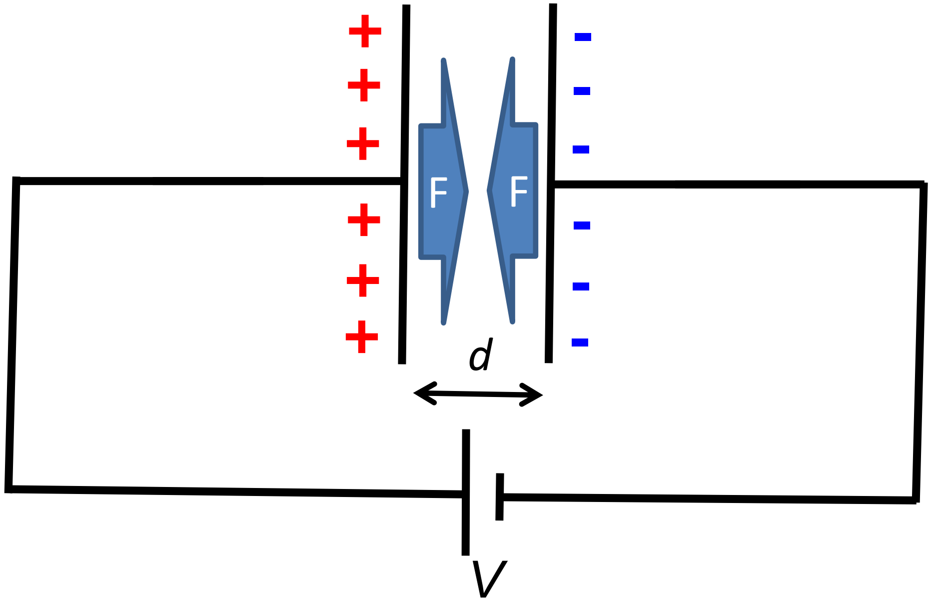
Complex Fabrication



Electrostatic MEMS Resonators



Pourkamali et al "Low-Impedance VHF and UHF Capacitive Silicon Bulk Acoustic Wave Resonators-Part I: Concept, IEEE transaction on electron devices



☐ **Actuation:**

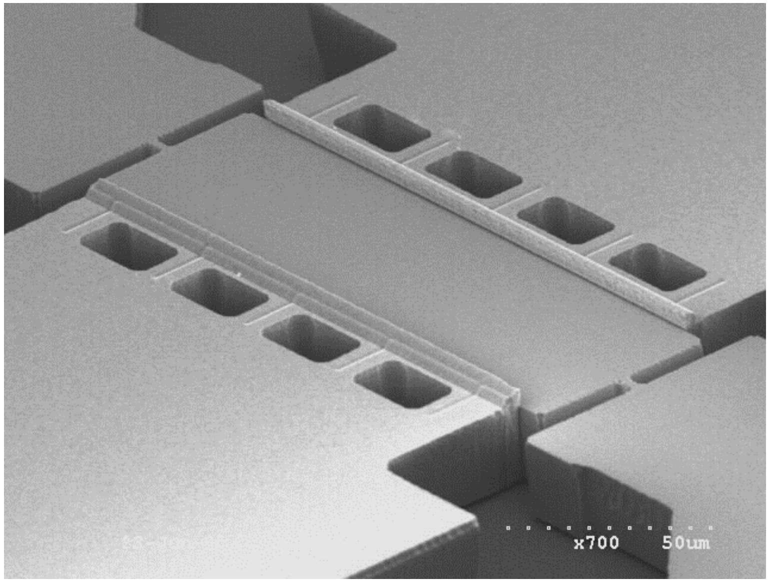
$$F = \frac{V^2 \varepsilon_0 A}{2d^2}$$

☐ **Read-out:**

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

Micro-Resonator Transduction

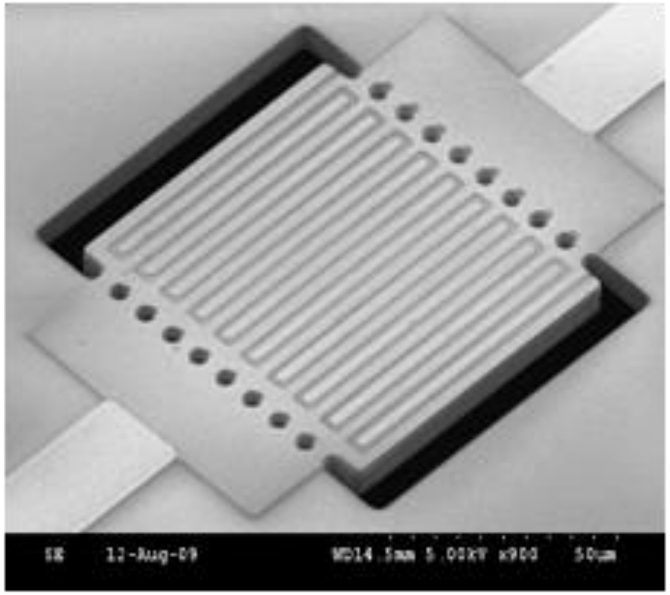
- ❑ **Common Micro-Resonator Transduction Mechanisms:**



Capacitive

Capacitive Silicon Bulk Acoustic Wave Resonator[1]

Piezoelectric



1GHz AlN on Silicon Piezoelectric Resonator[2]

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[1] S. Pourkamali, Z Hao, and F Ayazi, VHF Single Crystal Silicon Capacitive Elliptic Bulk-Mode Disk Resonators—Part I: Implementation and Characterization, JMEMS 2004.

[2] B. Harrington, M. Shahmohammadi, and R. Abdolvand, "Toward Ultimate Performance in GHz MEMS Resonators: Low Impedance and High Q," IEEE MEMS 2010

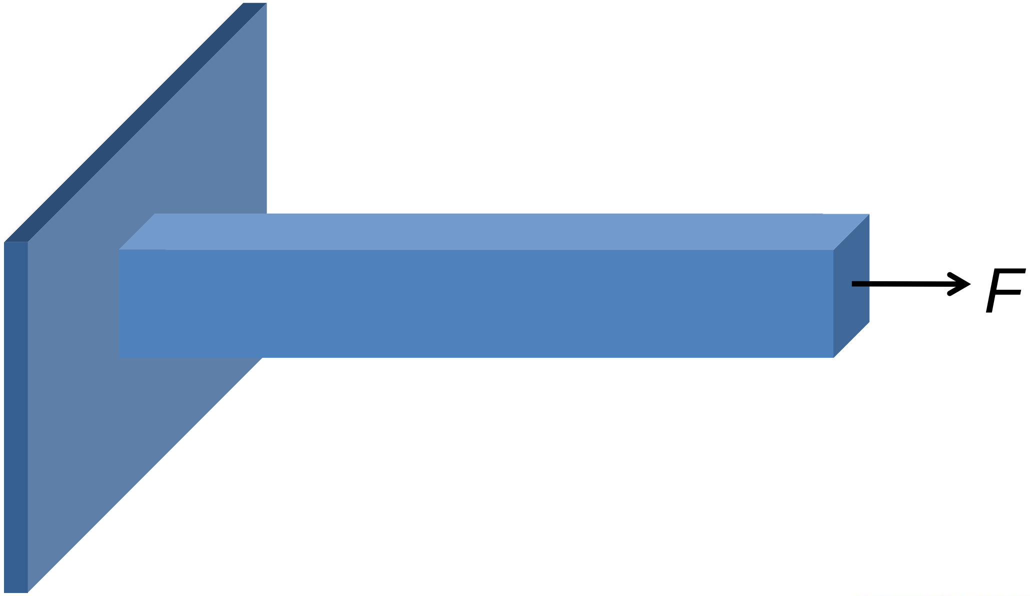
Thermal Actuation with Piezo-Resistive Readout

- **Thermal actuation:**

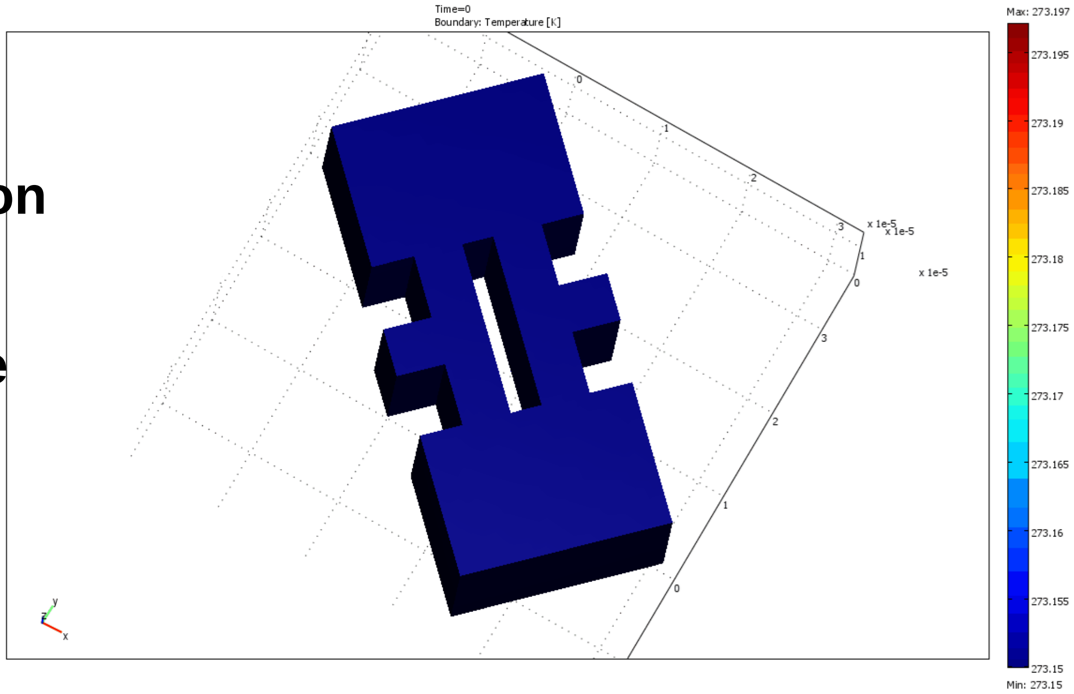
$$\Delta L = \alpha L \Delta T$$

- **Piezoresistive Effect:**

⬆ $\Delta R = R\pi_l\delta_l$



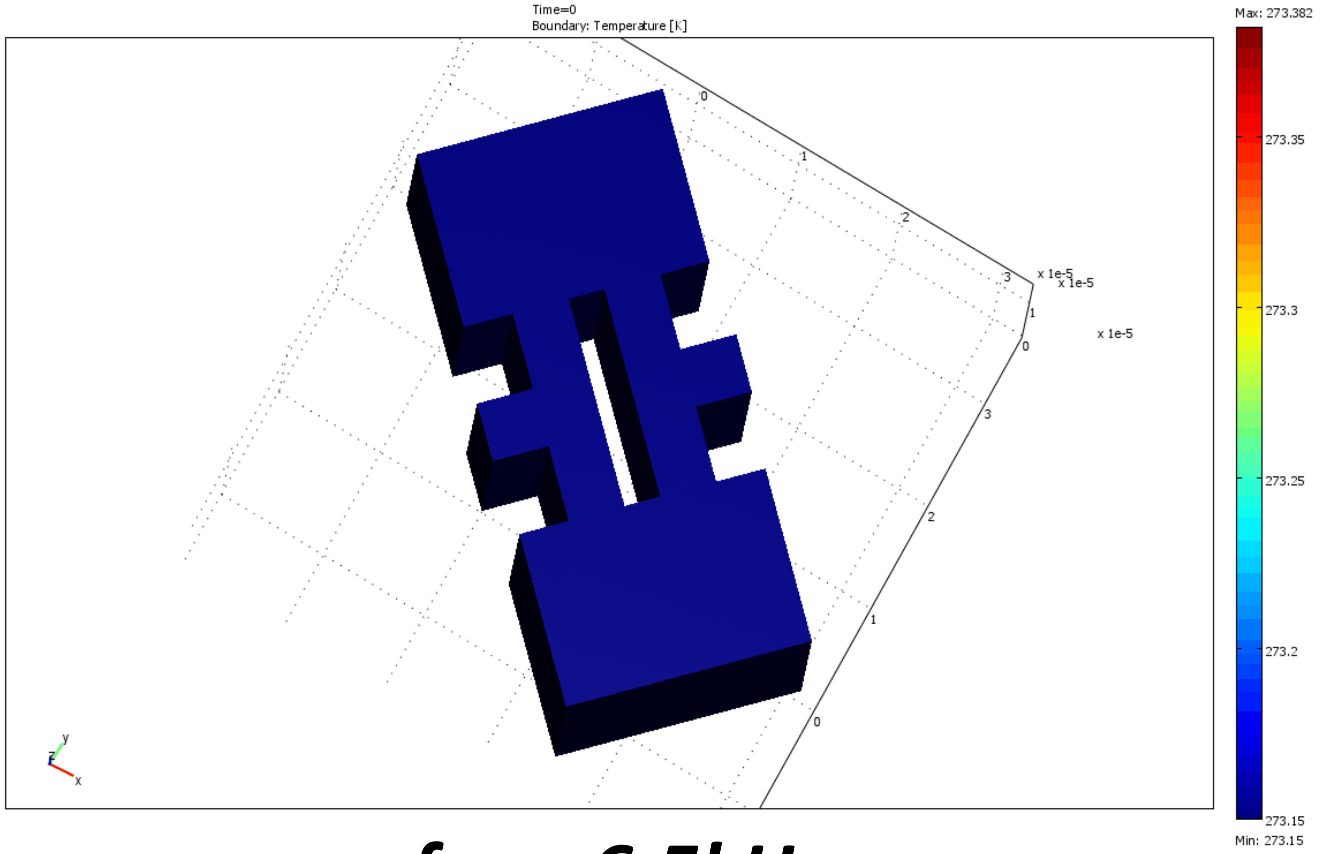
Thermally Actuated Resonators



- ☐ **Advantages**
  - ➢ **Simplicity of fabrication**
  - ➢ **Large actuation force**
  - ➢ **Low operating voltage**
  - ➢ **Robustness**
- ☐ **Disadvantage**
  - ➢ **Power consumption**
  - ➢ **Speed?**

Usually known as slow actuators suitable for DC or very low-frequency applications

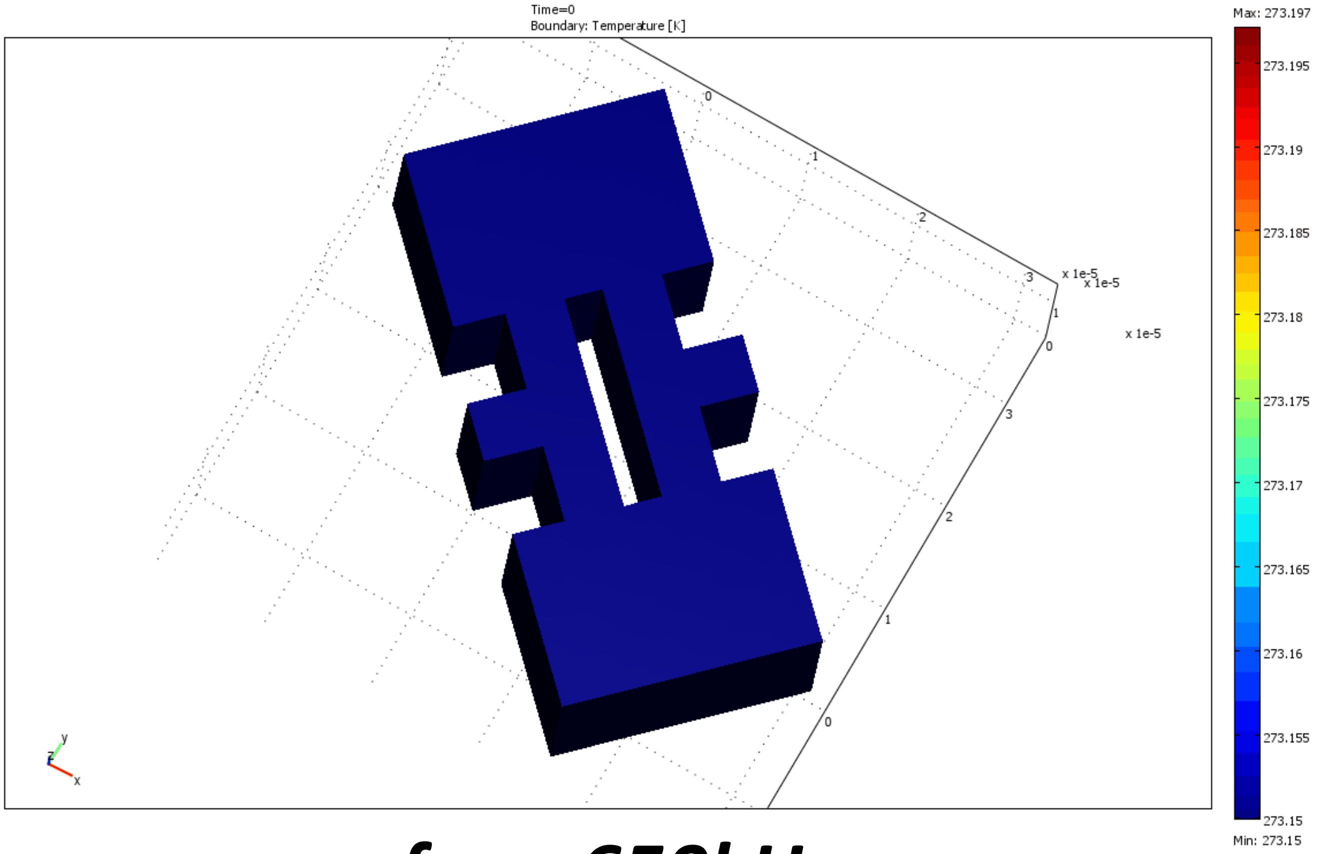
Thermal Time Response



$$f_{act} = 6.5kHz$$

$$\tau_{Thermal} = 100\mu s \rightarrow f_{thermal} = 10kHz$$

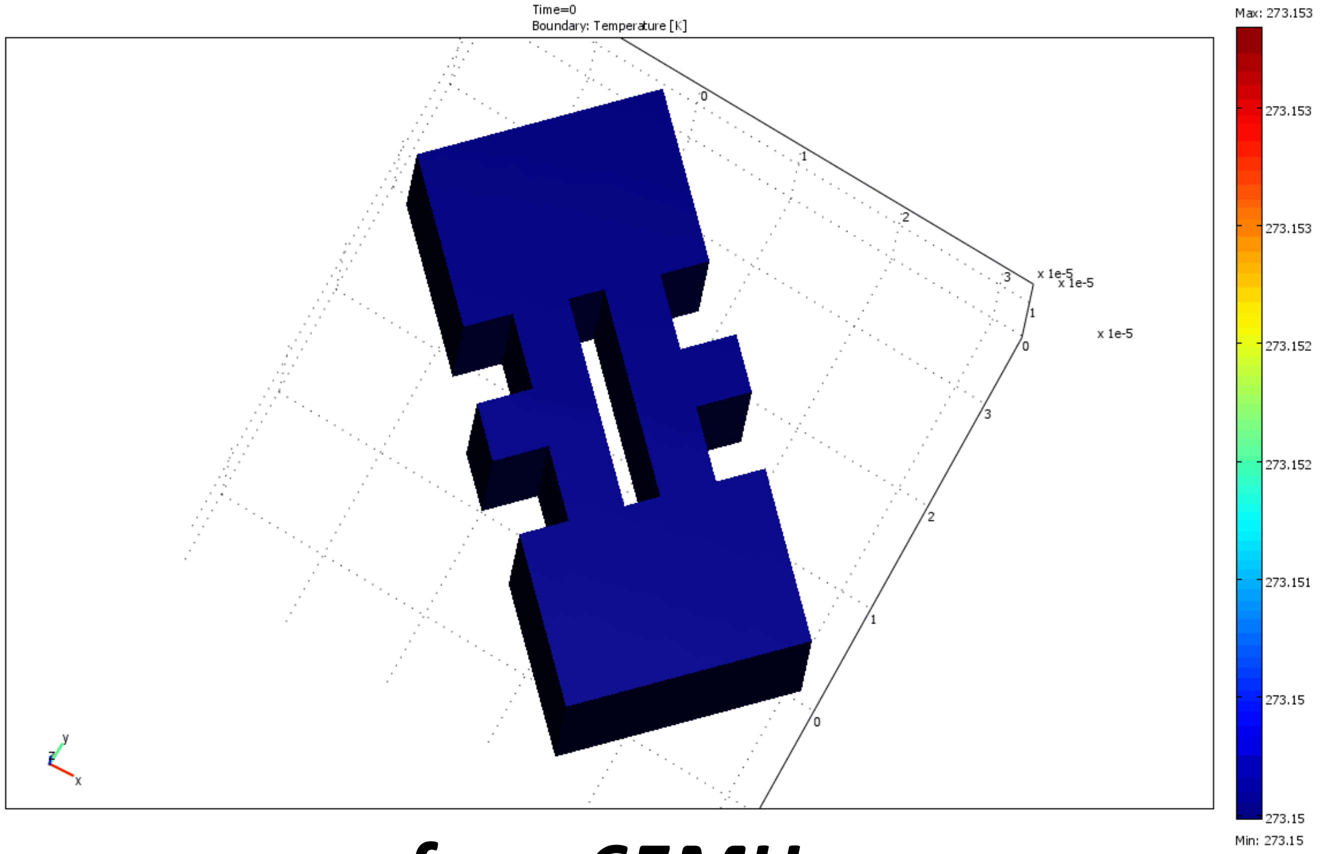
Thermal Time Response



$$f_{act} = 650kHz$$

$$\tau_{Thermal} = 100\mu s \longrightarrow f_{thermal} = 10kHz$$

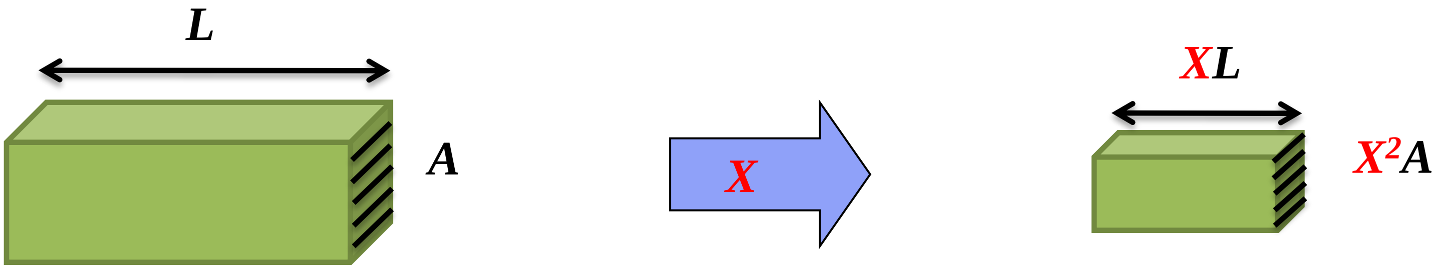
Thermal Time Response

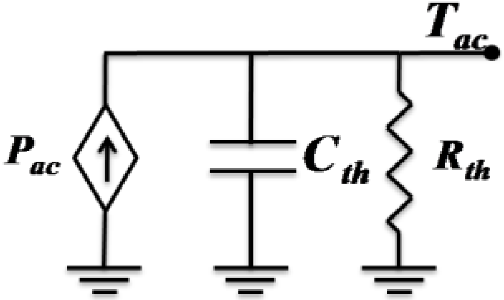


$$f_{act} = 65MHz$$

$$\tau_{Thermal} = 100\mu s \rightarrow f_{thermal} = 10kHz$$

Scaling Behavior of Thermal Actuation





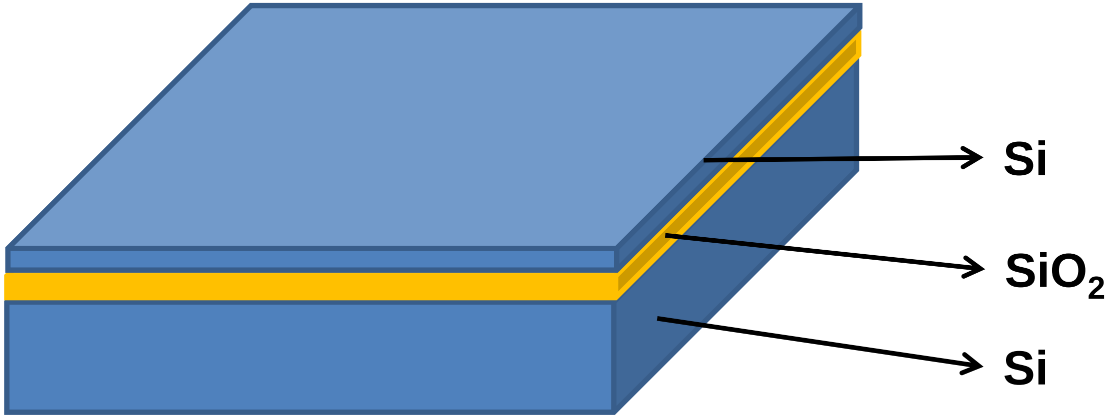
$$\tau_T = R_T C_T \begin{cases} R_T = \rho_T \dfrac{L}{A} \propto \dfrac{1}{X} \\ C_T \propto X^3 \end{cases}$$

$$\tau_T \propto X^2$$

Mechanical Time constant $\propto f_m^{-1} \propto X$

Thermal time constant shrinks faster than mechanical time constant

Fabrication Process



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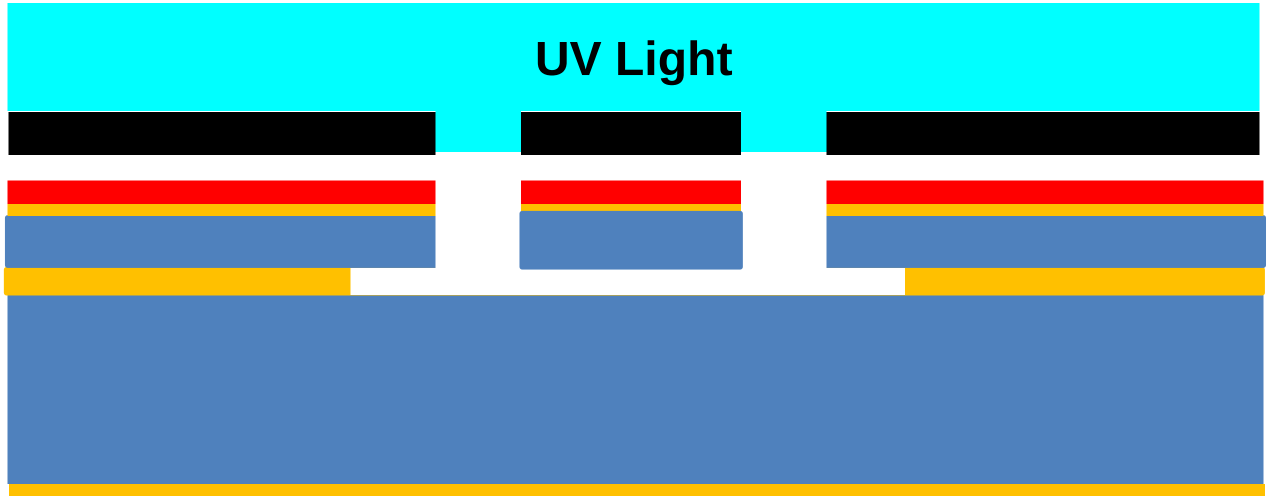
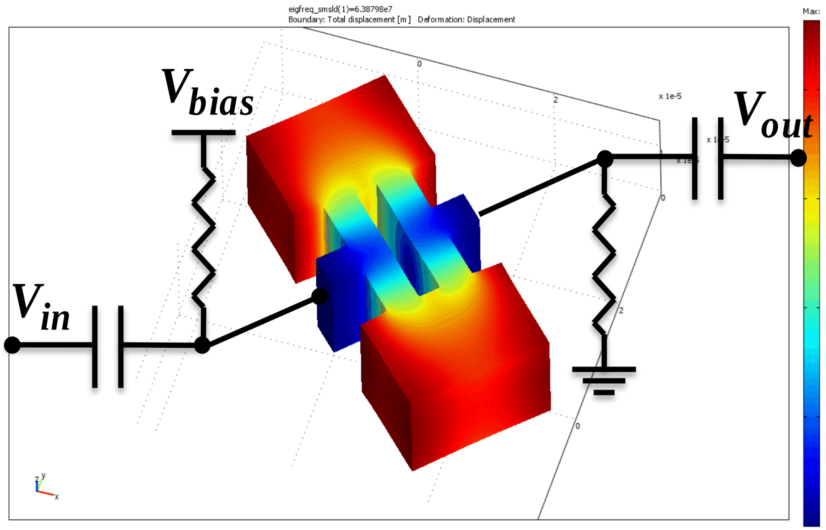
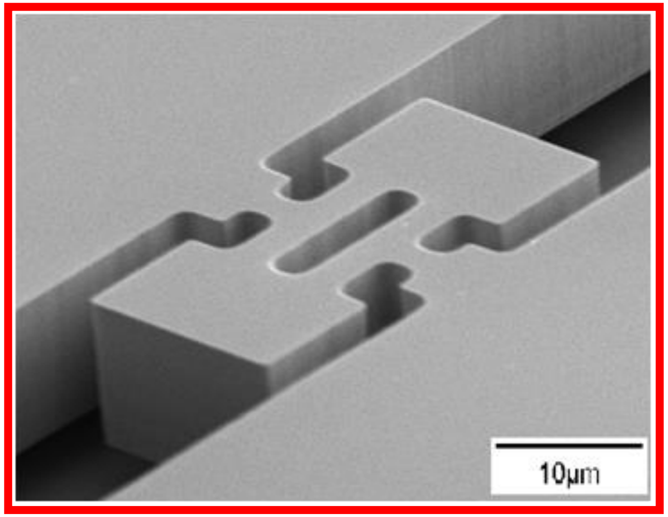
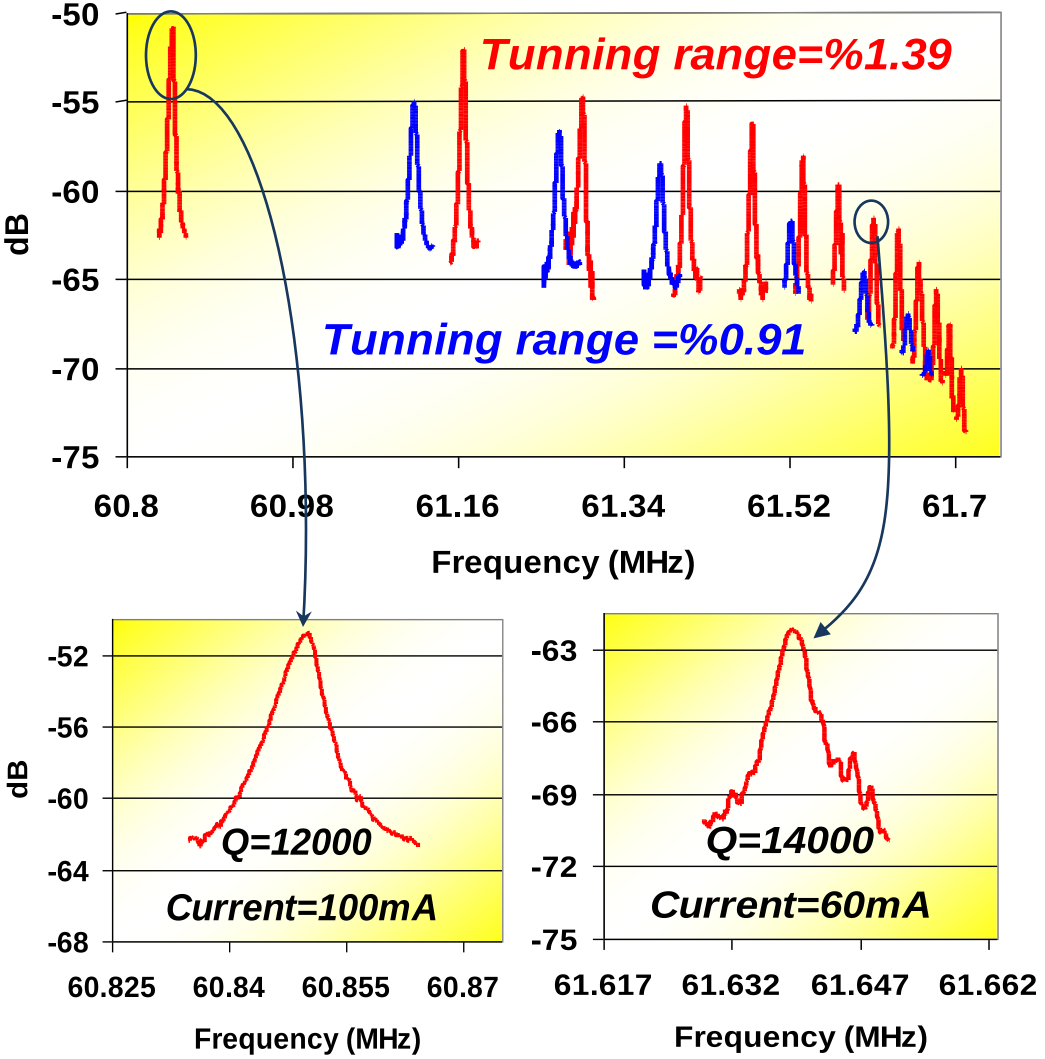


Measurement Results: 61MHz I^{2}-BAR



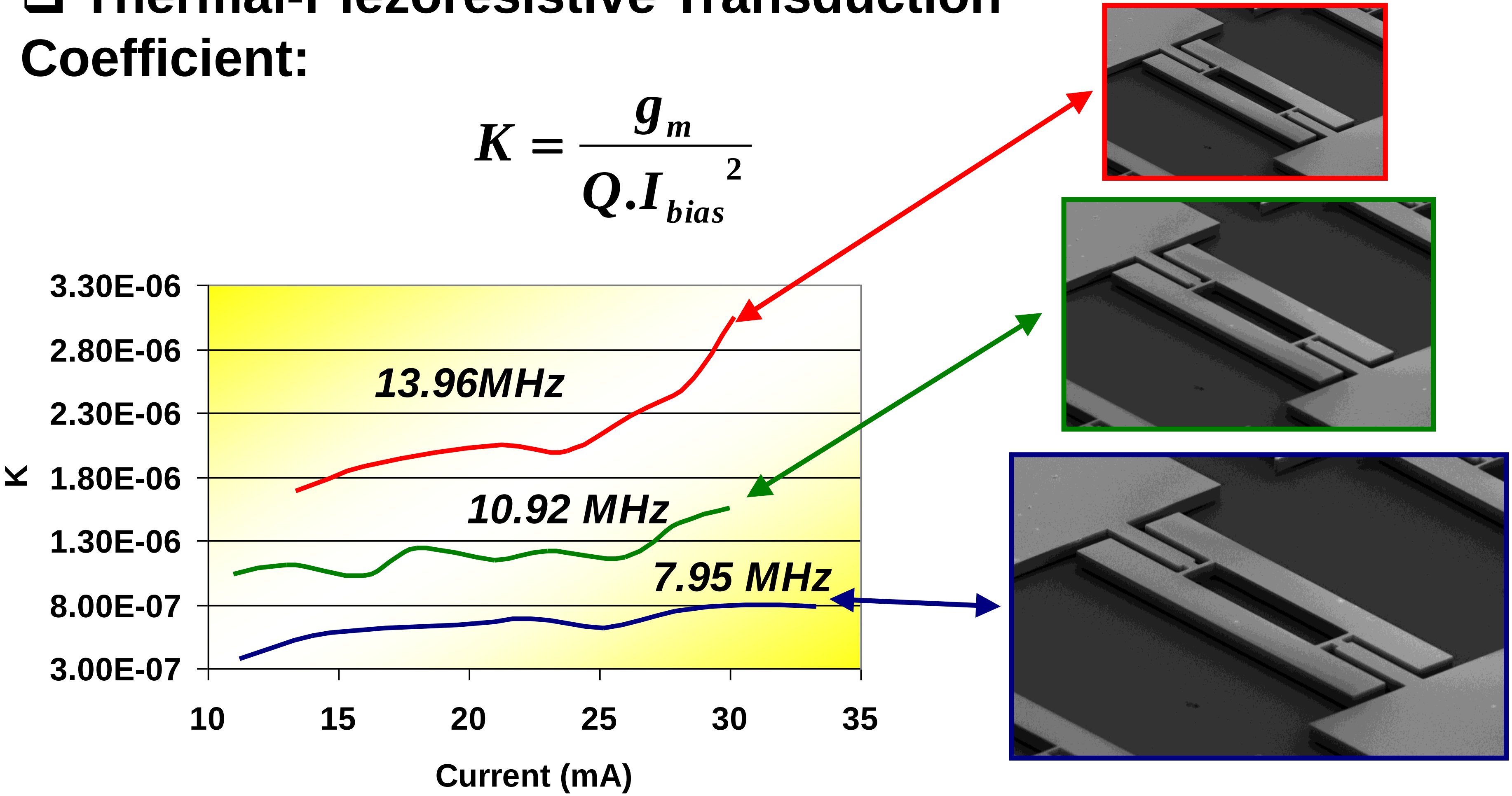




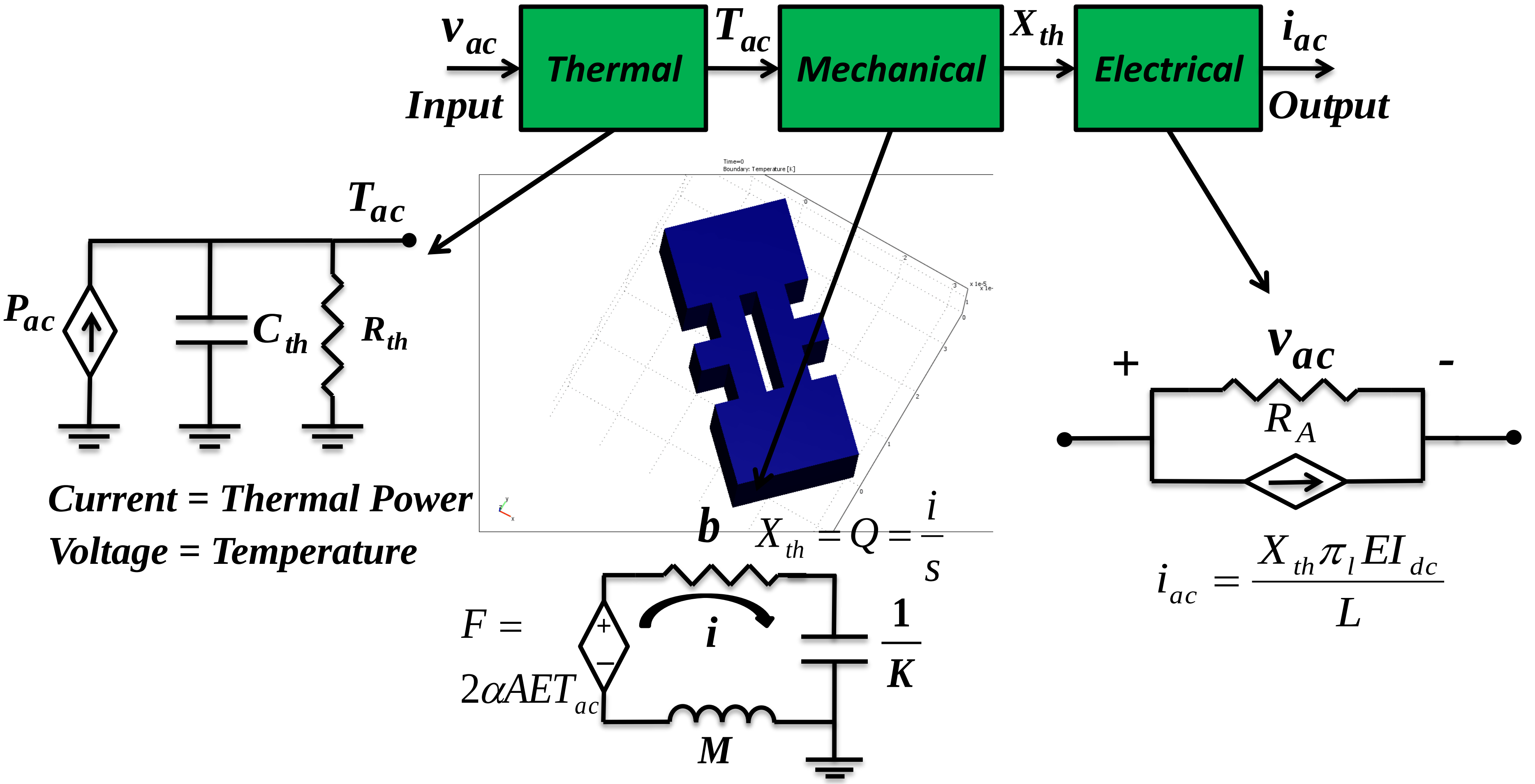
Measurement Results

- ❑ **Thermal-Piezoresistive Transduction Coefficient:**

$$K = \frac{g_m}{Q.I_{bias}^{\ 2}}$$



Resonator Operation



Current = Thermal Power

Voltage = Temperature

$$X_{th} = Q = \frac{i}{s}$$

$$F = 2\alpha AET_{ac}$$

$$\frac{1}{K}$$

$$i_{ac} = \frac{X_{th}\pi_l EI_{dc}}{L}$$

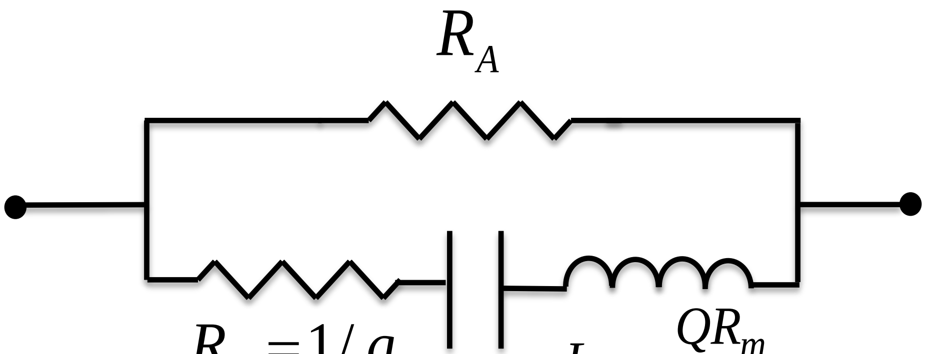
Voltage = Force Current = Velocity

Charge = Displacement

Resonator Electrical Model

Overall Equivalent Electrical Circuit

$$H_T\Big|_{s=j\omega_0} = g_m = 4\alpha E^2 \pi_l Q \frac{A I_{dc}^2}{K L C_{th} \omega_m}$$



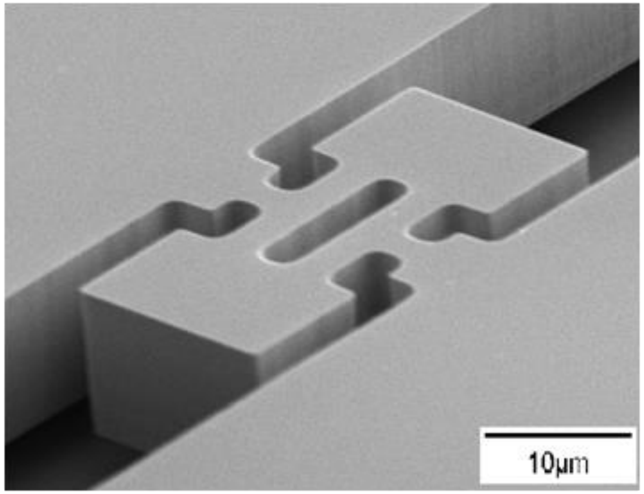
$R_m = 1/g_m$

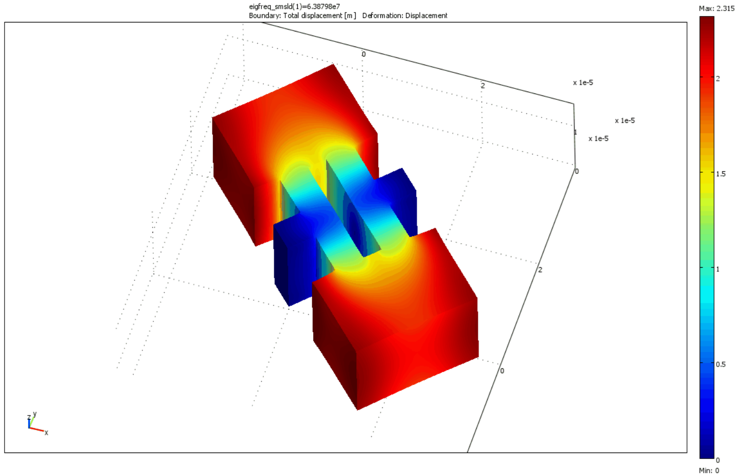
$C_m = \frac{1}{Q R_m \omega_0}$

$L_m = \frac{Q R_m}{\omega_0}$

Measurement and Simulation Results

Scale Factor	Measured/Assumed Parameters				Calculated Parameters			
	Current (mA)	Q. Factor	Freq. (MHz)	g_m (mS)	Power (mW)	R_A (Ω)	g_m (mS)	Power (μW) @ g_m=1 (mS)
1X	60	14000	61.64	16.5	18.0	2.34	17.3	1041
	100	12000	60.85	62.3	50.0	2.34	42.8	1169
	60	7500	61.65	9.76	18.0	2.34	9.26	1945
	100	7700	61.11	37.5	50.0	2.34	27.1	1845
🟨	= data obtained under atmospheric pressure							





Resonator Optimization

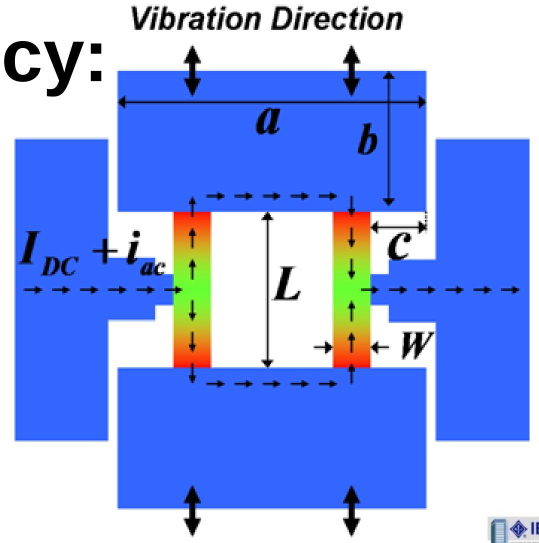
Scaling a Resonator:

$$F.M. = \frac{g_m}{P_{DC}} = 4\alpha E^2 \pi_l Q \frac{A}{\rho \underset{\frac{A}{L}}{\underset{\swarrow}{\boxed{K}}} L^2 \underset{LA}{\underset{\swarrow}{\boxed{C_{th}}}} \underset{\sqrt{\frac{A}{LM}}}{\underset{\swarrow}{\boxed{\omega_m}}}} \propto \frac{\overset{S^{\frac{3}{2}}}{\overset{\uparrow}{M^{\frac{1}{2}}}}}{\underset{S^{\frac{3}{2}}}{\underset{\searrow}{L^{\frac{3}{2}}}} \underset{S}{\underset{\searrow}{A^{\frac{1}{2}}}}} \propto \frac{1}{S}$$

S: scaling ratio

Optimizing at constant frequency:

$$F.M. \propto \frac{1}{L^{\frac{3}{2}} W^{\frac{1}{2}}} \propto \frac{1}{S^2}$$



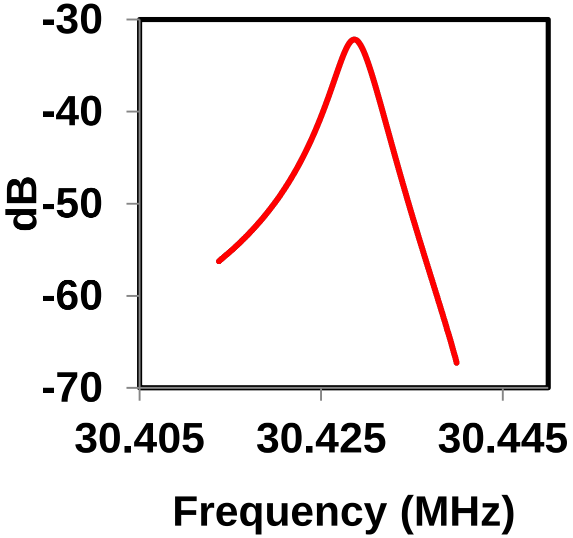
Low Power Devices

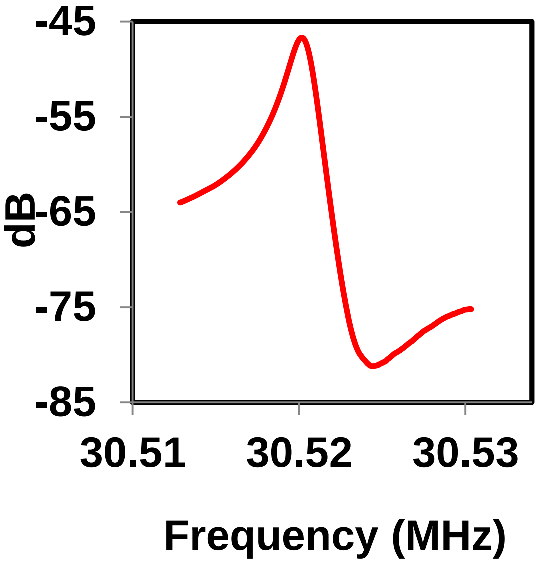
Q =9,200 (Air)

I_{DC} =2.69 mA

g_m = 233 µS

P_{DC} = 14.72 mW



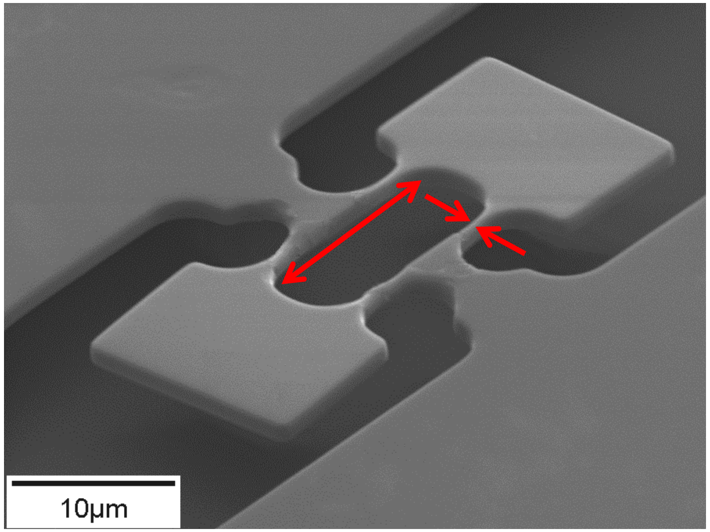


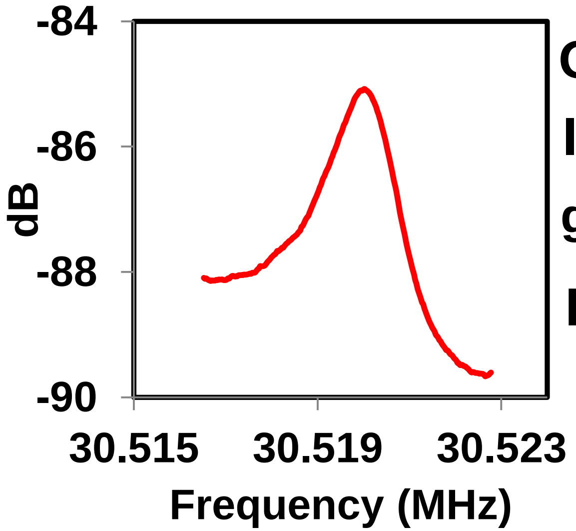
Q =24,400 (Vac.)

I_{DC} =720 µA

g_m = 43.6 µS

P_{DC} = 1.01 mW





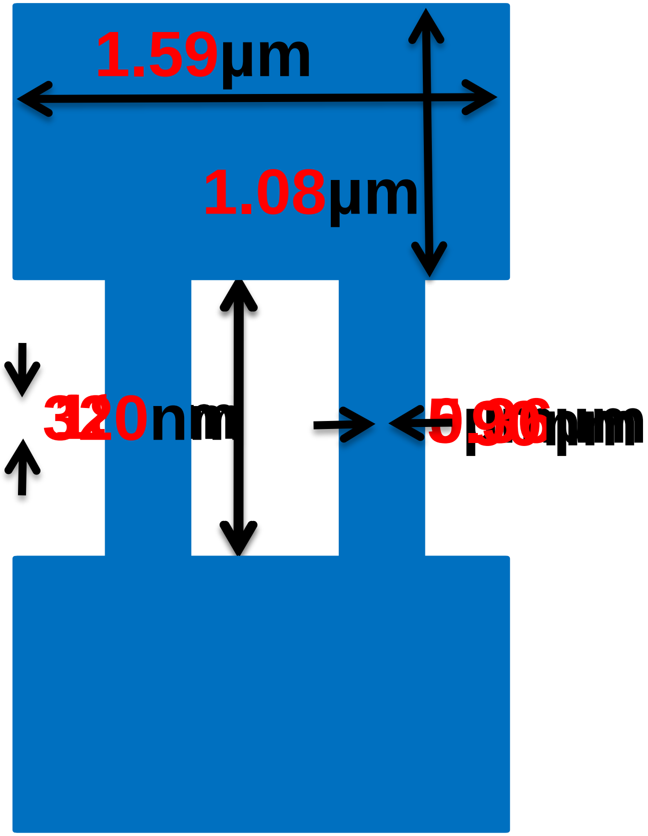
Q =35,900 (Vac.)

I_{DC} =43 µA

g_m = 0.207 µS

P_{DC} = 3.63 µW

Measurement and Simulation Results



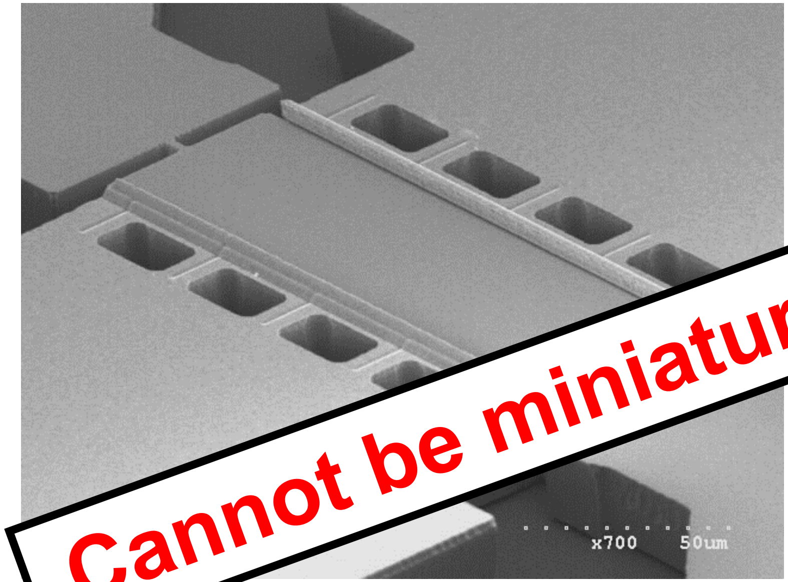
g_m= 1mA/V

Freq. (MHz)	F.M	P (µW)
61.6	0.686	1041
900	7.87	90.7
905.7	136	5.25
2100	18.5	38.6
2113	306	2.33

For all the calculations the bulk piezoresistive coefficient of silicon was used!

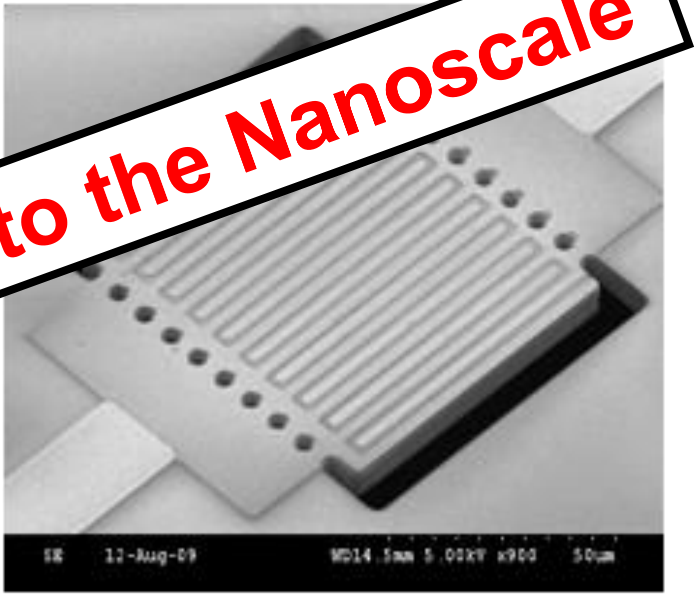
Micro-Resonator Transduction

- ☐ **Common Micro-Resonator Transduction Mechanisms:**



Capacitive

Piezoelectric



Cannot be miniaturized into the Nanoscale

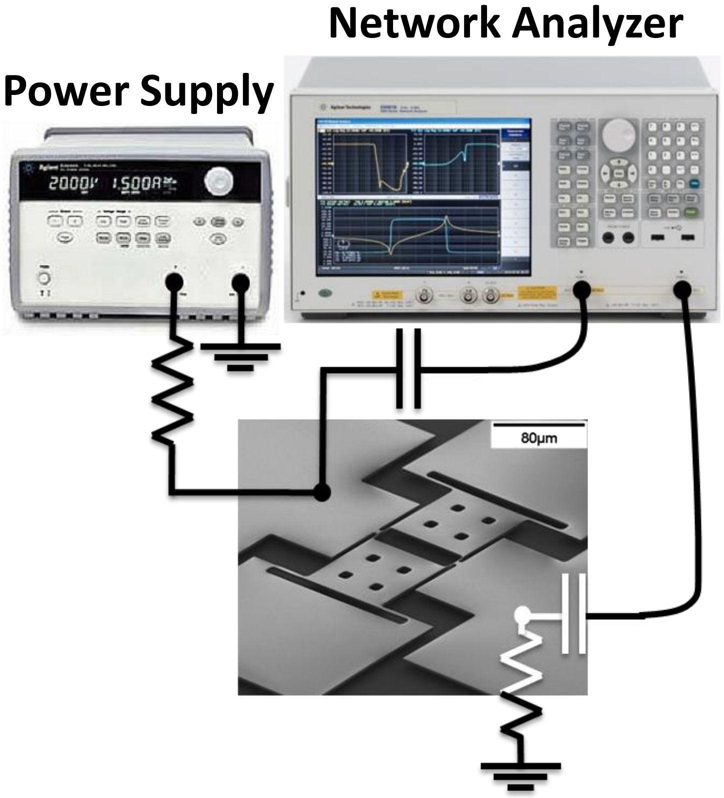
Capacitive Silicon Bulk Acoustic Wave Resonator[1]

1GHz AlN on Silicon Piezoelectric Resonator[2]

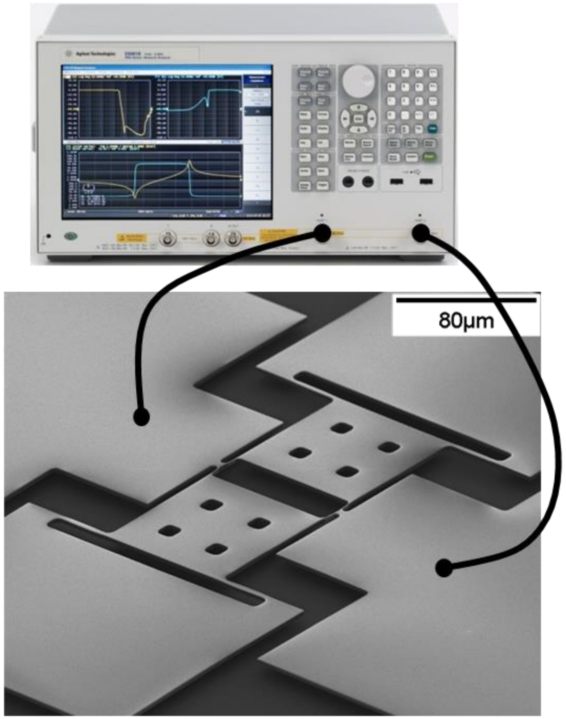
[1] S. Pourkamali, Z Hao, and F Ayazi, VHF Single Crystal Silicon Capacitive Elliptic Bulk-Mode Disk Resonators—Part I: Implementation and Characterization, JMEMS 2004.

[2] B. Harrington, M. Shahmohammadi, and R. Abdolvand, “Toward Ultimate Performance in GHz MEMS Resonators: Low Impedance and High Q,” IEEE MEMS 2010

Zero Bias Operation Via Internal Electromechanical Mixing



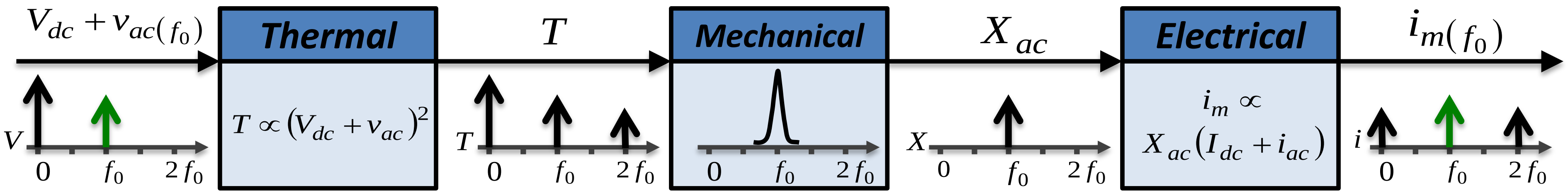
Conventional Operation (DC+AC)



Zero Bias Operation (AC)

Zero Bias Operation Via Internal Electromechanical Mixing

Operation with DC Bias



$V_{dc} + v_{ac}(f_0)$

Thermal

$T \propto (V_{dc} + v_{ac})^2$

T

Mechanical

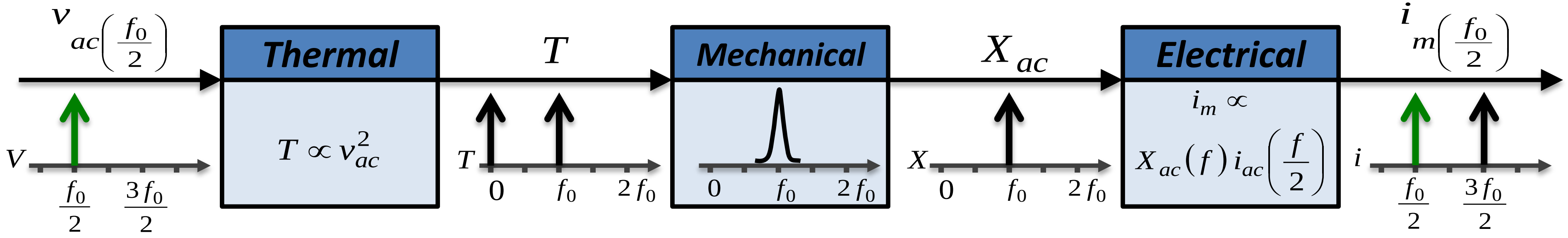
X_{ac}

Electrical

$i_m \propto X_{ac}(I_{dc} + i_{ac})$

$i_m(f_0)$

Operation without DC Bias



$v_{ac}\left(\frac{f_0}{2}\right)$

Thermal

$T \propto v_{ac}^2$

T

Mechanical

X_{ac}

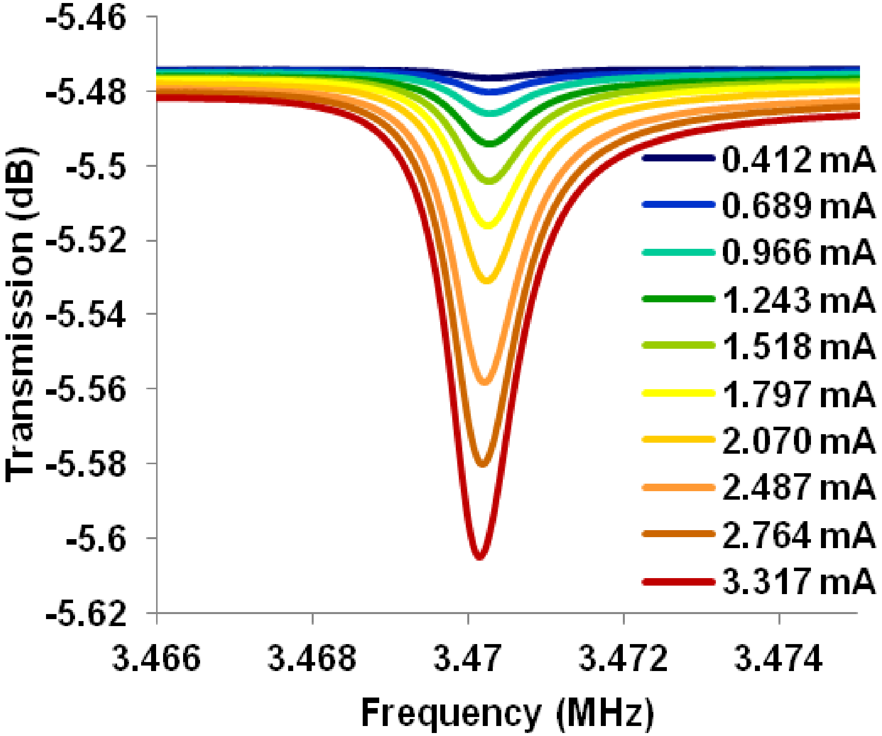
Electrical

$i_m \propto X_{ac}(f)\, i_{ac}\left(\frac{f}{2}\right)$

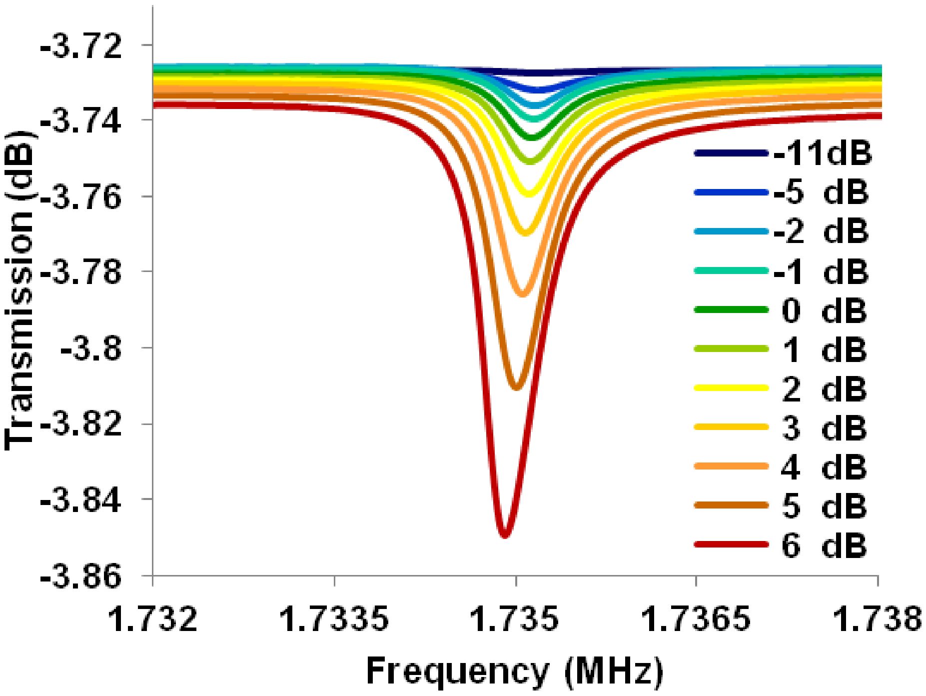
$i_m\left(\frac{f_0}{2}\right)$

Zero Bias Operation Via Internal Electromechanical Mixing

Operation with DC Bias

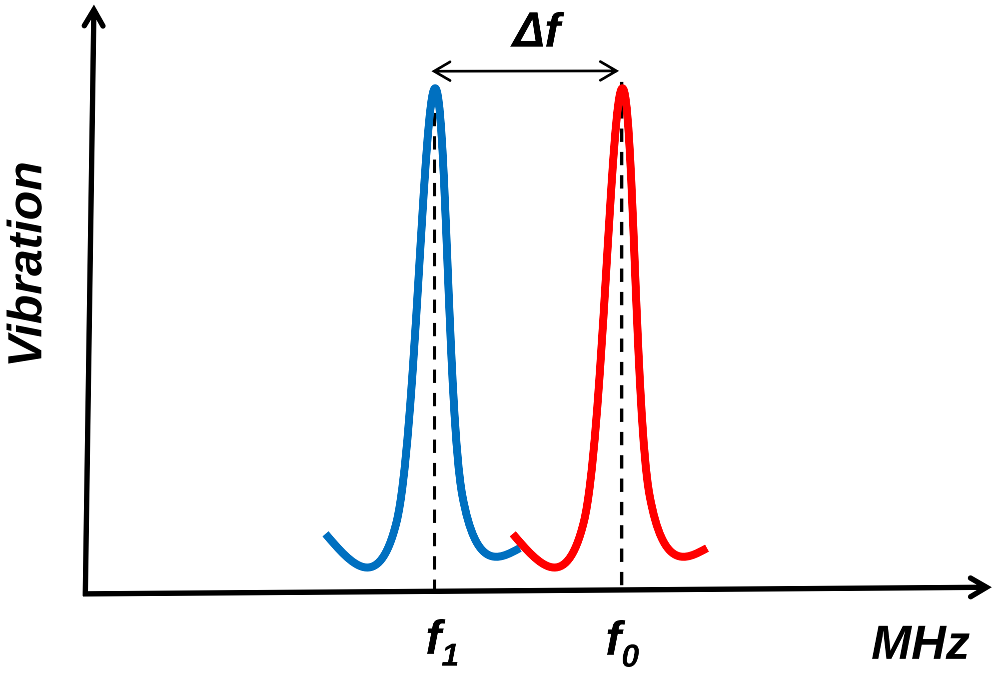


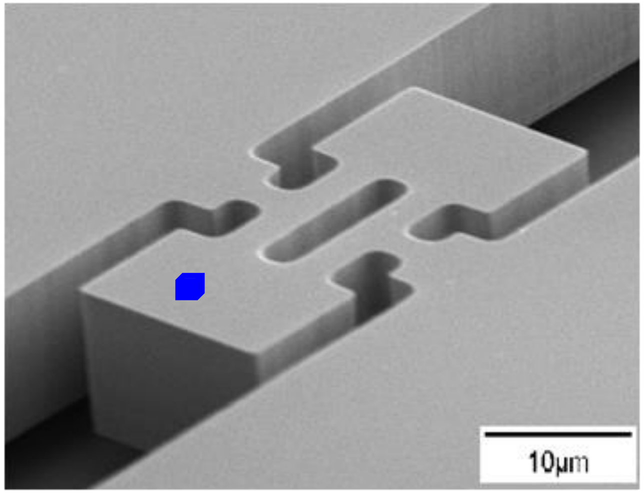
Operation without DC Bias



Applications (Mass Sensing)

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \quad \Rightarrow \quad \frac{\Delta f}{f} = -\frac{\Delta m}{2m}$$

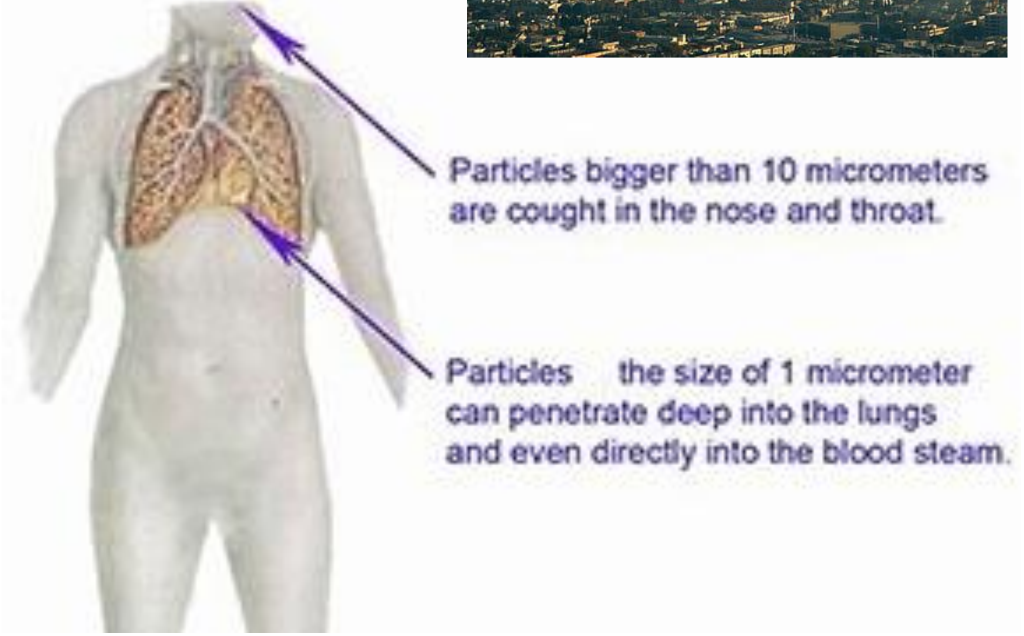




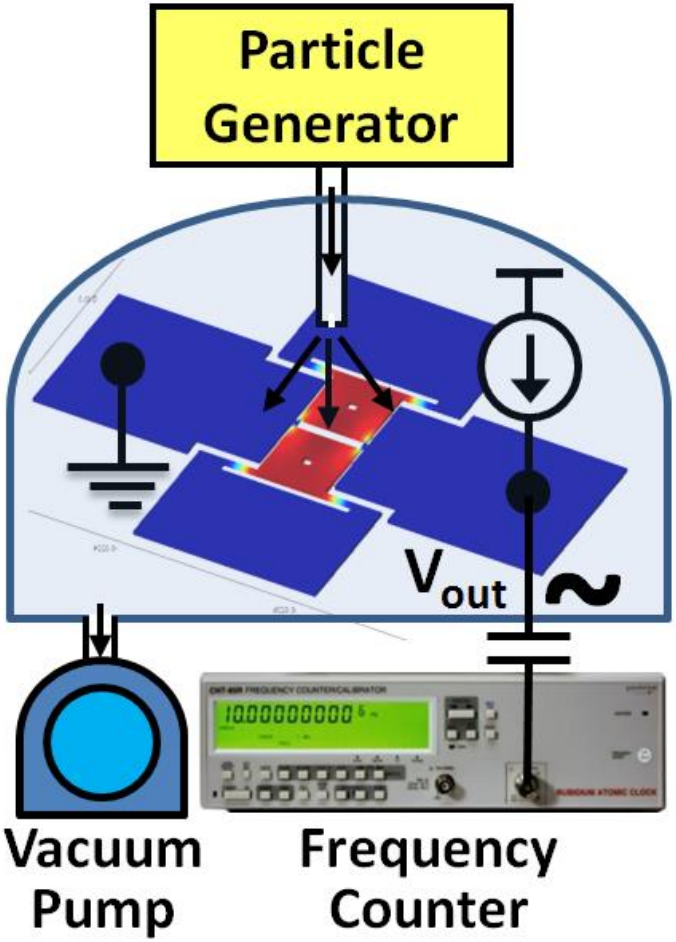
☐ Mechanical resonators vibrate more slowly (at lower frequencies) if they become heavier

Airborne Micro/Nanoscale Particles

- ❑ **Air-borne particle concentration and Size distribution measurement and monitoring**
- ❑ **Importance**
  - ➢ **Human health**
  - ➢ **Climate change**
  - ➢ **Controlled Environments**

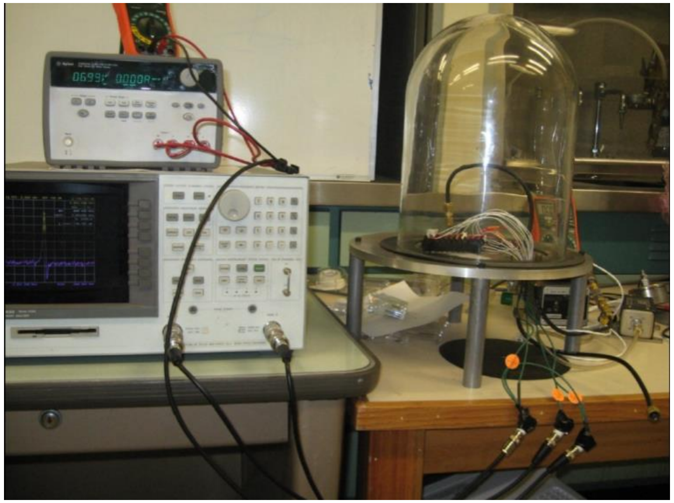


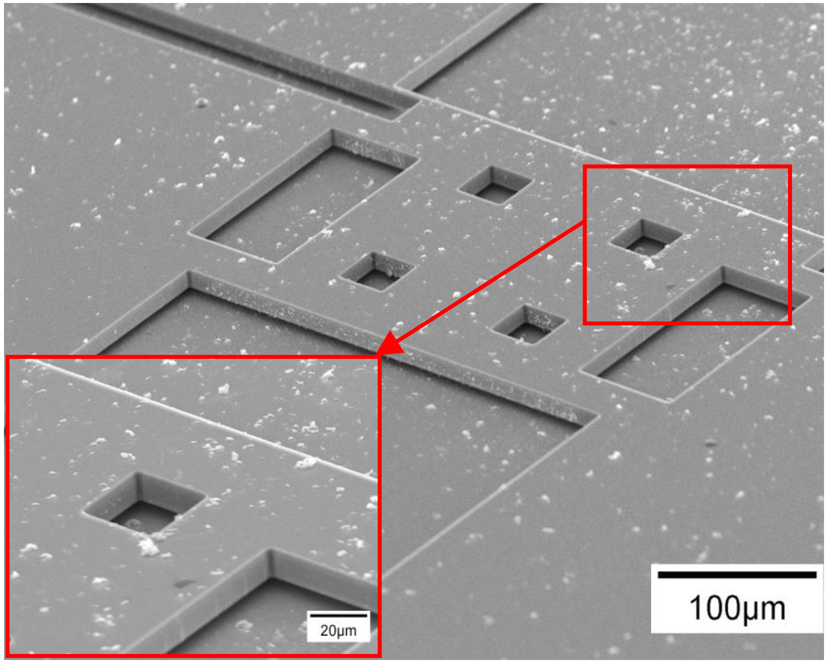
Measurement Setup

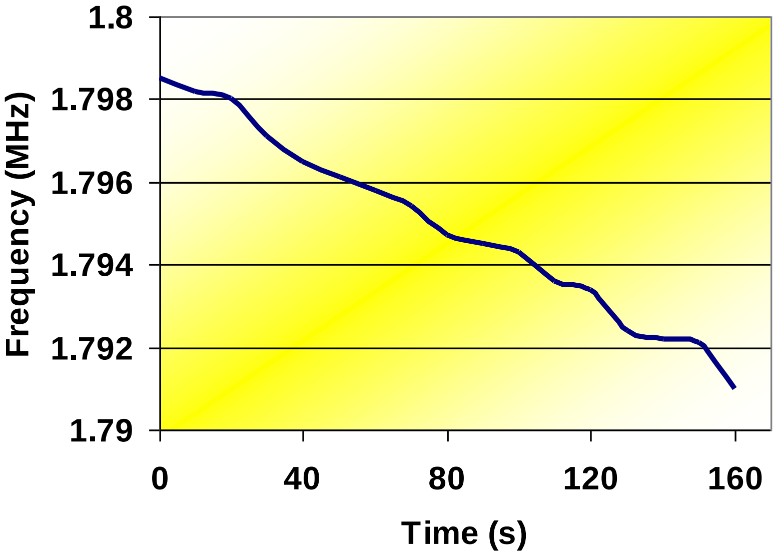


Weighing Air-Borne Particle

- ❑ **Deposited mass in 10s intervals = 1-5 ng**
- ❑ **Particle mass density in lab air = 14.2 µg/m^3**

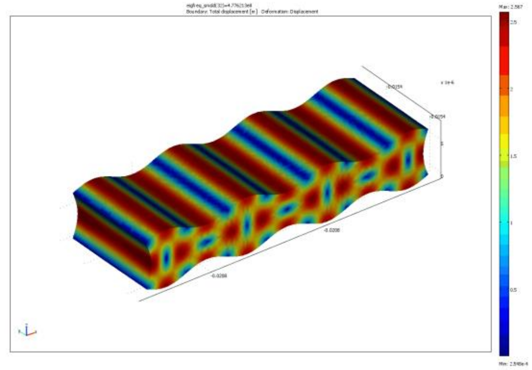






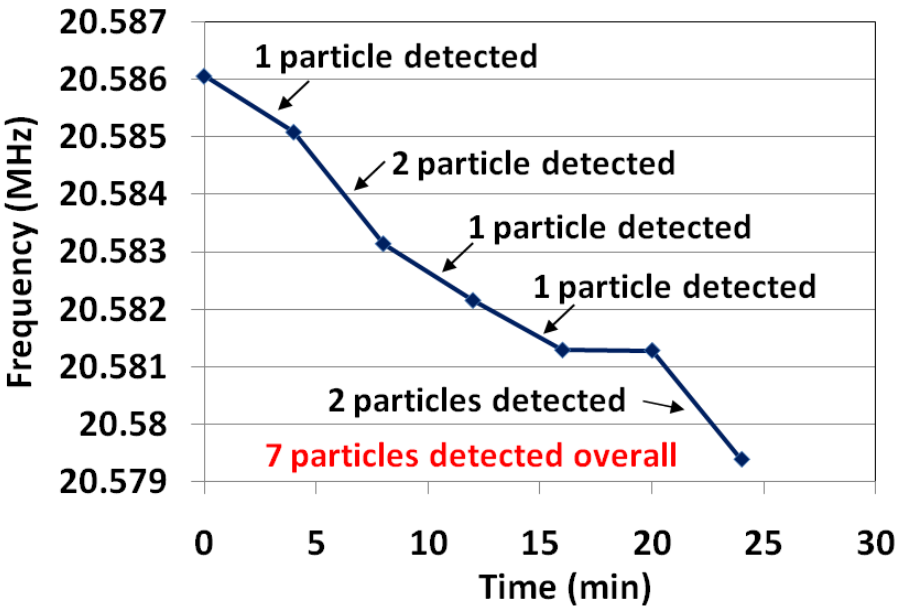
Single Particle Detection

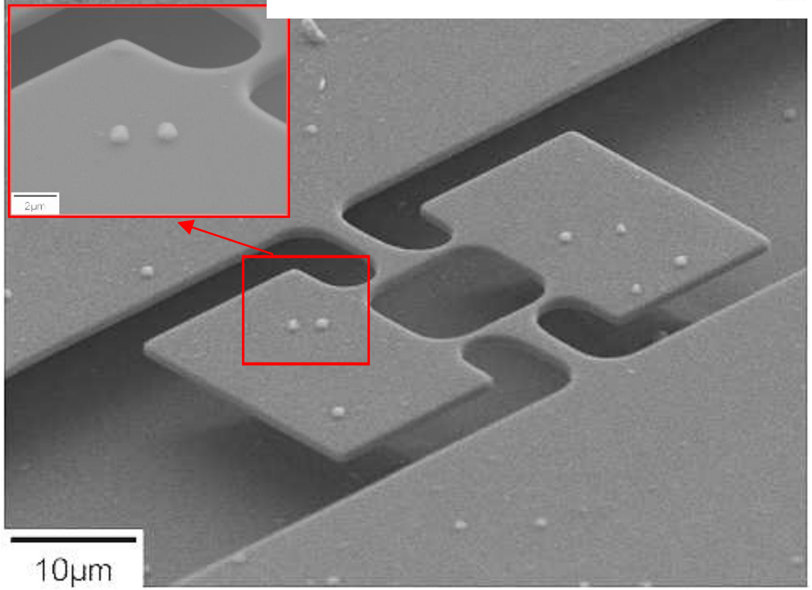
- ☐ Shift in frequency quantized, multiples of
- ☐ Some intervals shift is double
- ☐ One interval no shift



7 partic

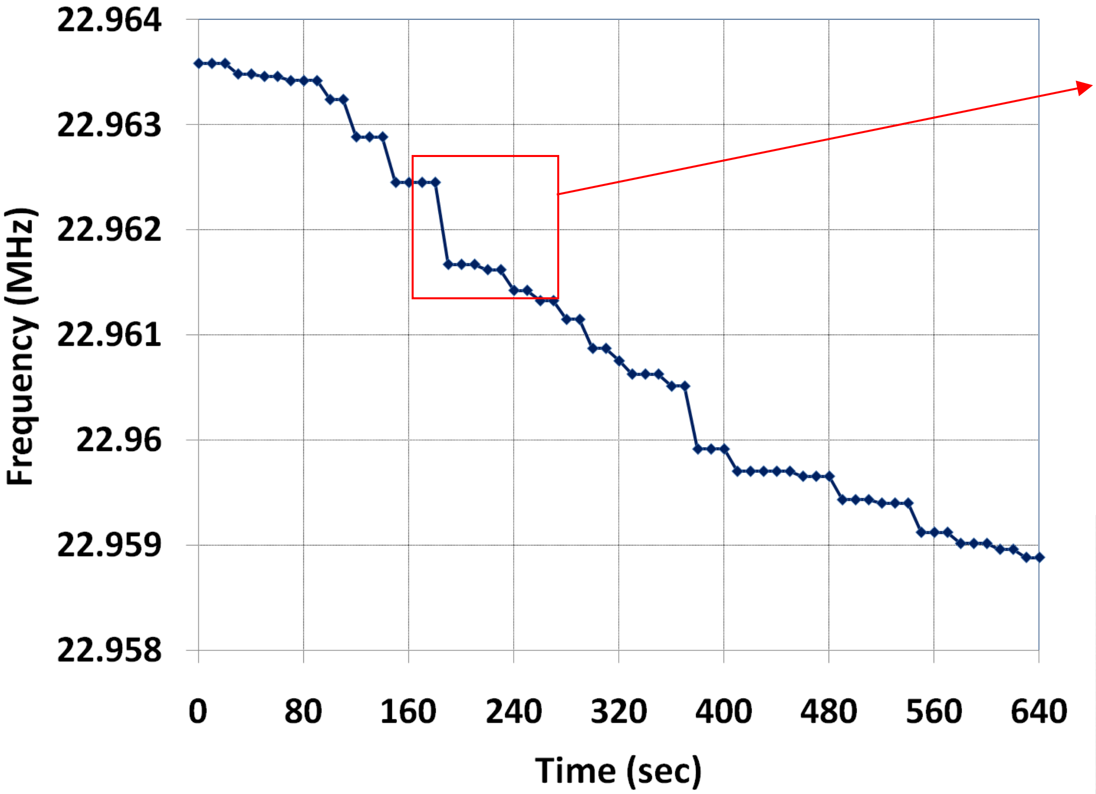
~900Hz shift per particle

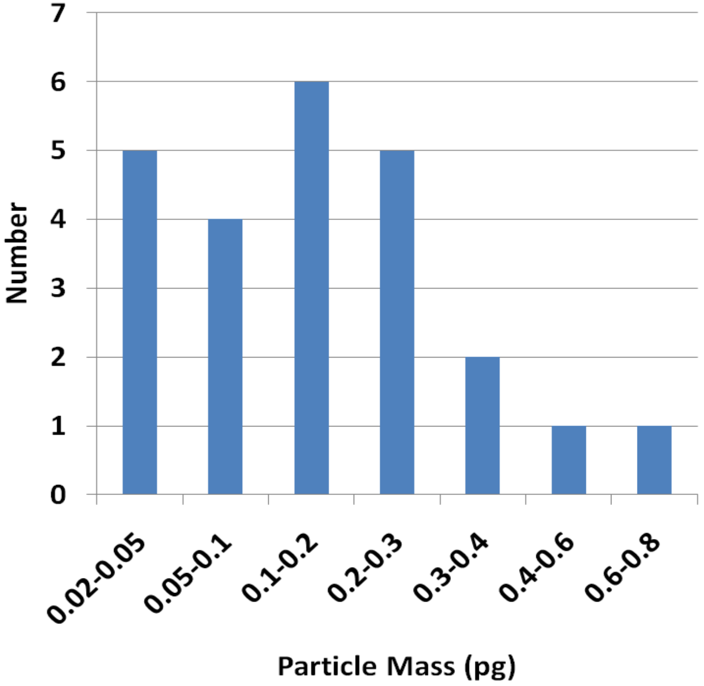


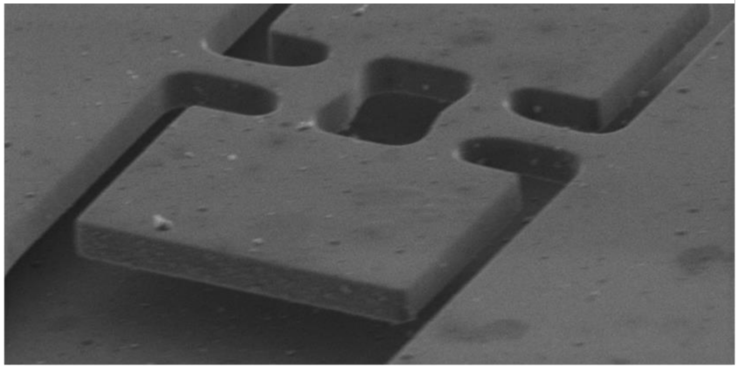


SEM of the resonator after deposition

Particle Mass Distribution Analysis







Inertial Aerosol Impactor

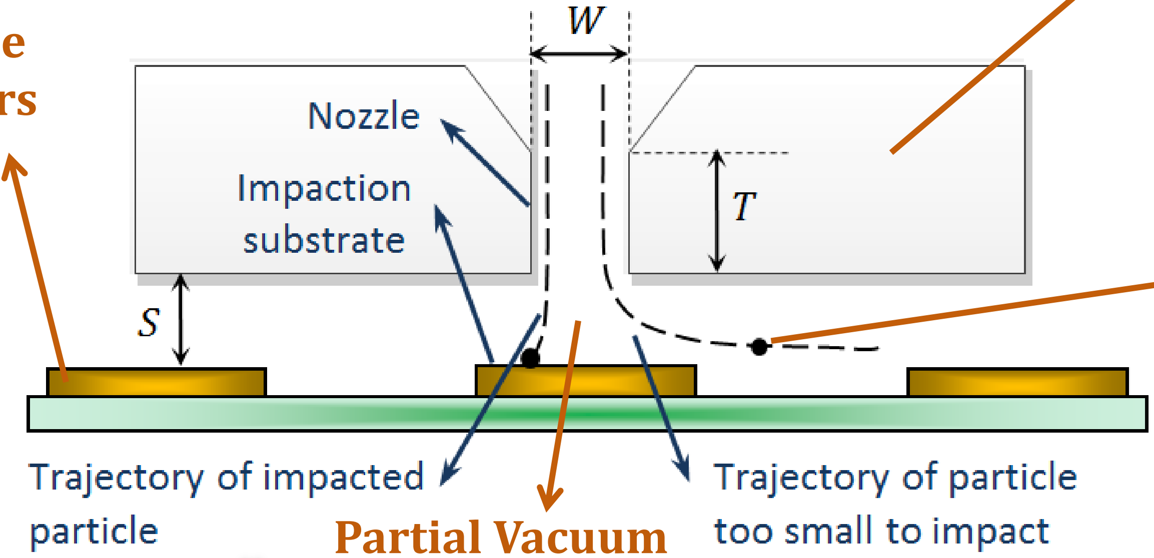
Jet directed onto impaction substrate

Plate with one or multiple micro-orifices (nozzles)

Microscale Resonators

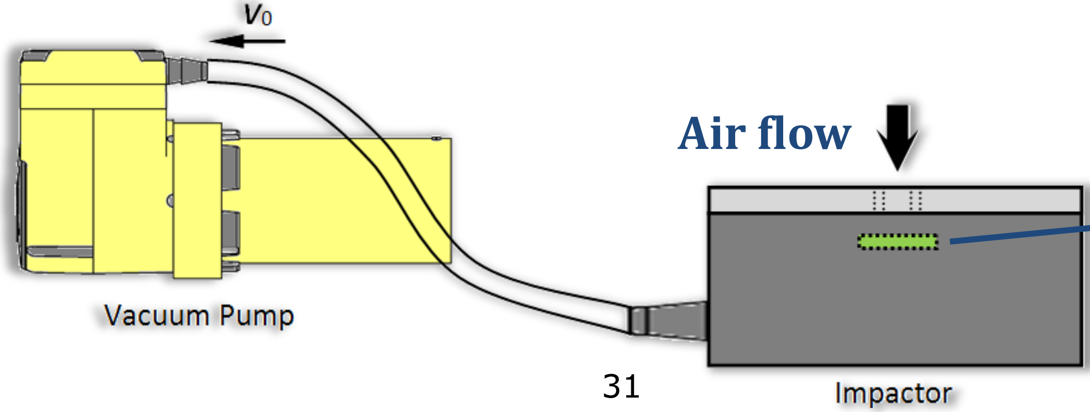
Airborne particles

Partial Vacuum



Air flow

Impaction Substrate



Fully MEMS Cascade Impactor

Weight: 12kg (26lb)

Diameter: 220mm

Height: 560mm

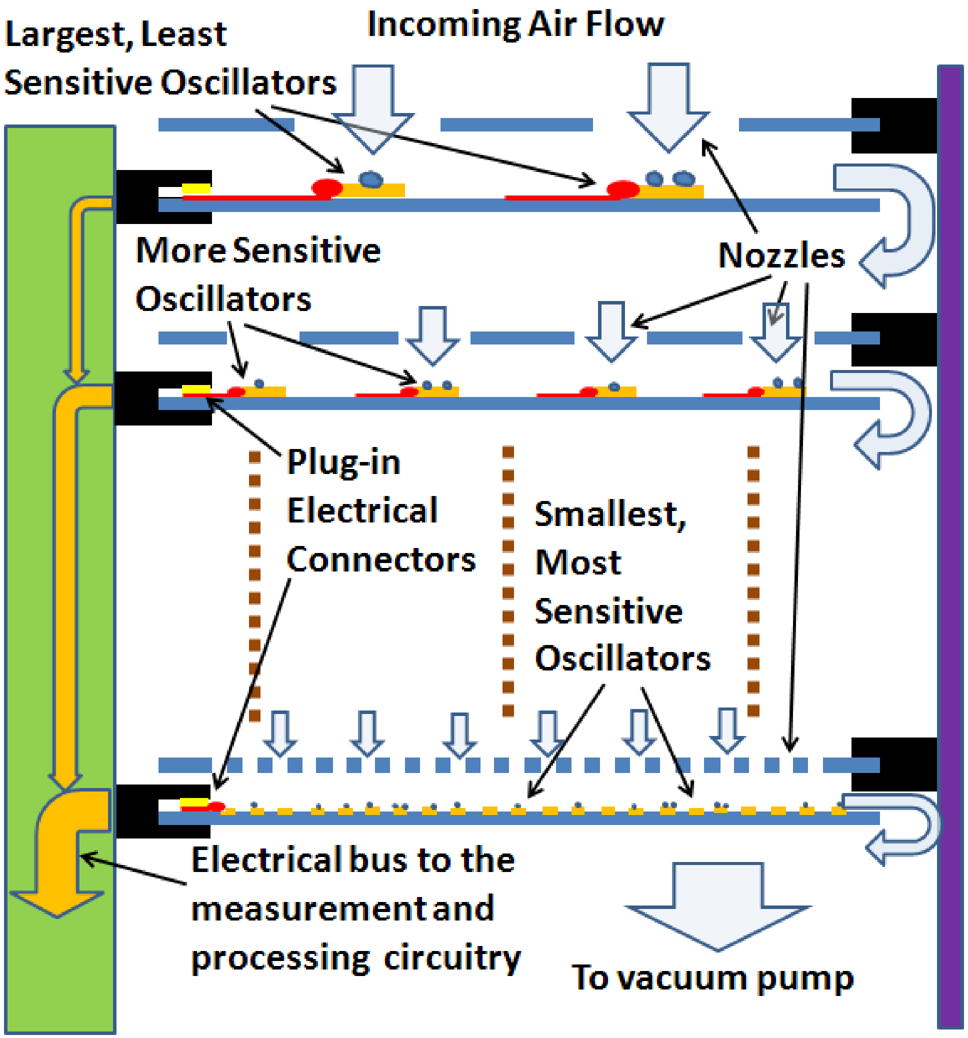
Power: 1.5kW

Stages: 13

Flow Rate: 30L/min

Real time Monitoring: NO

Model 122
30 L/min 13 Stage MOUDI-II



Largest, Least Sensitive Oscillators

Incoming Air Flow

More Sensitive Oscillators

Nozzles

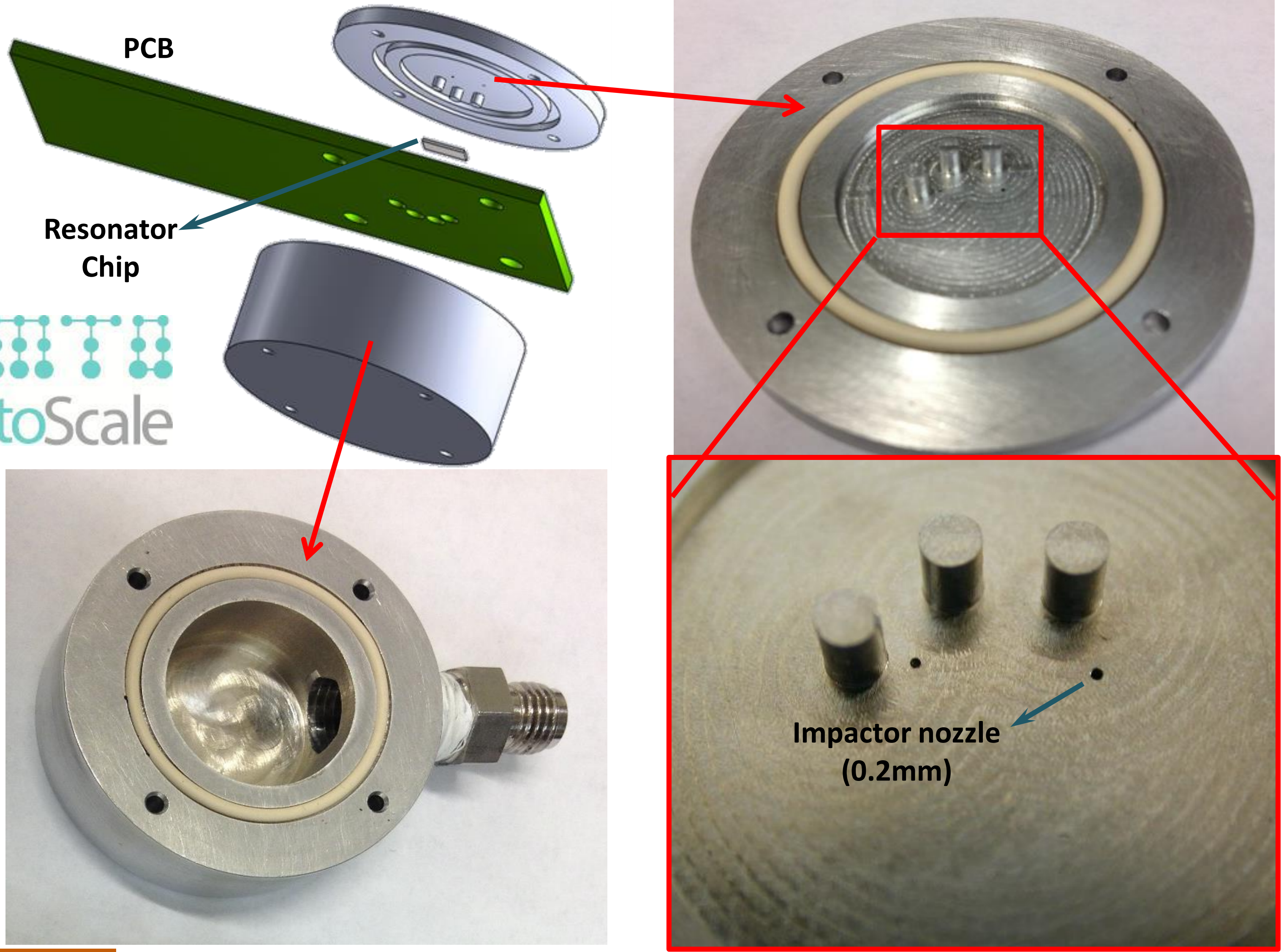
Plug-in Electrical Connectors

Smallest, Most Sensitive Oscillators

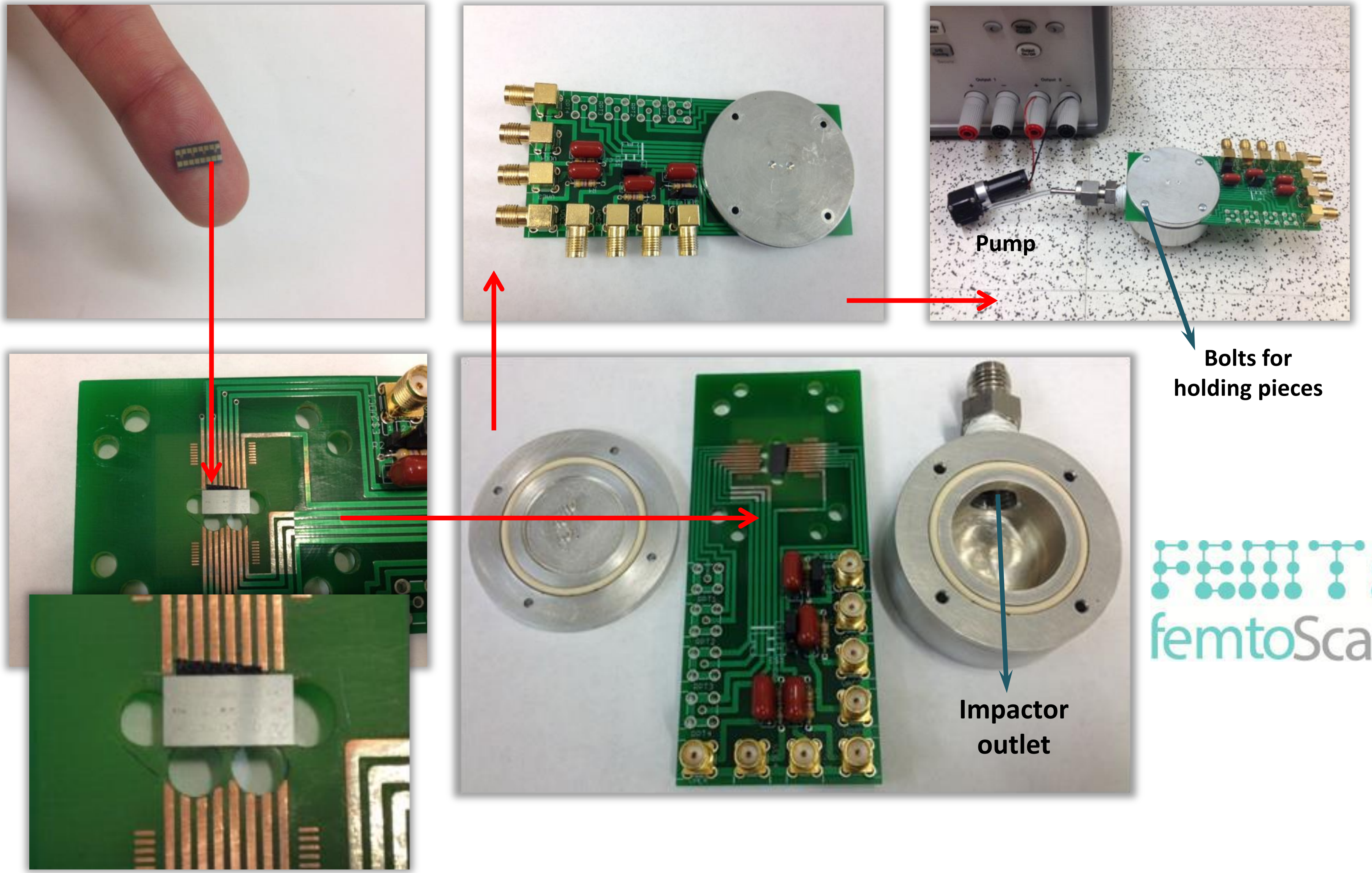
Electrical bus to the measurement and processing circuitry

To vacuum pump

Impactor Fabrication

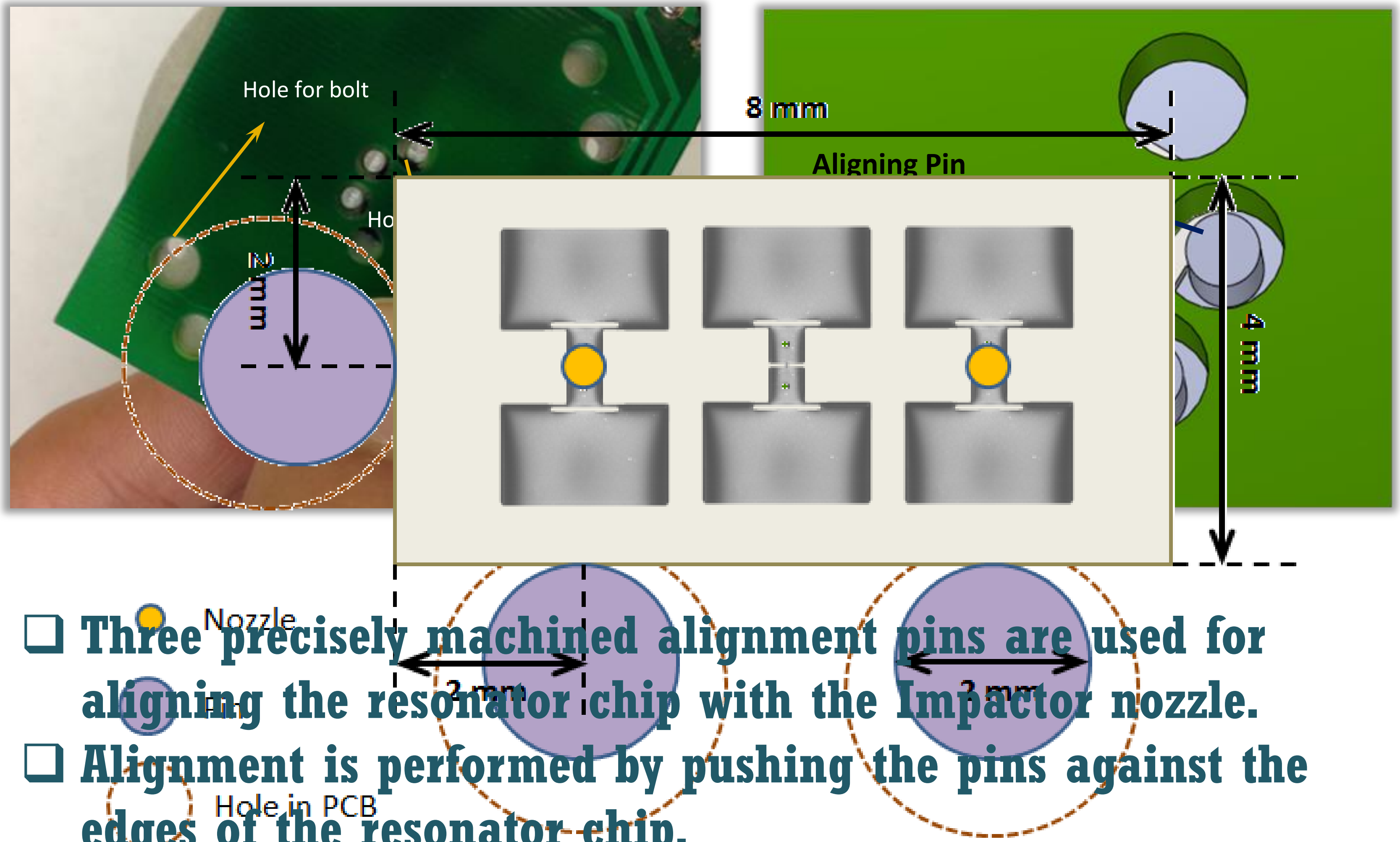


Assembly Procedure



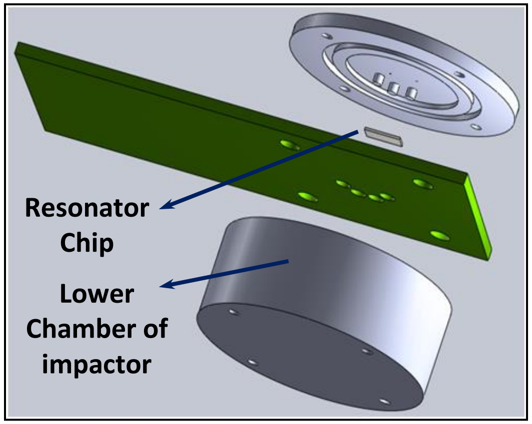
femtoScale

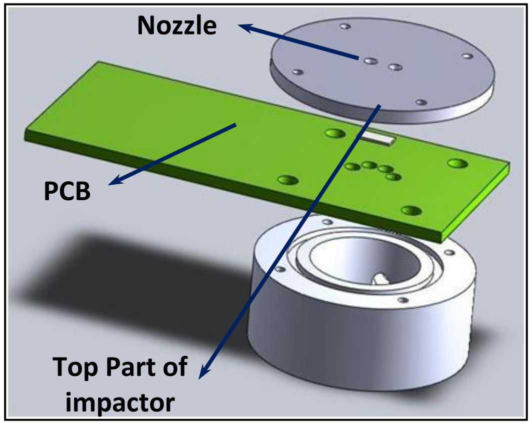
Alignment Technique

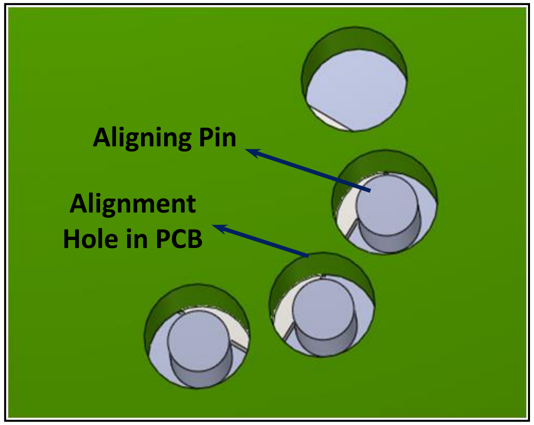


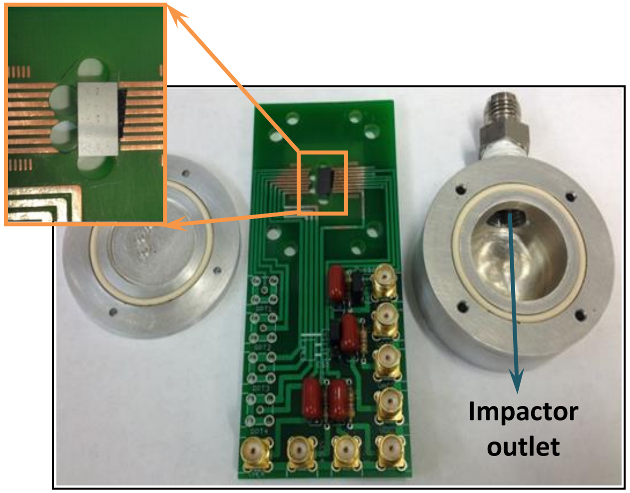
- ❑ Three precisely machined alignment pins are used for aligning the resonator chip with the Impactor nozzle.
- ❑ Alignment is performed by pushing the pins against the edges of the resonator chip.

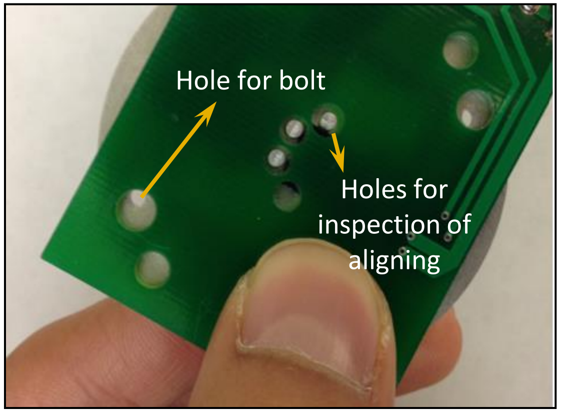
Combined Resonator/Impactor System Assembly

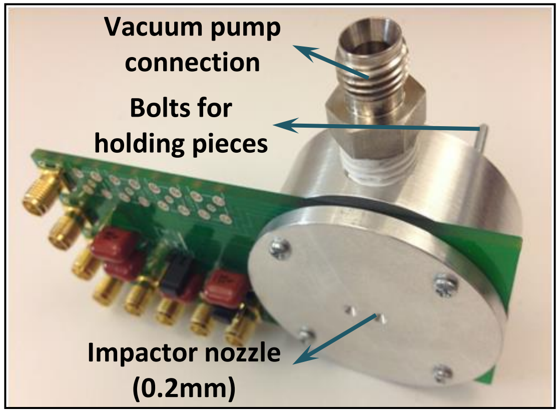




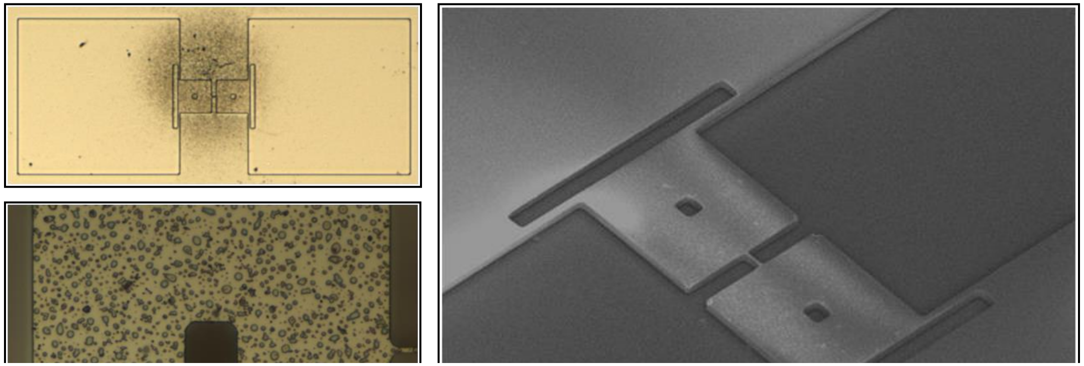


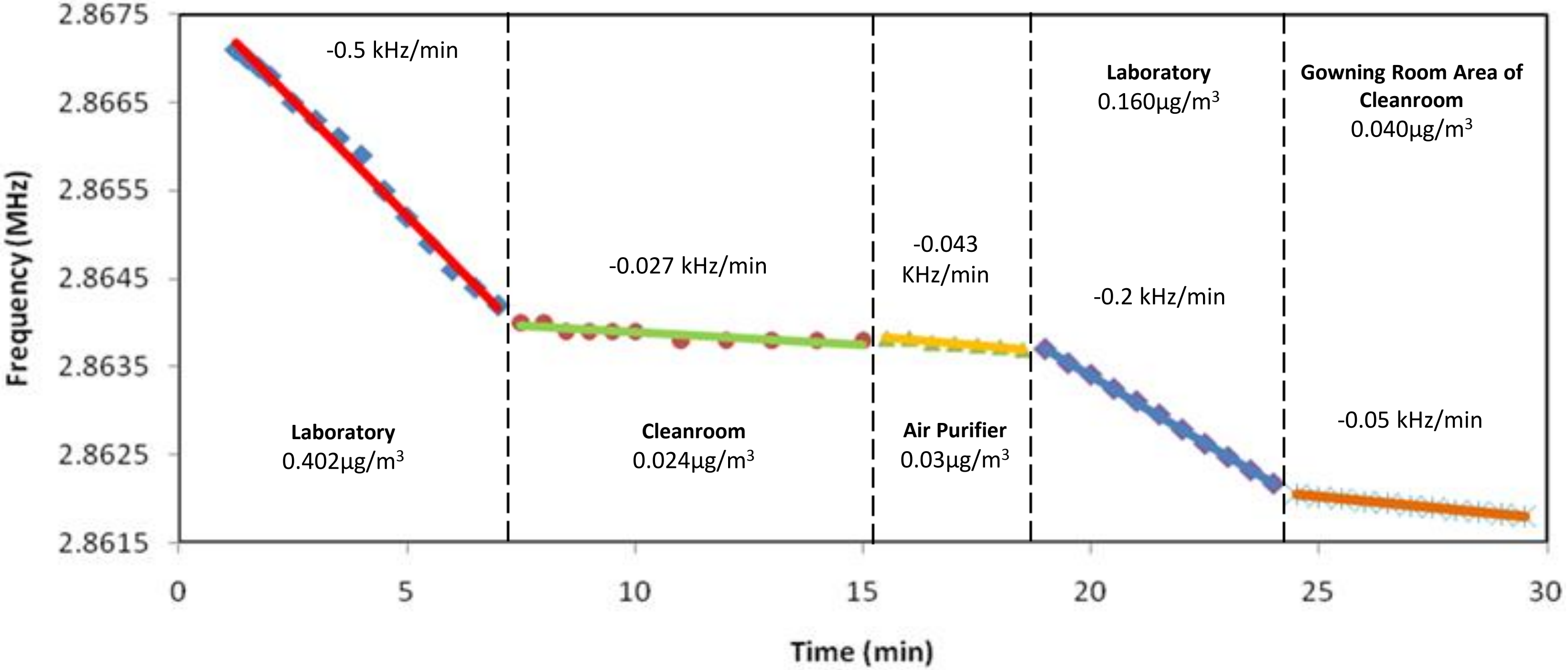




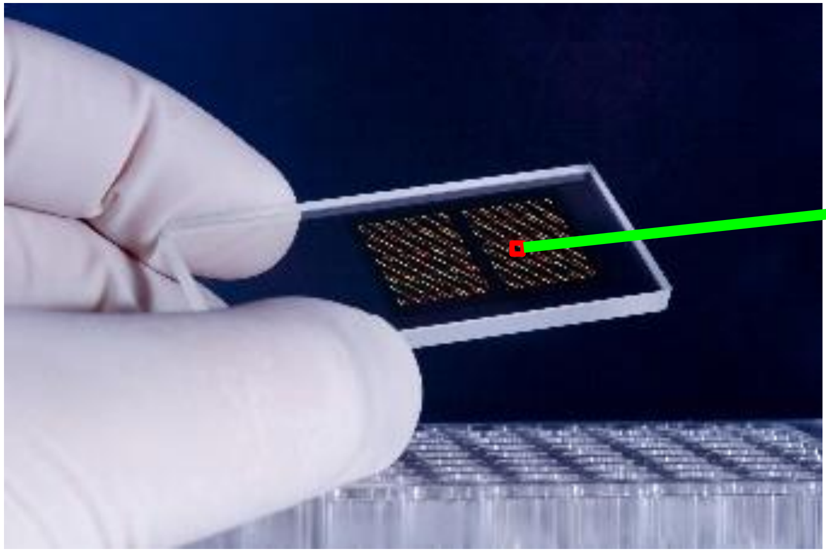


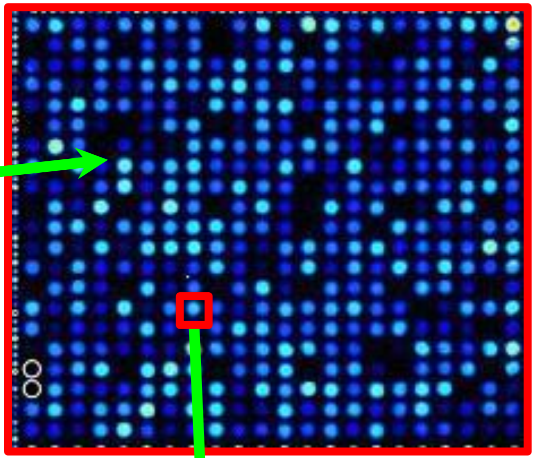
Test Results

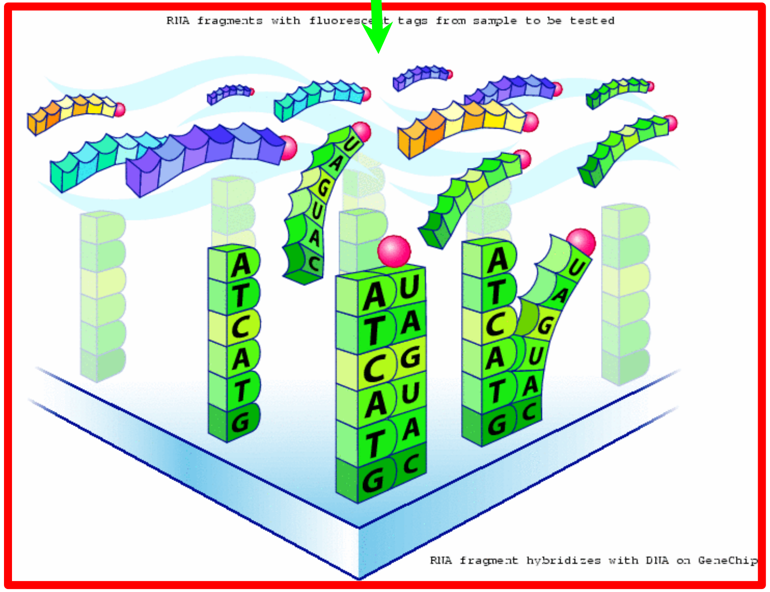


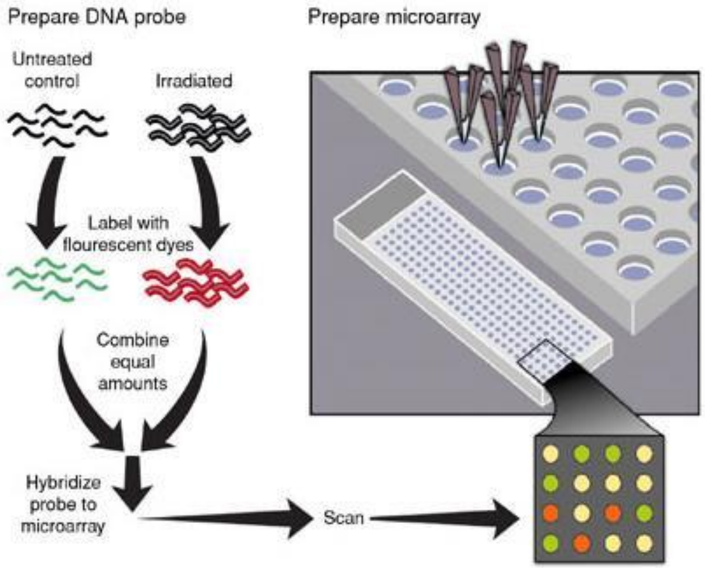


Biosensing: Microarray Technology

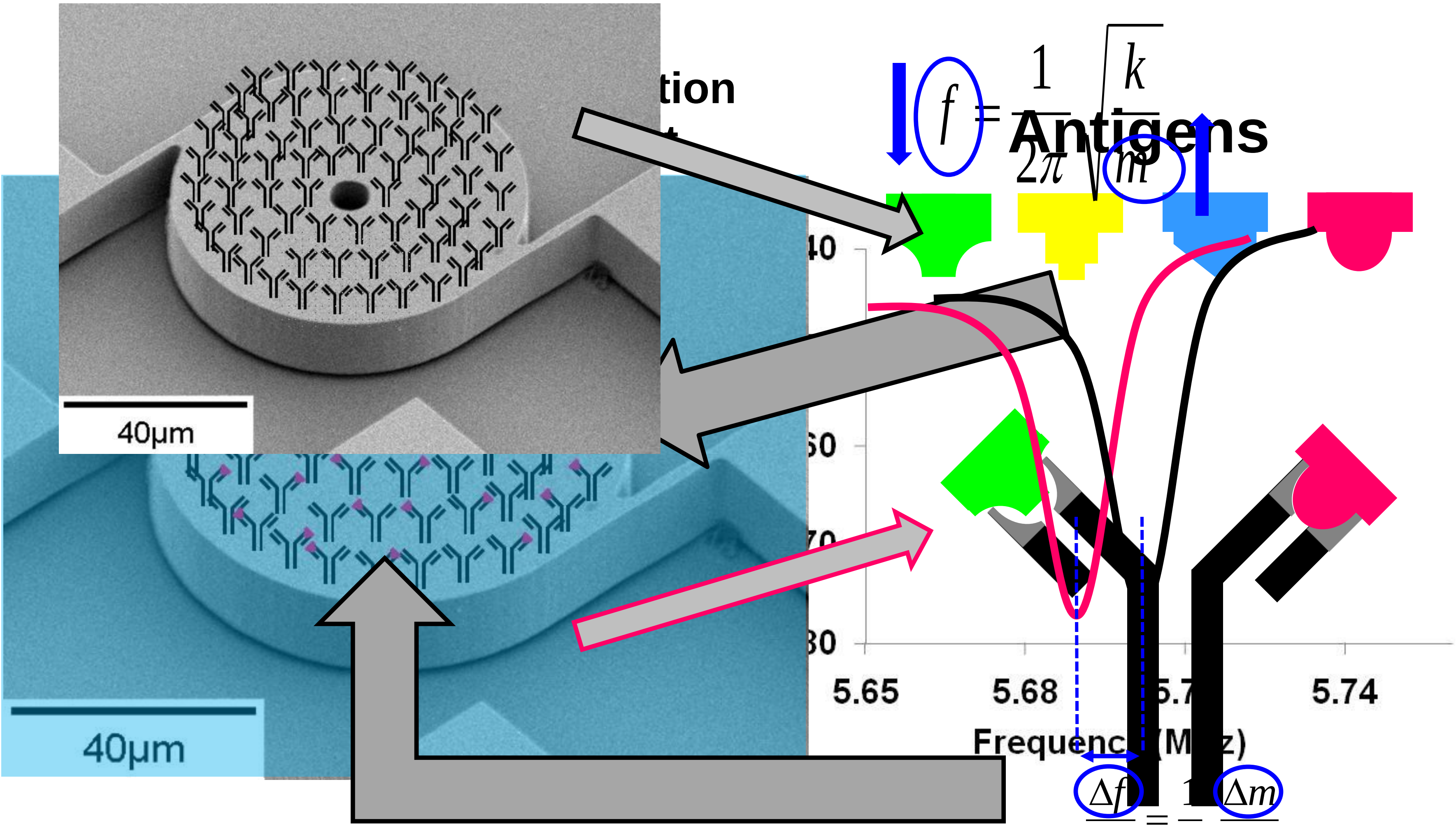








Biomolecular Mass Sensing

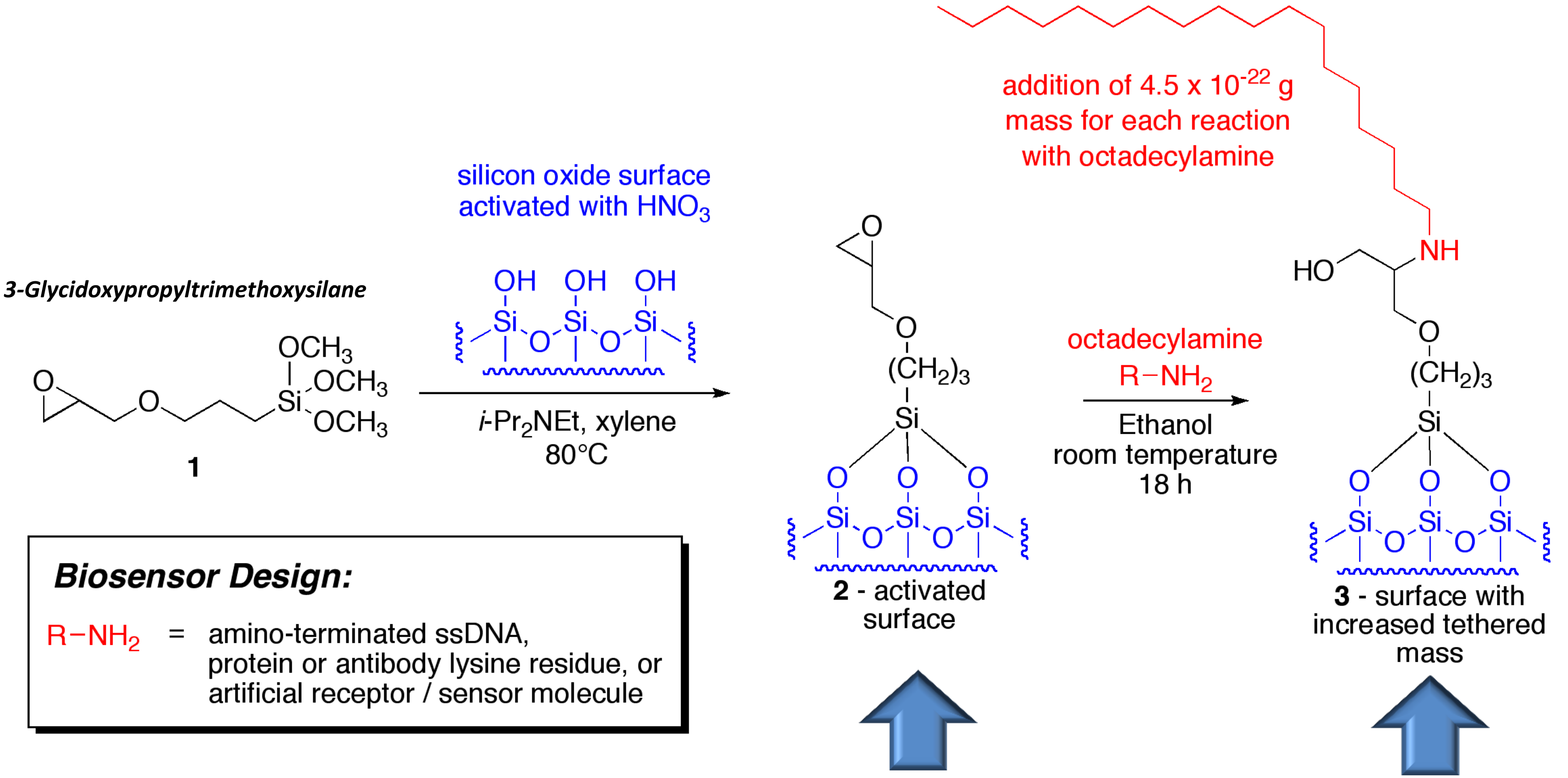


$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

$$\frac{\Delta f}{f} = \frac{1}{2} \cdot \frac{\Delta m}{m}$$

Antibody

Surface Linking Synthetic Scheme



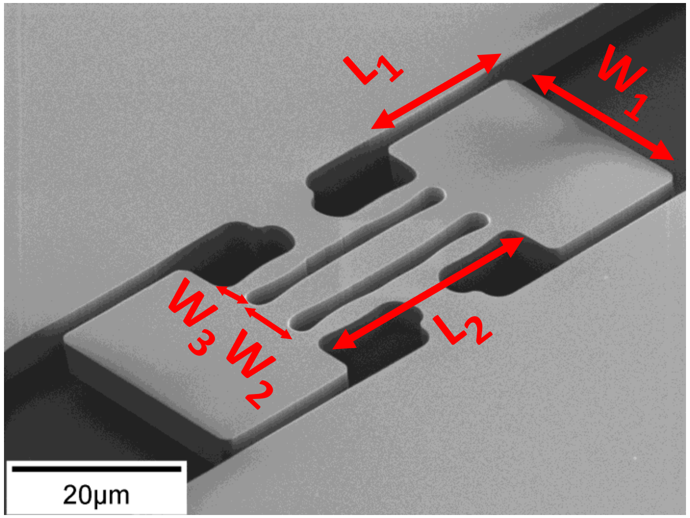
Frequency Measurement 1

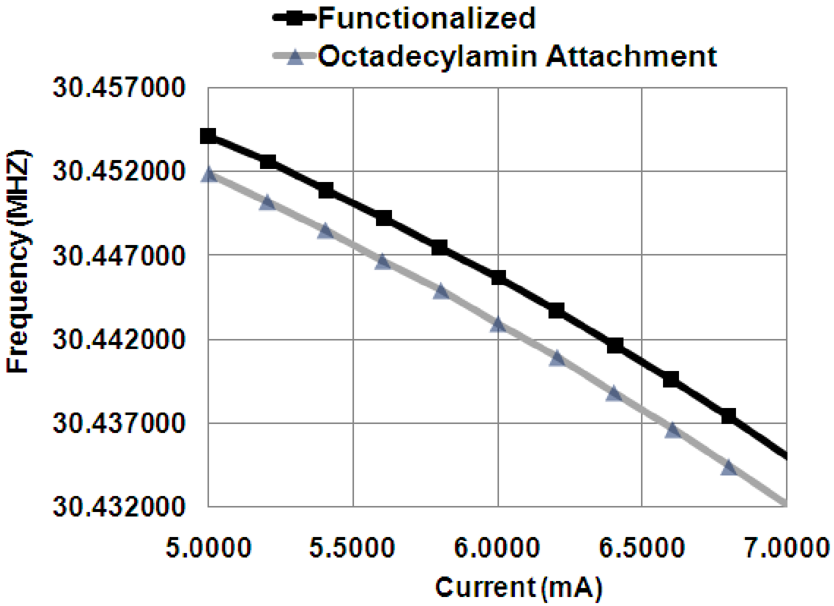
Frequency Measurement 2

Biosensor Design:

R−NH$_2$ = amino-terminated ssDNA, protein or antibody lysine residue, or artificial receptor / sensor molecule

Single Molecular Layer Detection





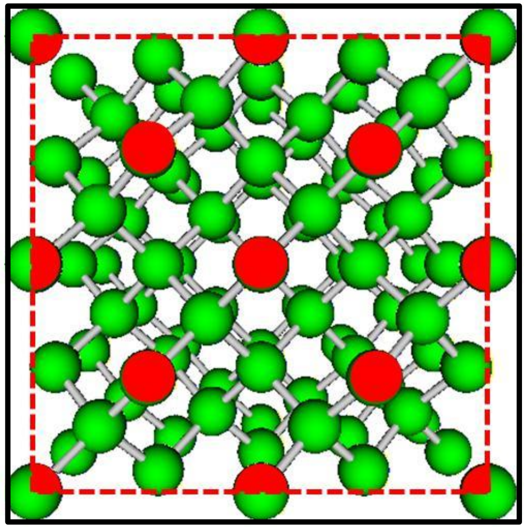
L_1, L_2, W_1, W_2, W_3 (μm)	f_1(MHz) Functionalized	f_2(MHz) Octadecylamine	Δf(Hz)	Δf(ppm)
23,36,33,4,2	30.437427	30.434413	3014	99
23,36,33,4,2	29.891373	29.888322	3051	100
23,36,33,--, 2	23.809419	23.805919	3400	140
23,36,33,--, 2	27.001593	26.998914	2679	99

Resonator Surface Coverage

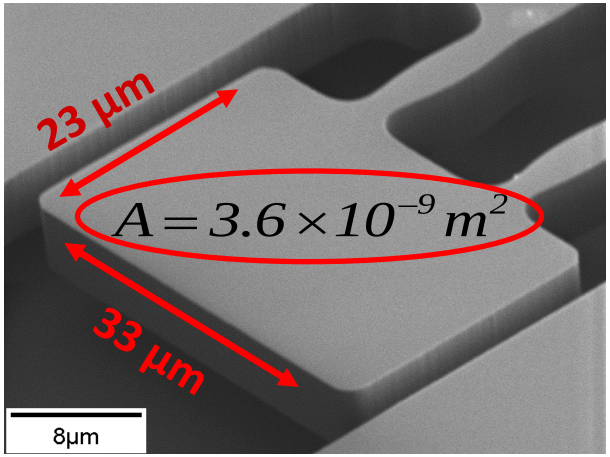
- ☐ Based on the frequency shift, device mass and frequency

$$\frac{\Delta f}{f} = -\frac{\Delta m?}{2m} \Rightarrow \Delta m = 1pg$$

- ☐ Considering the theoretical maximum possible added mass in **1 nm^2 = 4x10^{-9} pg**

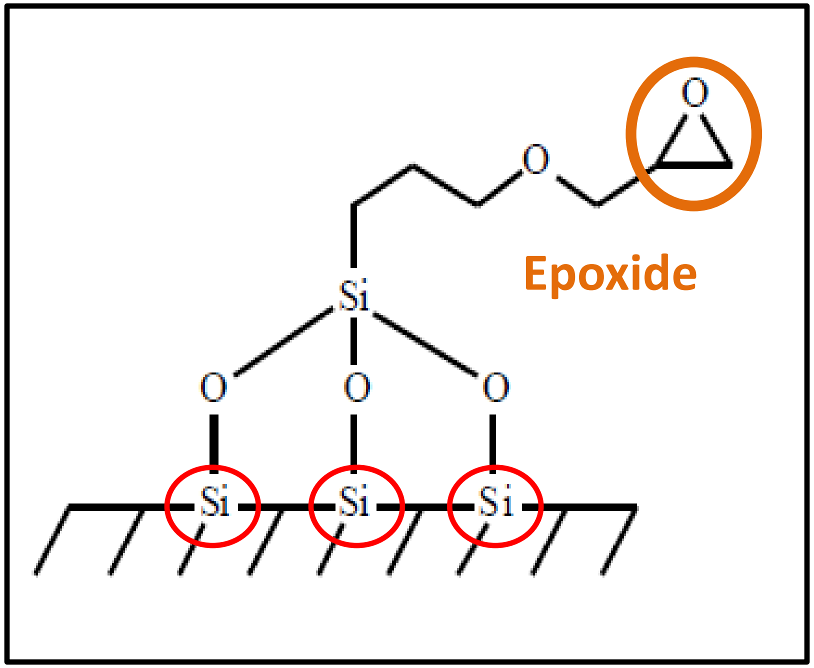


8 **Dangling Bonds in every silicon crystal for <u>Surface Linking</u>**



$\Rightarrow$ **Surface Coverage = 6.9%**

Resonator Surface Coverage



Dangling Bonds/3 = Epoxides

The Maximum Possible Number of Octadecylamine in

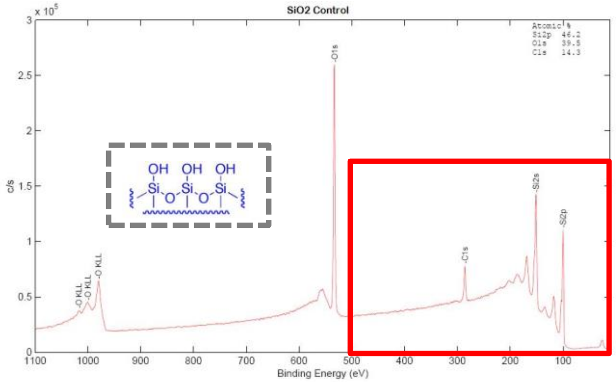
1 nm^2 = 8.8 Molecules

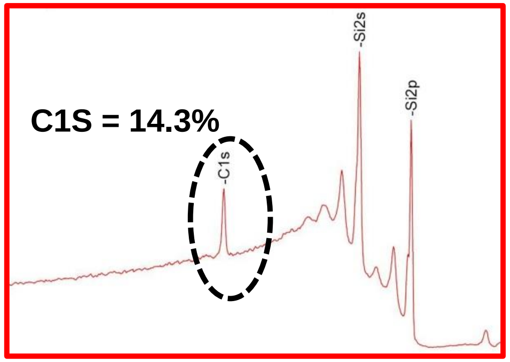
The Theoretical Added Mass in

1 nm^2 = 4×10^{-9} pg

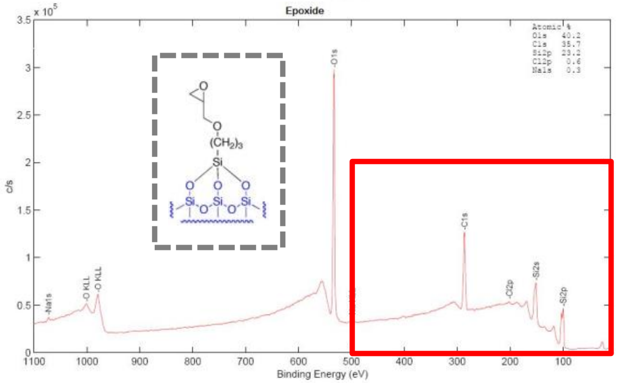
Surface X-ray Photoelectron Spectroscopy (XPS) Analysis

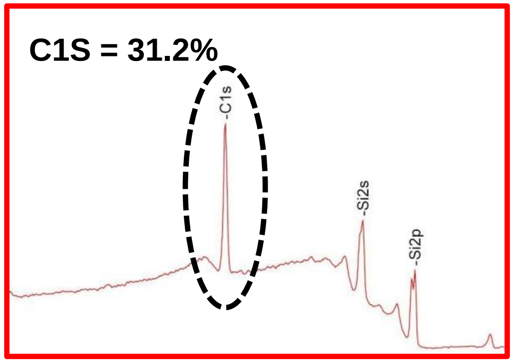
SiO2



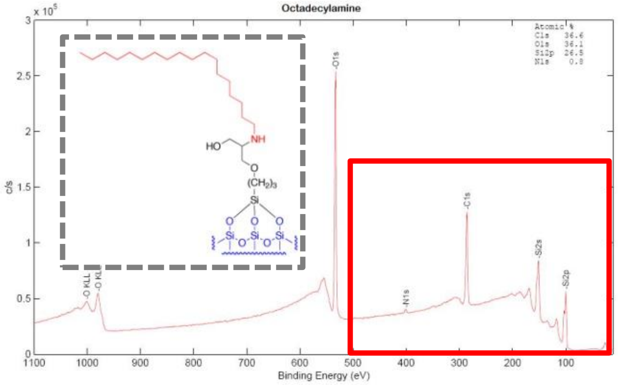

C1S = 14.3%

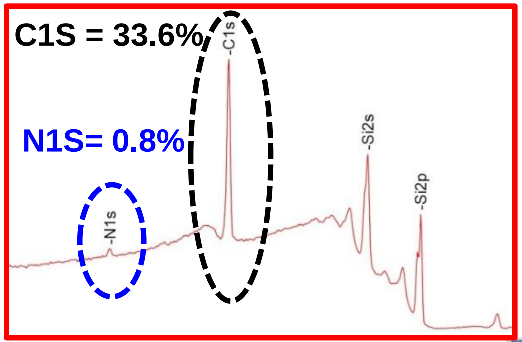
Epoxide




C1S = 31.2%

Octadecylamine

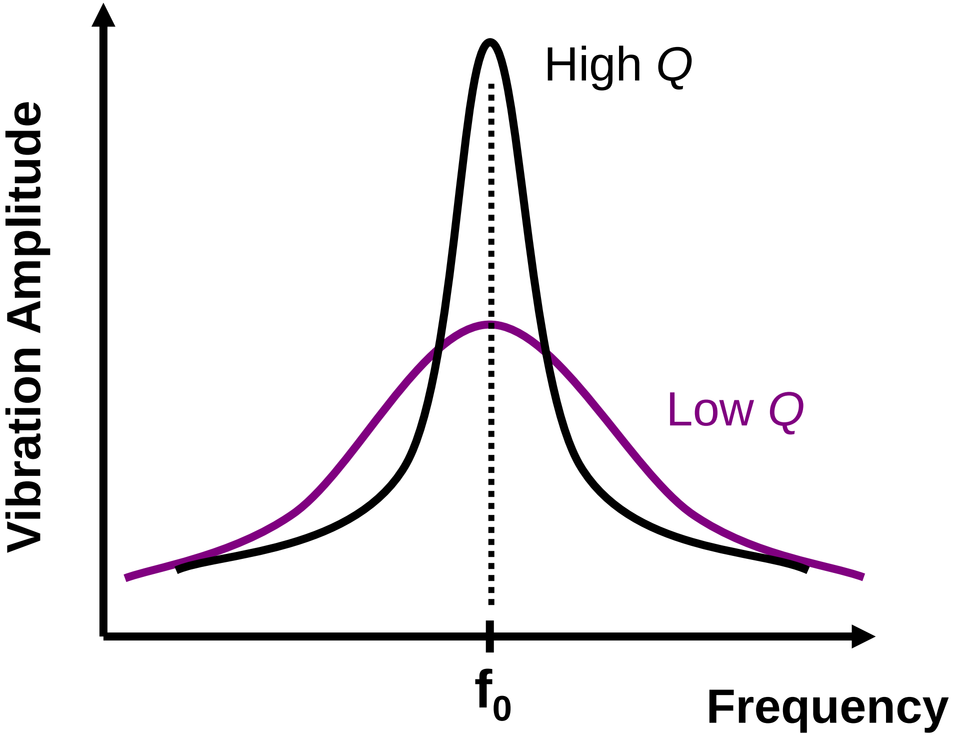



C1S = 33.6%

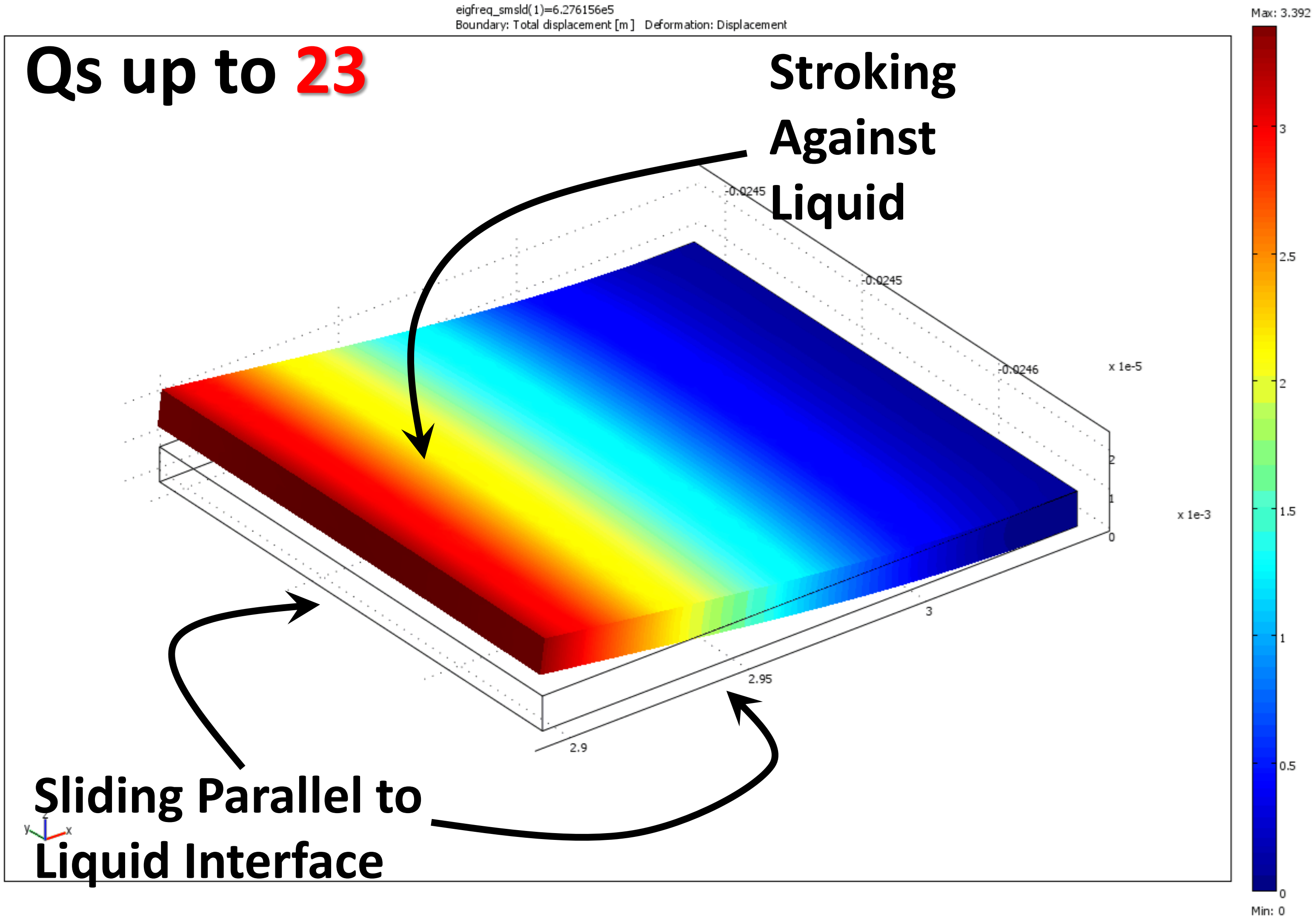
N1S= 0.8%

Direct in-Liquid Measurement

- ❑ **Viscous damping from surrounding liquid significantly suppresses mechanical resonance and lowers quality factor (Q)**
- ❑ **High Q is needed for accurate frequency measurement and effective resonator transduction**



Direct in Liquid Measurement: Out-of-Plane Microcantilever

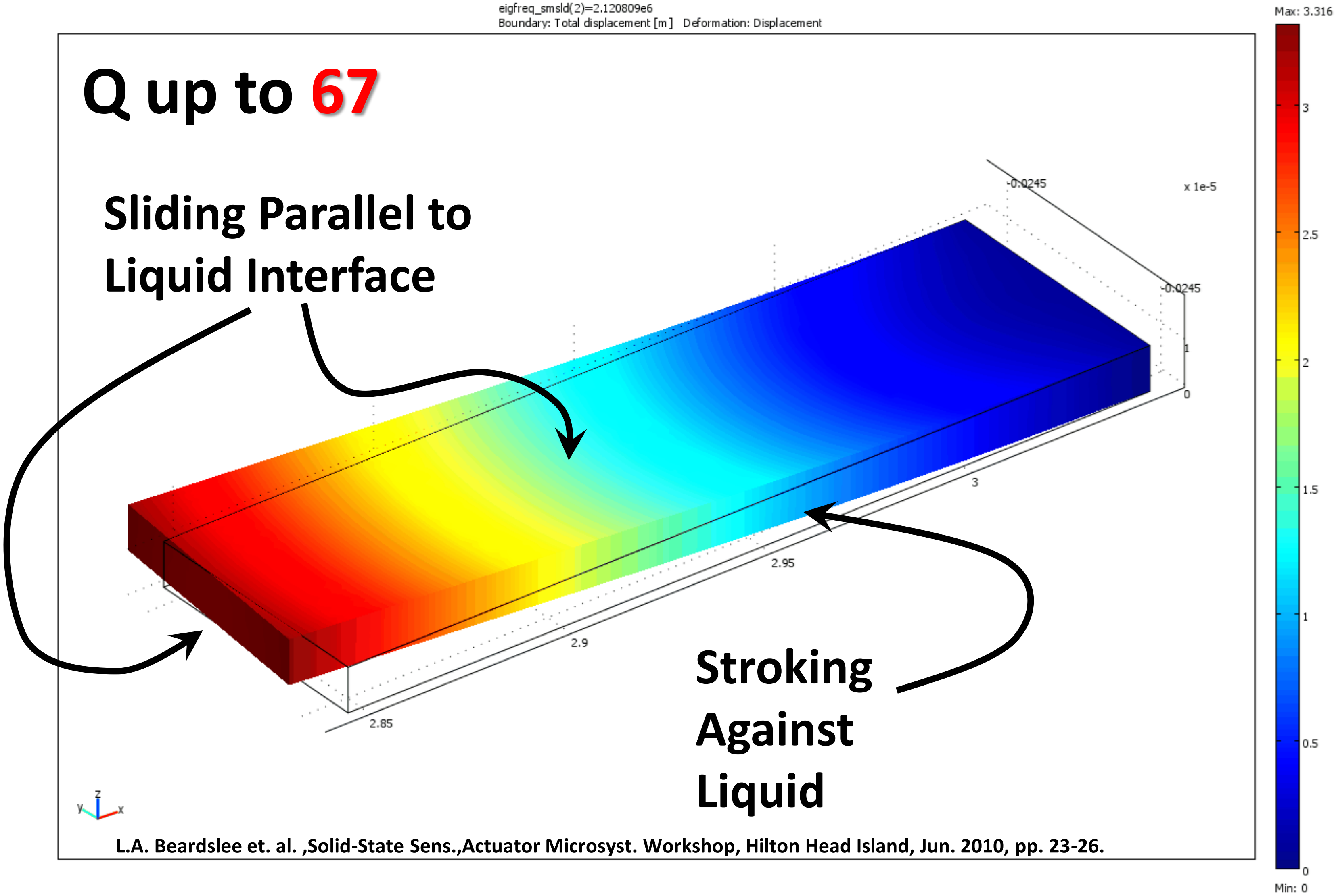


Qs up to **23**

Stroking Against Liquid

Sliding Parallel to Liquid Interface

Direct in Liquid Measurement: In-Plane Microcantilever



Q up to 67

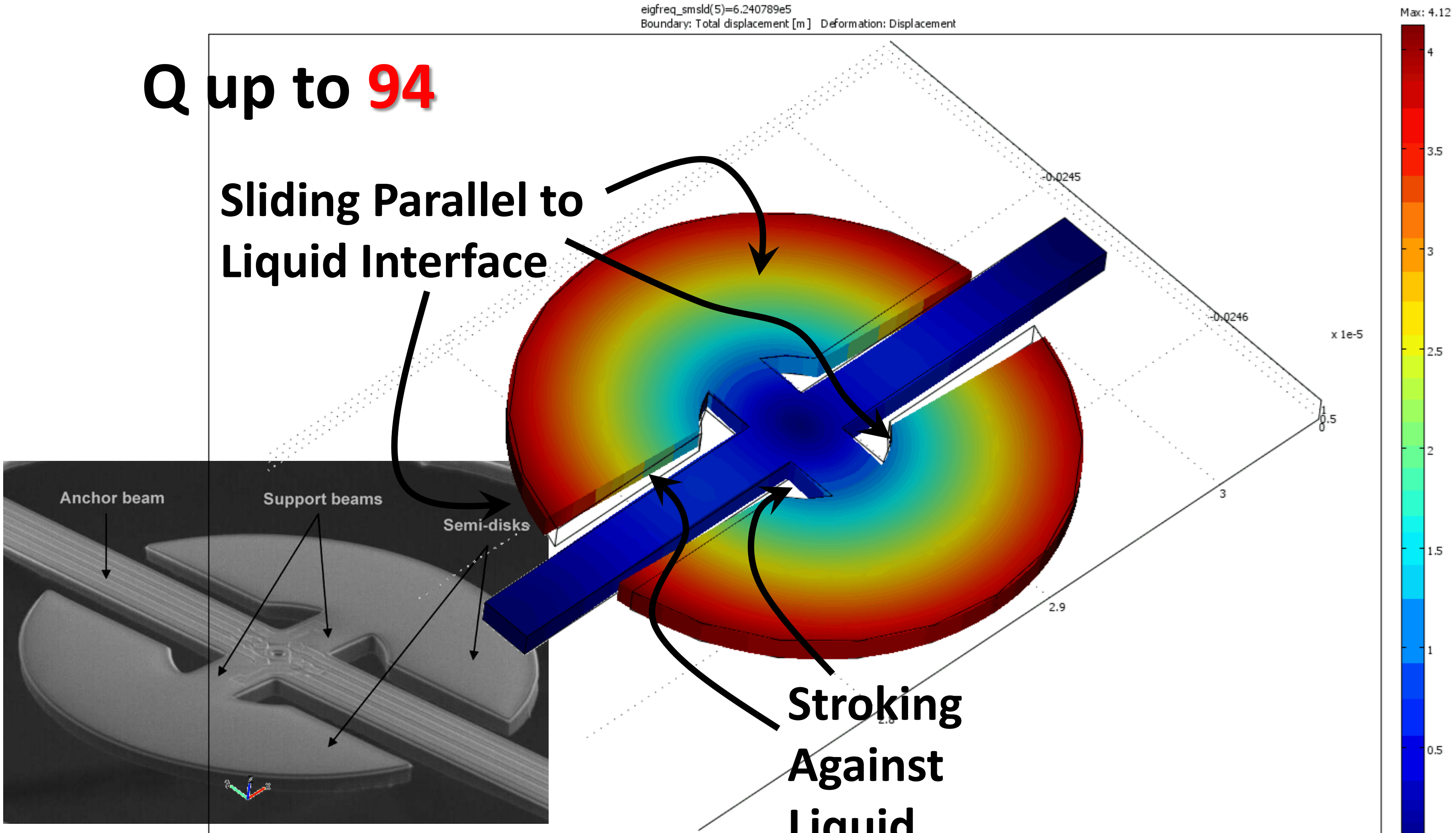
Sliding Parallel to Liquid Interface

Stroking Against Liquid

L.A. Beardslee et. al. ,Solid-State Sens.,Actuator Microsyst. Workshop, Hilton Head Island, Jun. 2010, pp. 23-26.

Quasi-Rotational Dual-Half-Disk

Q up to **94**

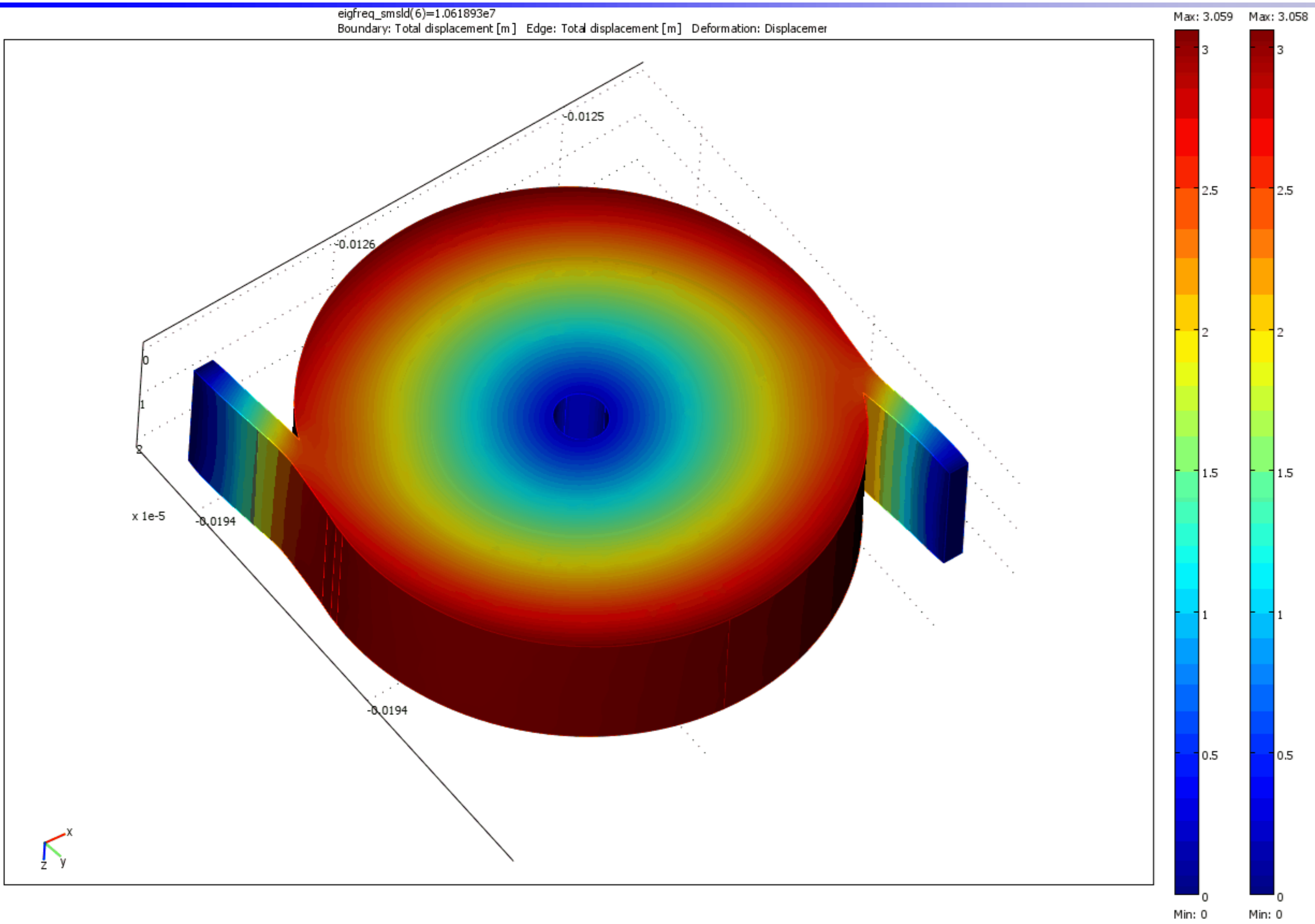


Sliding Parallel to Liquid Interface

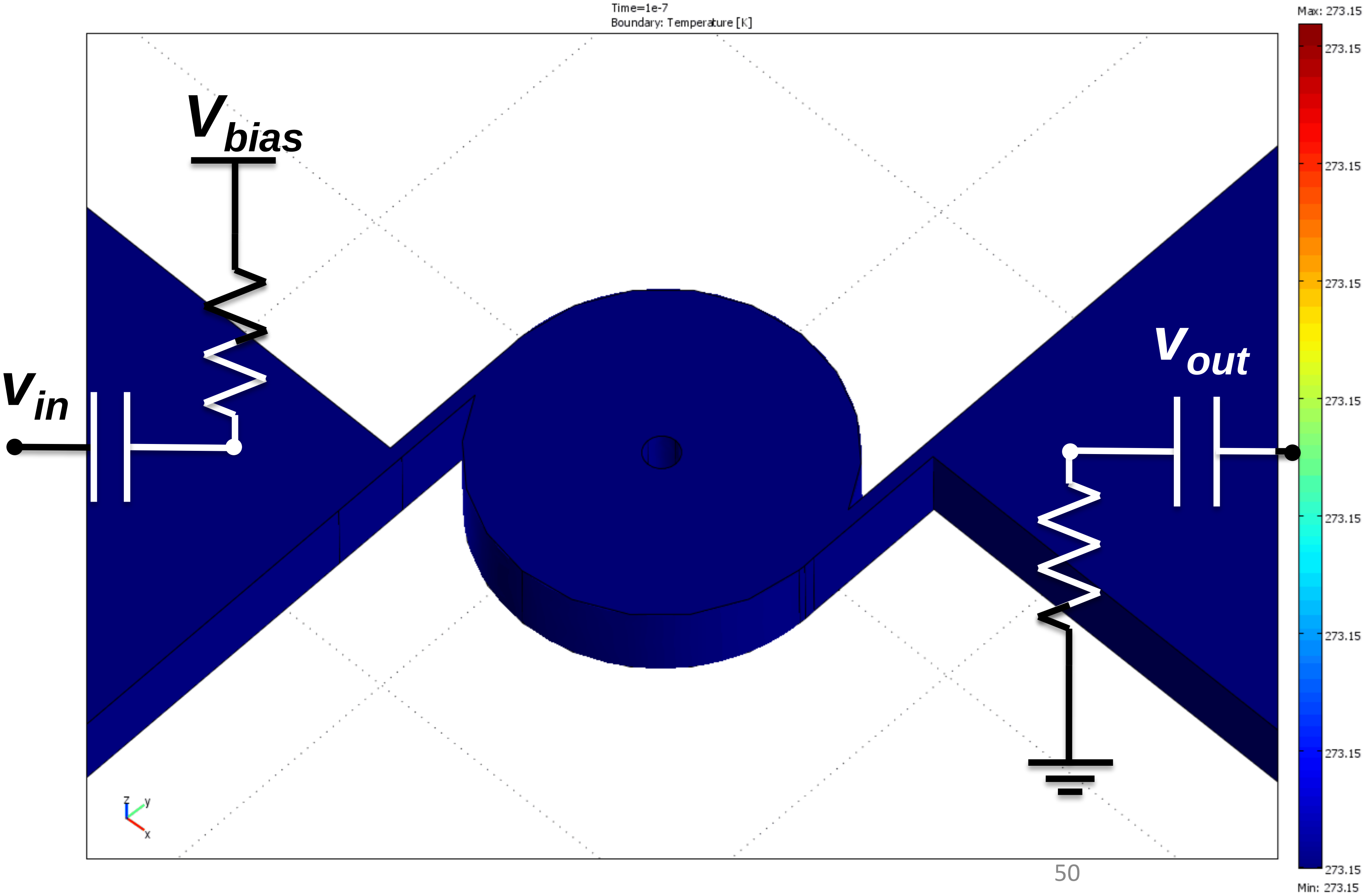
Stroking Against Liquid

J. H. Seo and O. Brand, JMEMS 2008, Vol. 17, issue 2, pp. 483-493.

Our Approach: Rotational Mode Disk



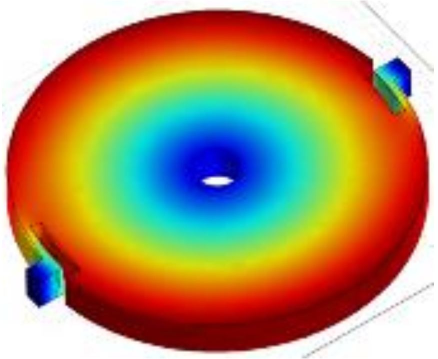
Resonator Operation

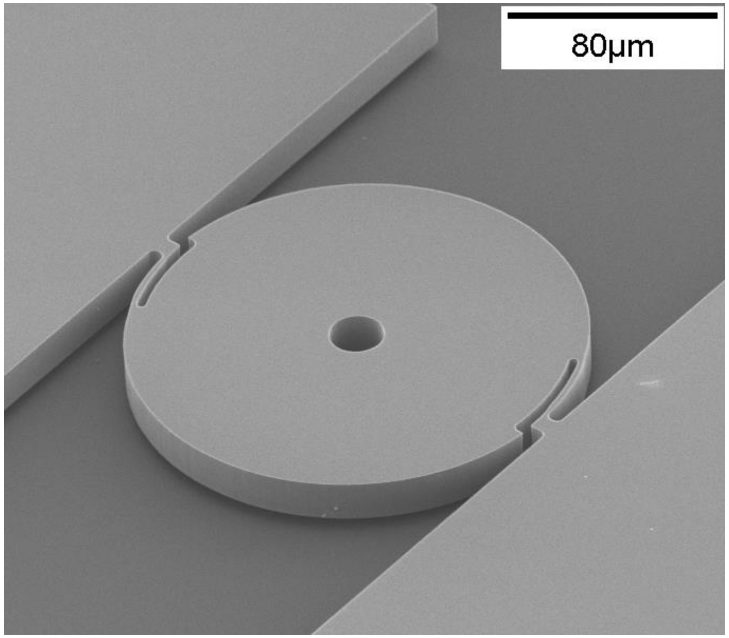


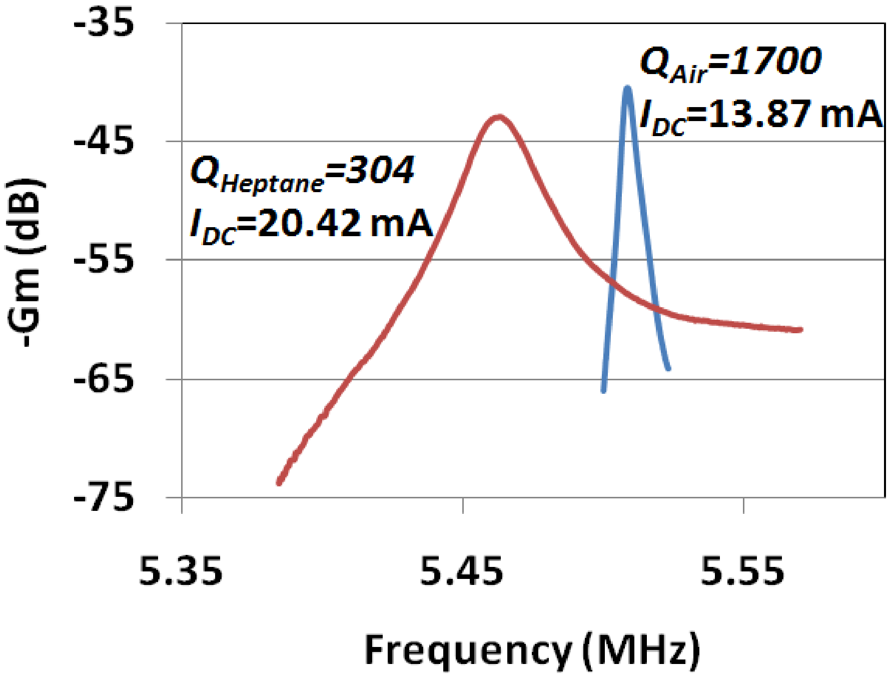
50

Measurement Results

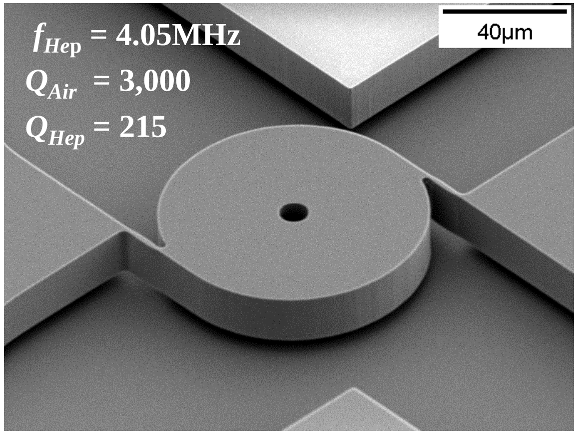
- ☐ Record high quality factor of 304 measured in liquid
- ☐ Potential for direct sensing of biomolecules in biological samples

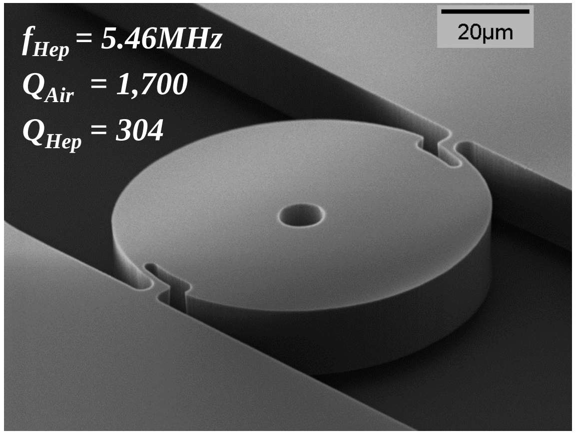


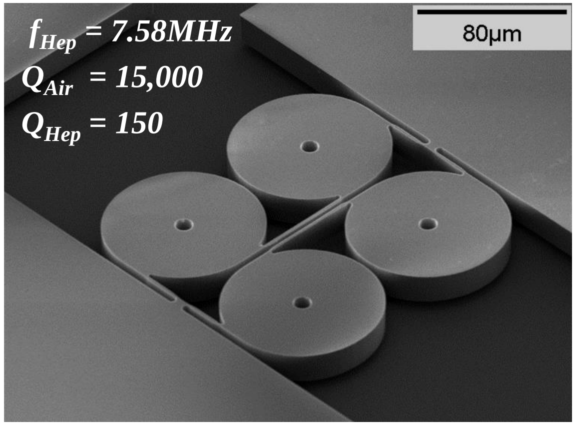


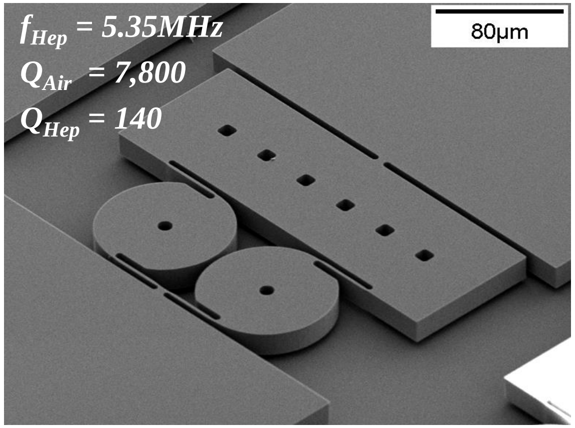


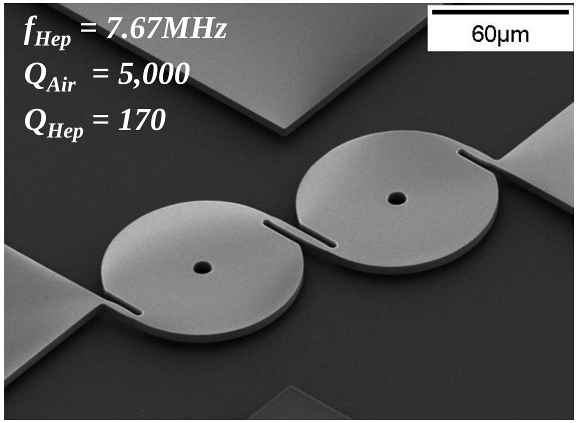
Different Disk Resonator Topologies


f_{Hep} = 4.05MHz
Q_{Air} = 3,000
Q_{Hep} = 215

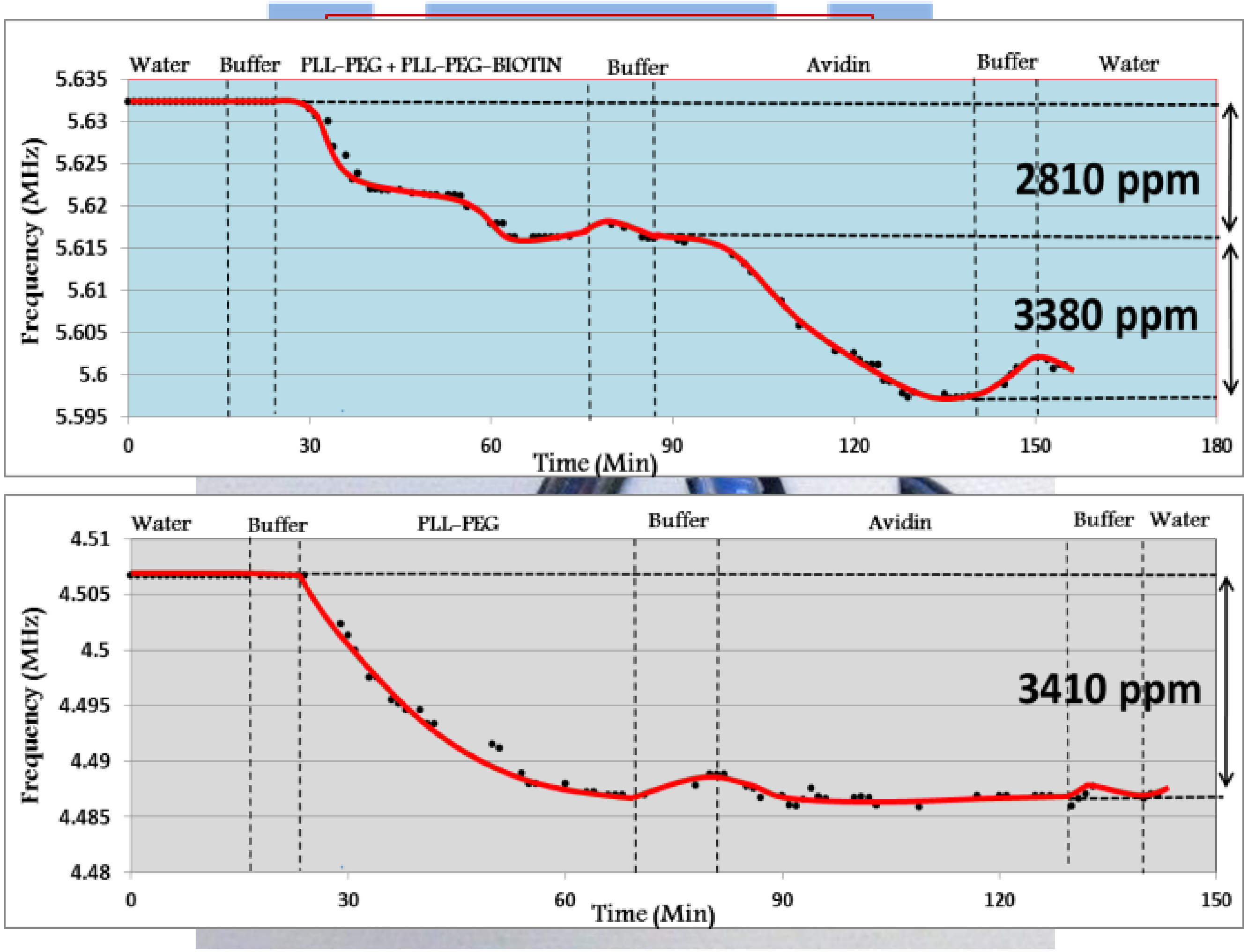

f_{Hep} = 5.46MHz
Q_{Air} = 1,700
Q_{Hep} = 304


f_{Hep} = 7.58MHz
Q_{Air} = 15,000
Q_{Hep} = 150


f_{Hep} = 5.35MHz
Q_{Air} = 7,800
Q_{Hep} = 140

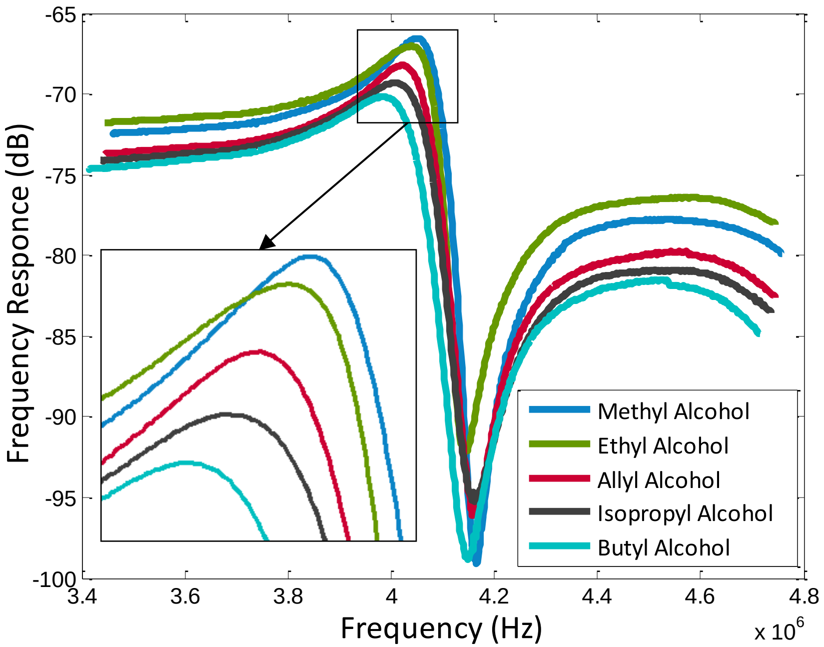

f_{Hep} = 7.67MHz
Q_{Air} = 5,000
Q_{Hep} = 170

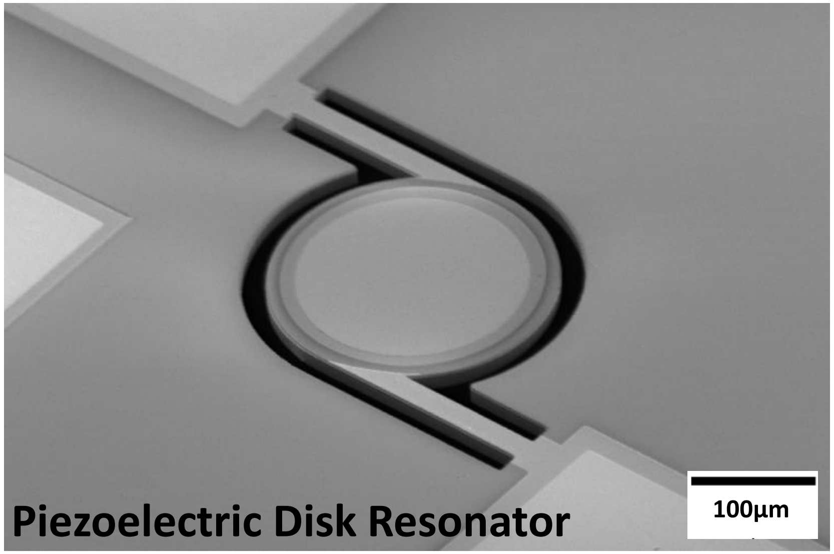
Resonators Encapsulated in Micro-Fluidic Channels



Liquid Viscosity Monitoring

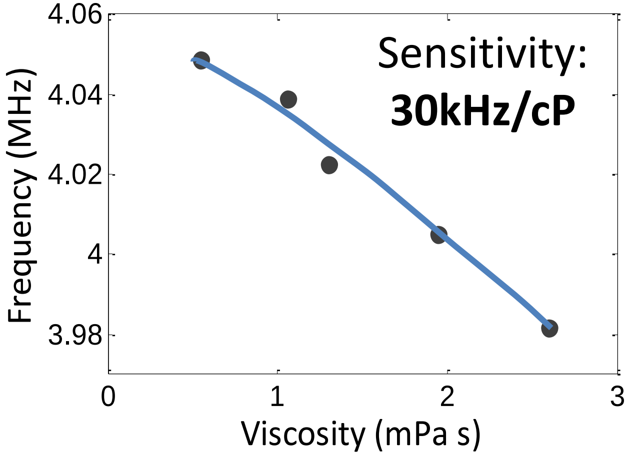
- ❑ **Piezoelectric Rotational Mode Disk Resonators as viscosity monitors**





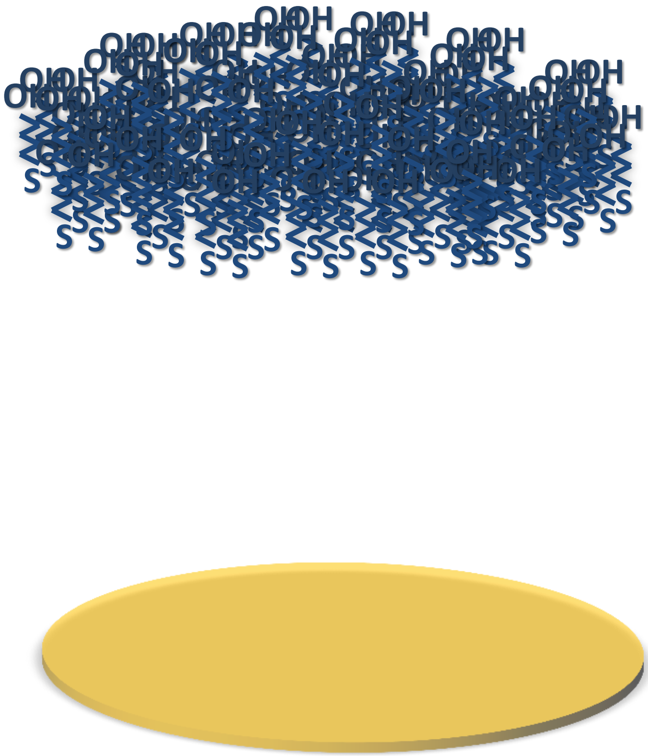
Piezoelectric Disk Resonator

Prof. Abdolvand Group, Oklahoma State University



Experiments and Results

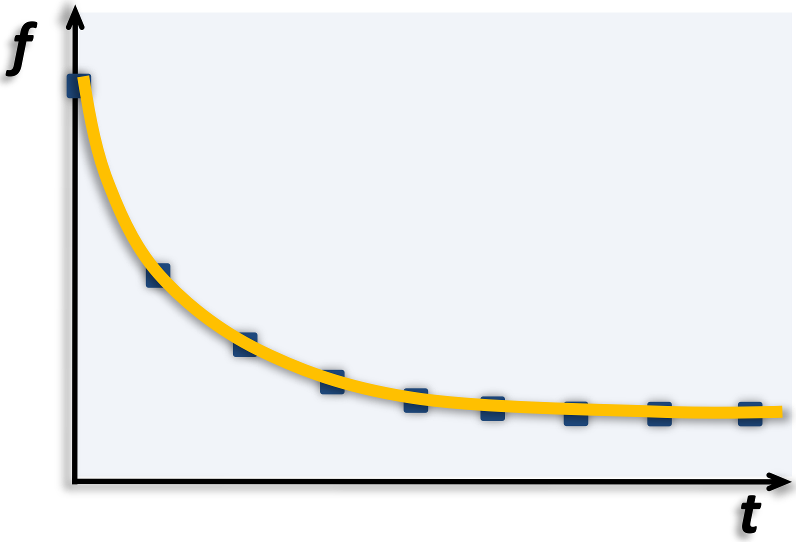
- **Direct detection of MCH molecules in liquid media**
- **MCH interact easily with Au through the sulfur atom**



Blank Gold surface

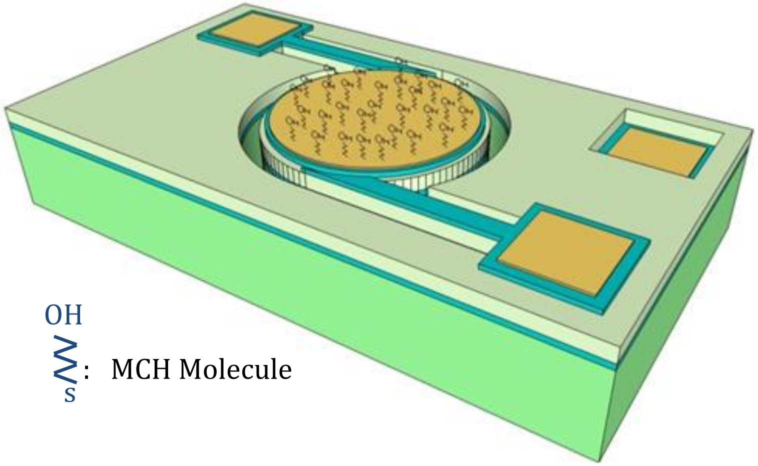
Mercapto-Hexanol (MCH)

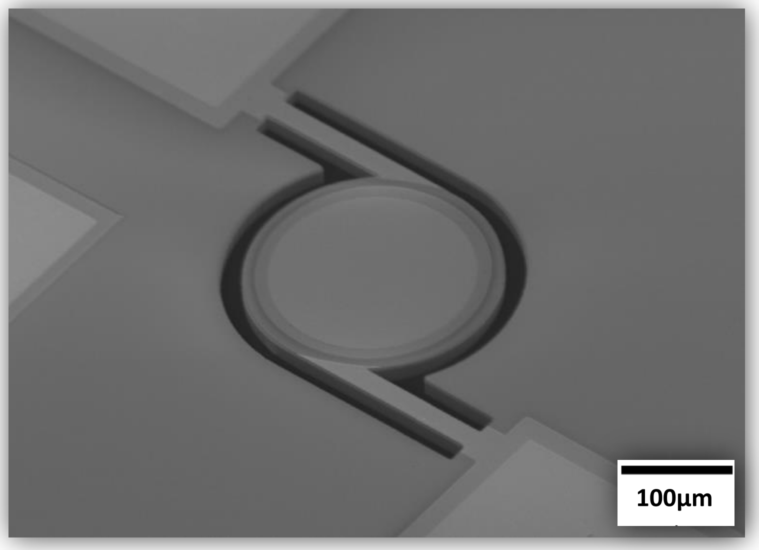
$SH\,CH_2(CH_2)_4CH_2OH$

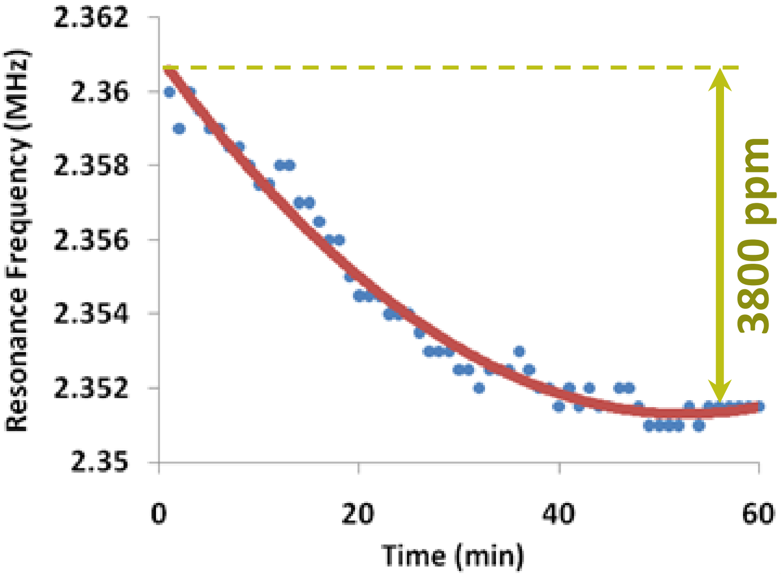


Piezoelectric Disk Resonators for Direct Molecular Sensing

- Rotational mode disk resonators are demonstrated as direct real-time bio-molecule monitors
- Exposure to 1.0 mM MCH in aqueous solution
- Saturation is reached after 1hr

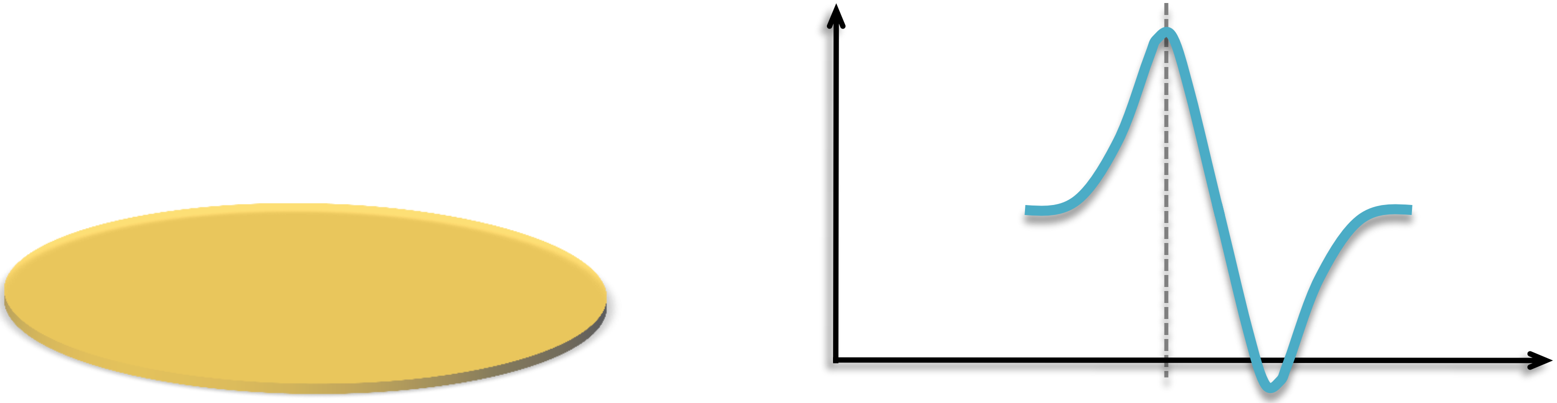






Experiments and Results

DNA Detection Mechanism



Blank gold surface

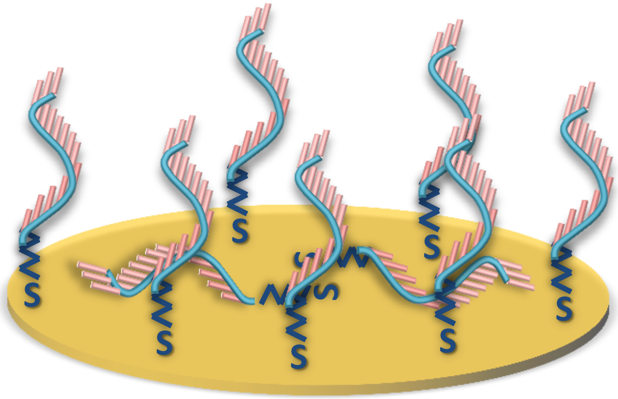
(I) Treatment with HS-ssDNA (2.0 μM/1.0 M KH_2PO_4, PH 4.2)

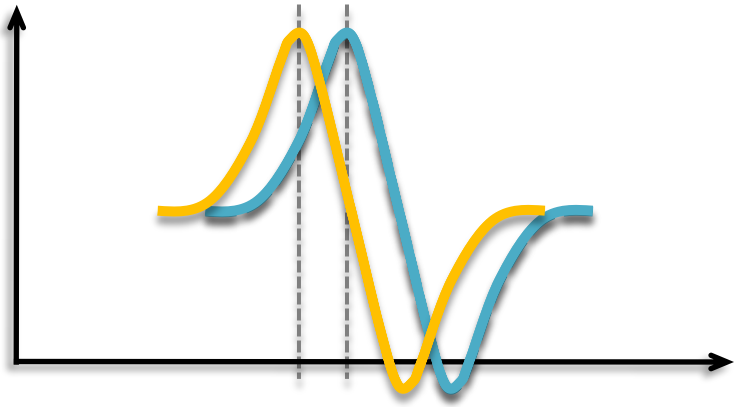
(II) Exposure to 1.0 mM Mercapto-Hexanol in aqueous solution

(III) Hybridization with Complementary DNA Solution (1.0 μM/1.0 M NaCl Tris-HCl 1.0 mM EDTA)

Experiments and Results

DNA Detection Mechanism





Blank gold surface

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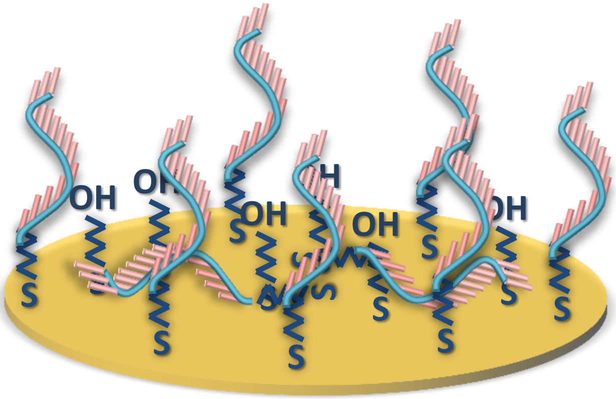
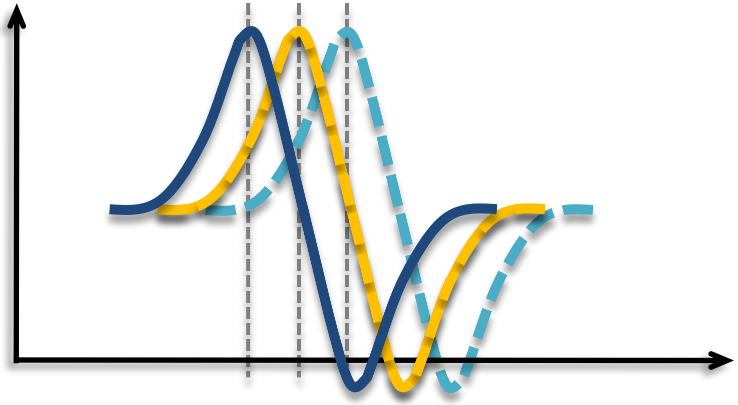
Experiments and Results

DNA Detection Mechanism





Blank gold surface

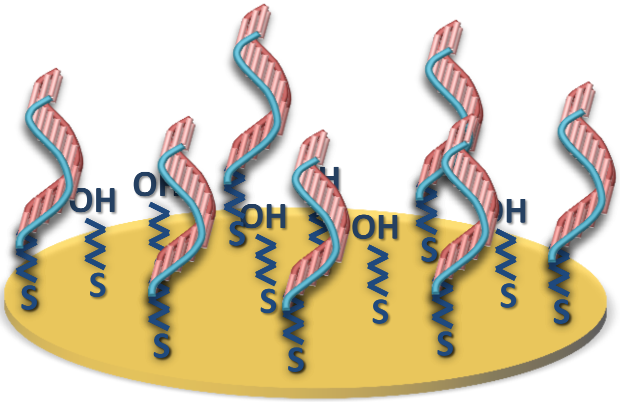
(I) Treatment with HS-ssDNA (2.0 μM/1.0 M KH_2PO_4, PH 4.2)

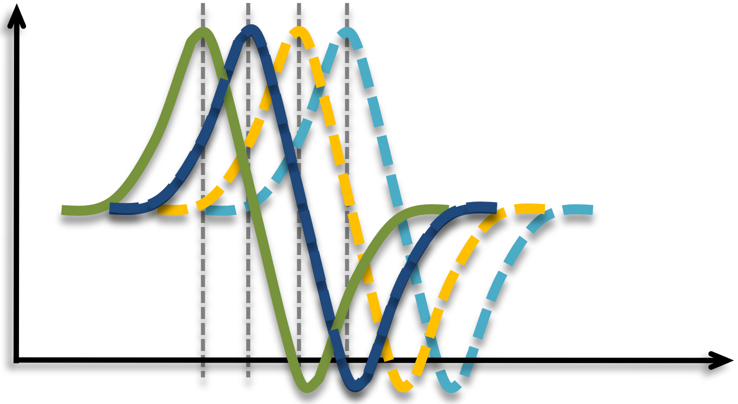
(II) Exposure to 1.0 mM Mercapto-Hexanol in aqueous solution

(III) Hybridization with Complementary DNA Solution (1.0 μM/1.0 M NaCl Tris-HCl 1.0 mM EDTA)

Experiments and Results

DNA Detection Mechanism





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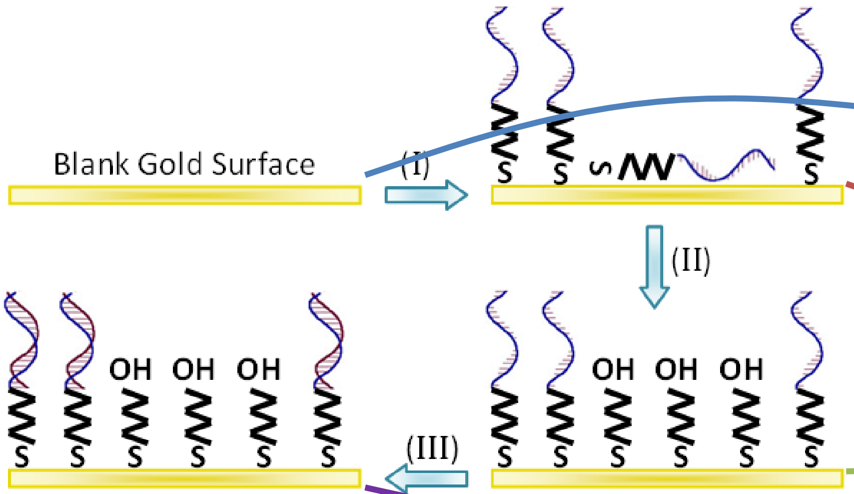
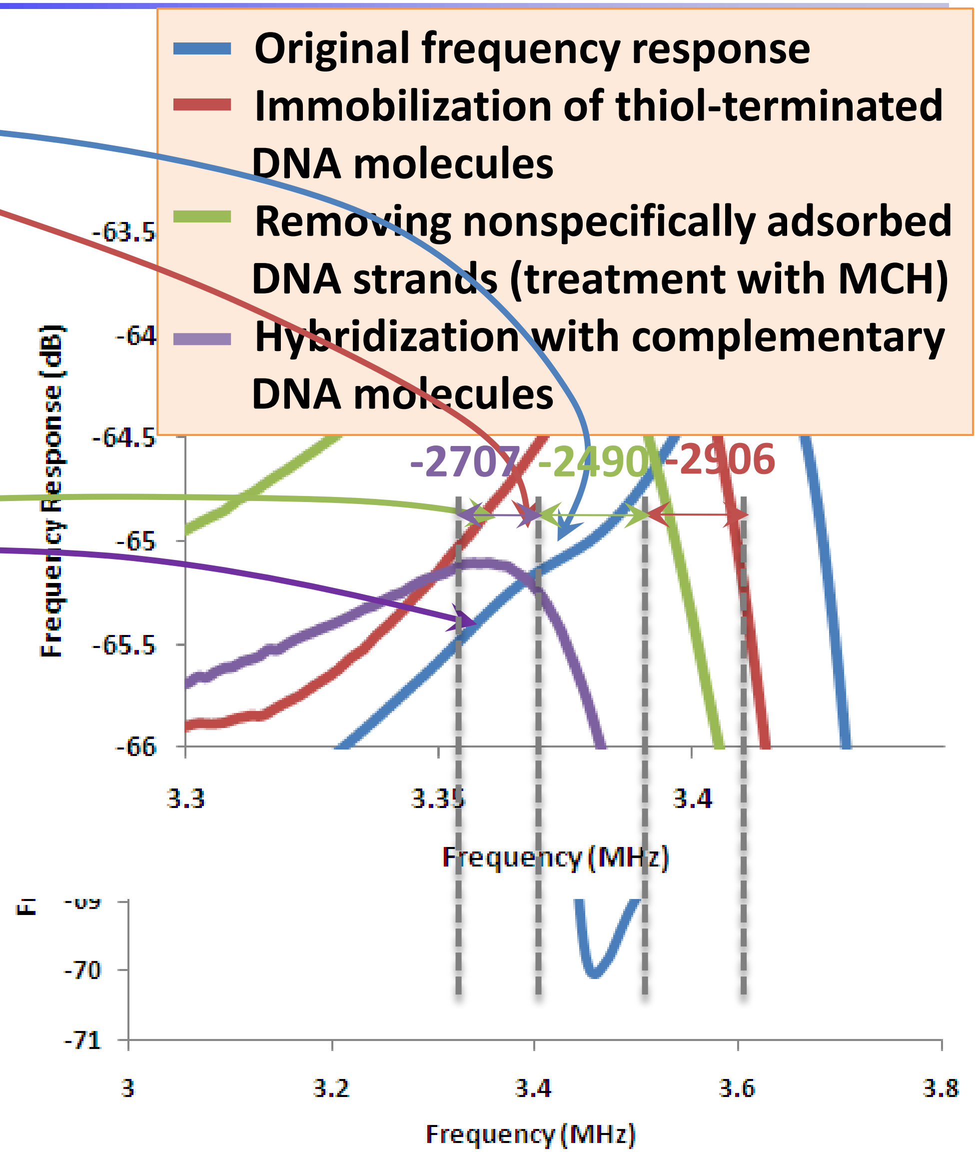




Thiol-terminated DNA

Entry	Sequence (65 mer DNA molecules)
(1)	5'-(HS-C$_6$)-CA GGA GTG TCA ACG CCA ATA TTC TCC TAG CCT GCA CAG ACA GTC GTG CTC TAC TAT GAC AAG GTT-3'
(2)	3'-AAC CTT GTC ATA GTA GAG CAC GAC TGT CTG TGC AGG CTA GGA GAA TAT TGG CGT TGA CAC TCC TG-5'

Complementary DNA

Gas Sensing: Detection of Volatile Organic Compounds

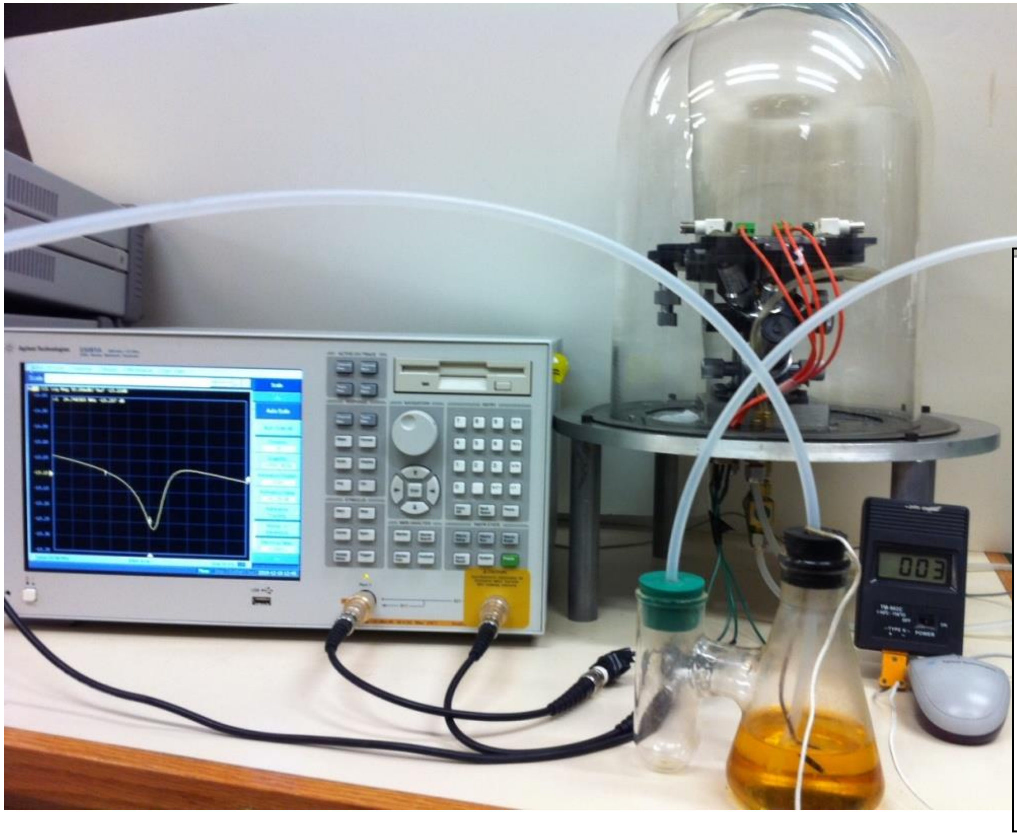
☐ Sensors capable of organic compounds detection in gas phase have numerous applications in oil and gas industry

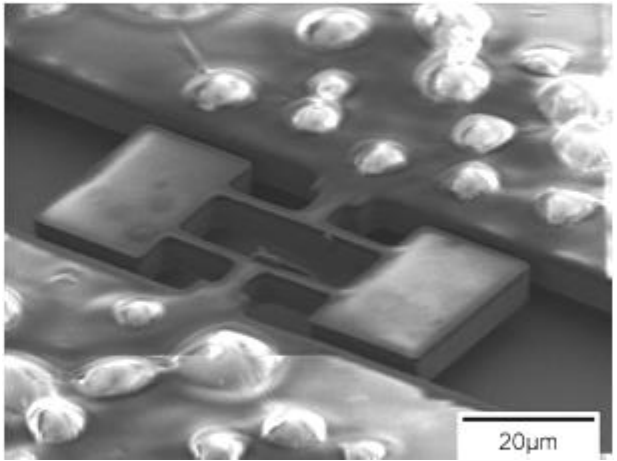
☐ Rapid estimation of oil content of oil sand samples and early detection of hazardous leaks

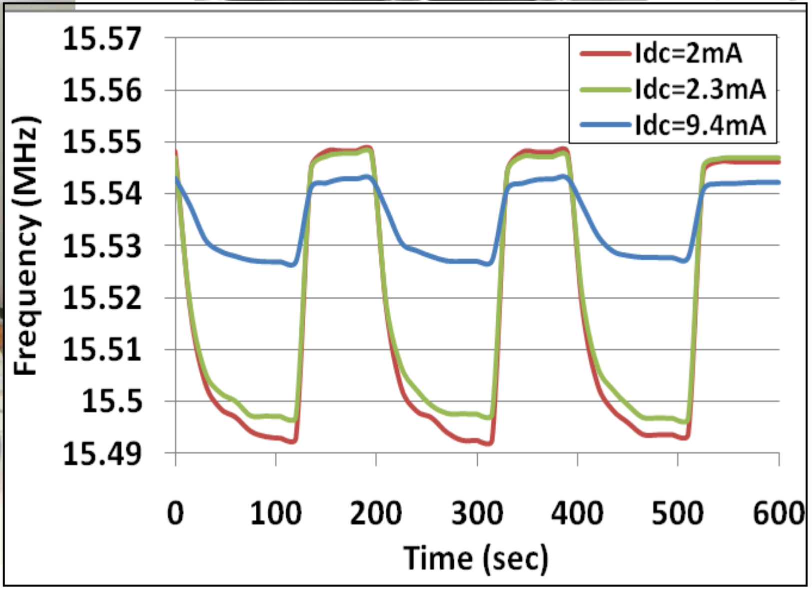
☐ Costly and time consuming process of using off-site laboratory analysis avoided

Detection of Gasoline Vapor

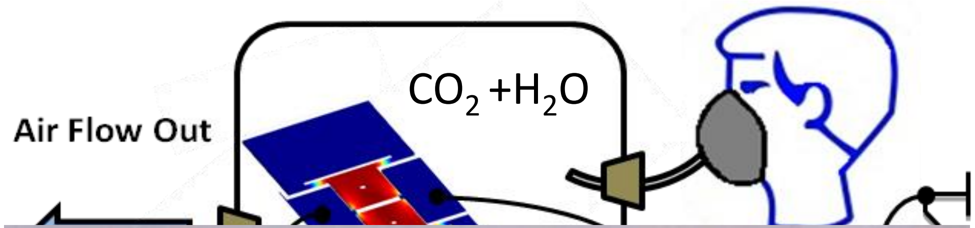
- ❑ Thin polymer coating to absorb organic vapors





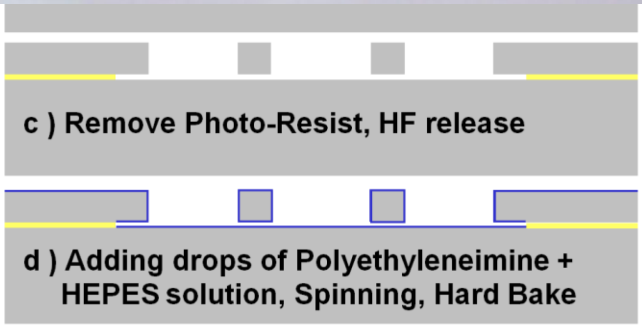


Disaster Survivor Detection!



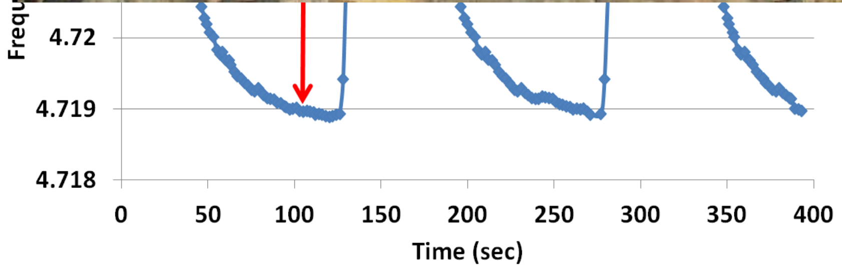
Resonator with poly-ethyleneimine (PEI) Coating

Terminator-Bot Search and Rescue Robot
Prof. Richard Voyles
University of Denver

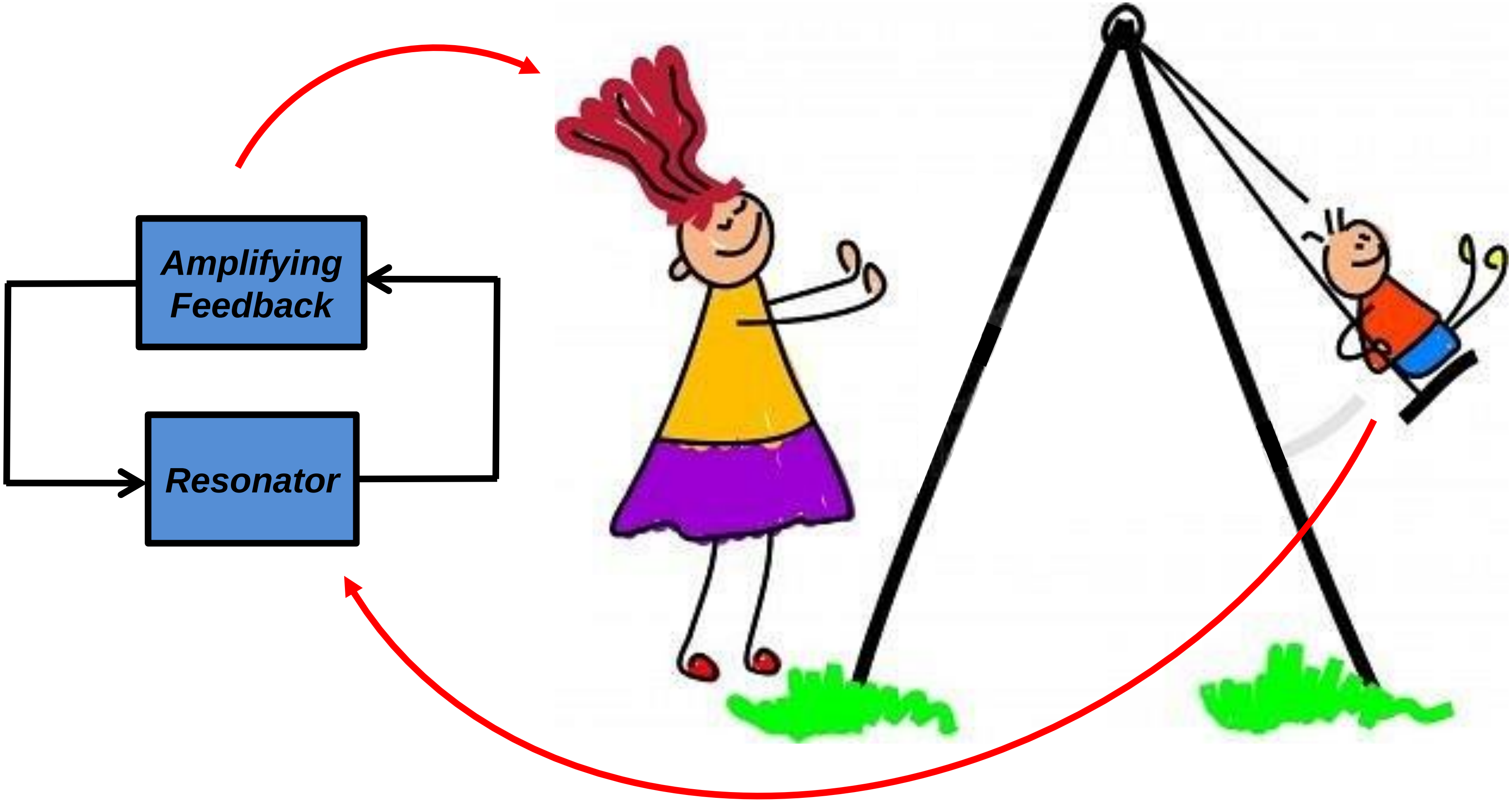


c) Remove Photo-Resist, HF release

d) Adding drops of Polyethyleneimine + HEPES solution, Spinning, Hard Bake



Oscillator vs. Resonator

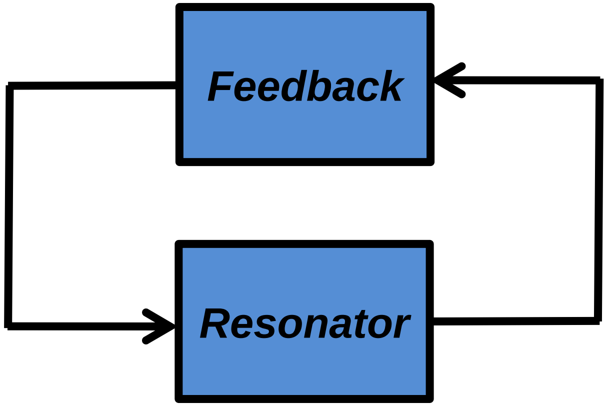


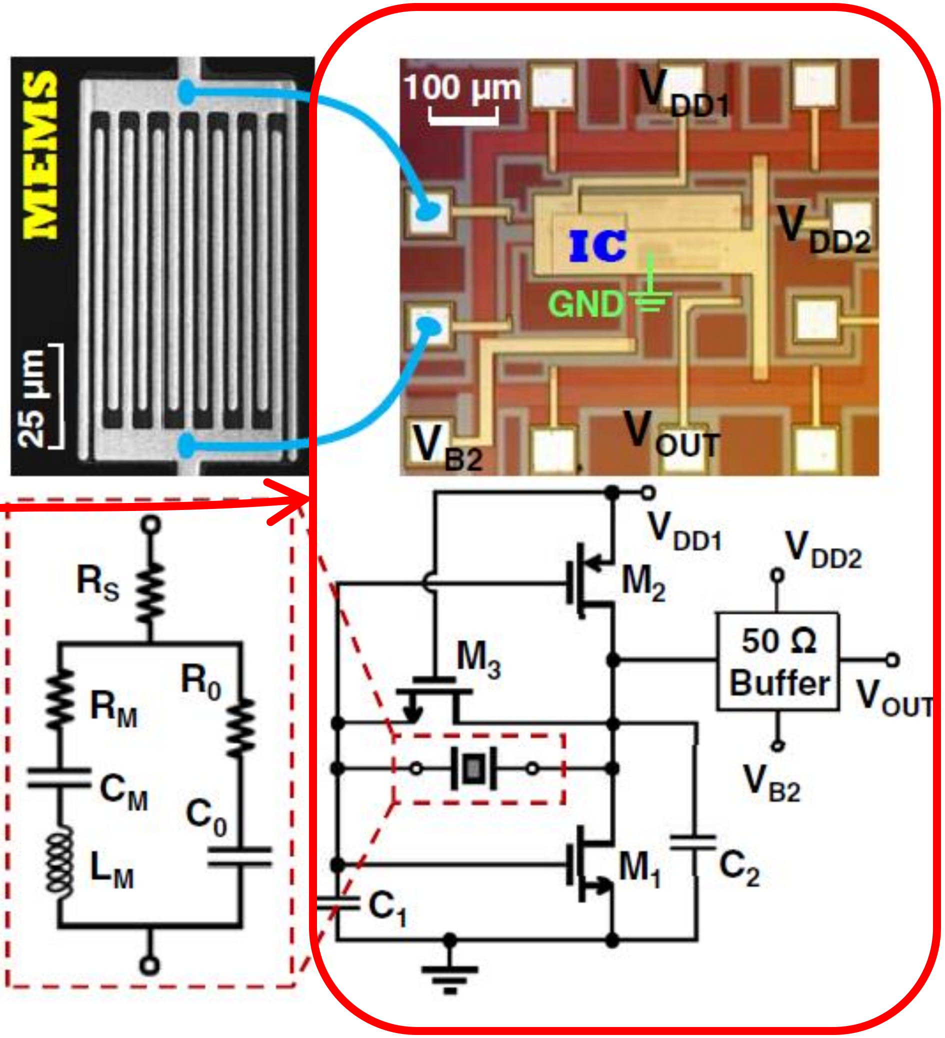
Amplifying Feedback

Resonator

Oscillation Requirement

- ❑ **Piezoelectric and Electrostatic MEMS Resonators (External Amplification)**

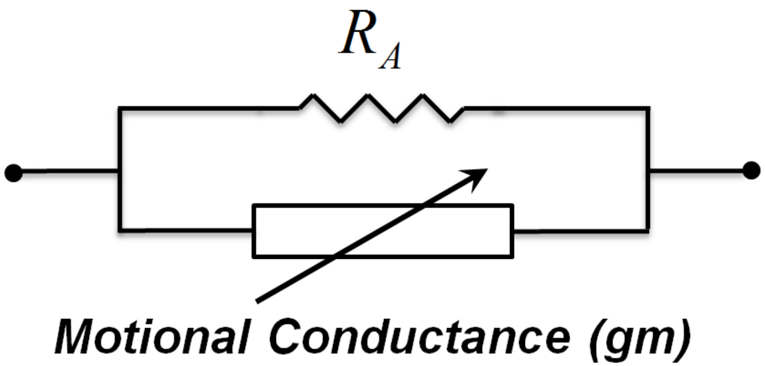




Chengjie Zuo; Van der Spiegel, J.; Piazza, G.; , "1.5-GHz CMOS voltage-controlled oscillator based on thickness-field-excited piezoelectric AlN contour-mode MEMS resonators," *Custom Integrated Circuits Conference (CICC), 2010 IEEE* , vol., no., pp.1-4, 19-22 Sept. 2010

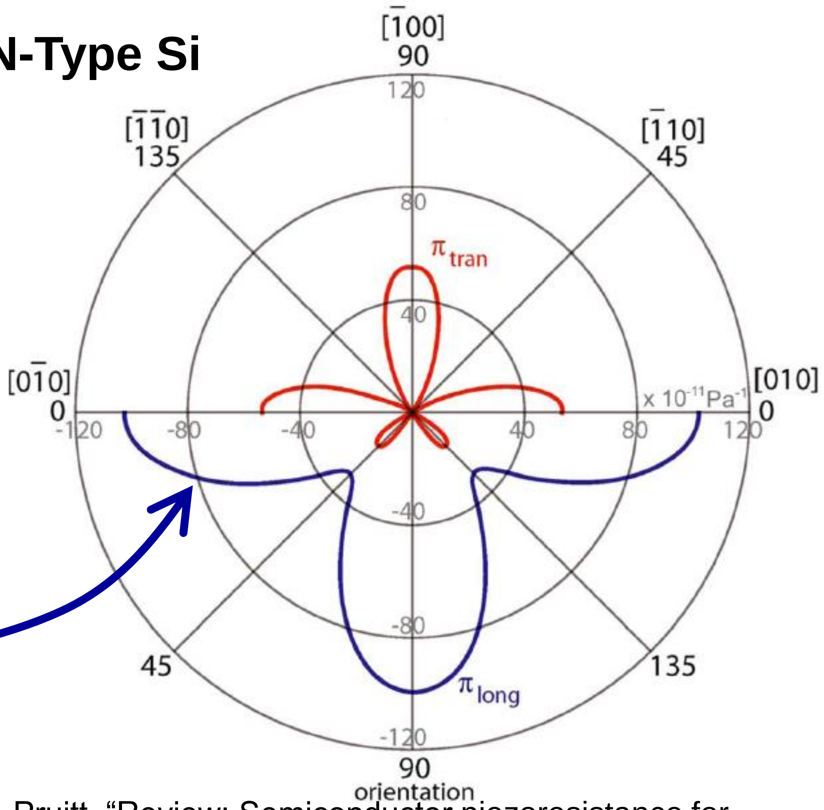
Positive Feedback Loop for Oscillation

- ❑ **Thermal- Piezoresistive Resonators (Internal Amplification)**



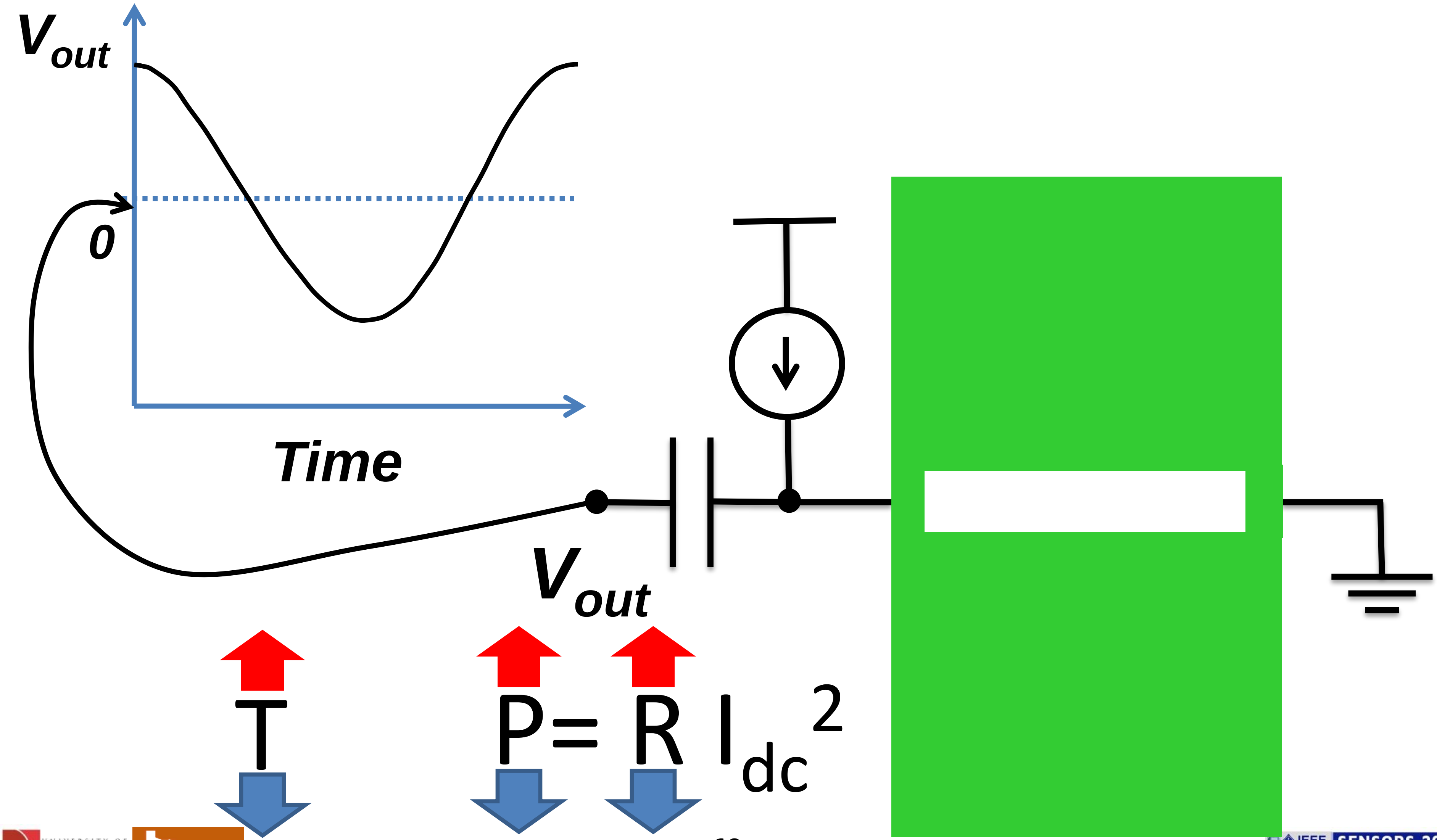
$$g_m = 4\alpha E^2 \pi_l Q \frac{A I_{dc}^2}{K L C_{th} \omega_m}$$

N-Type Si

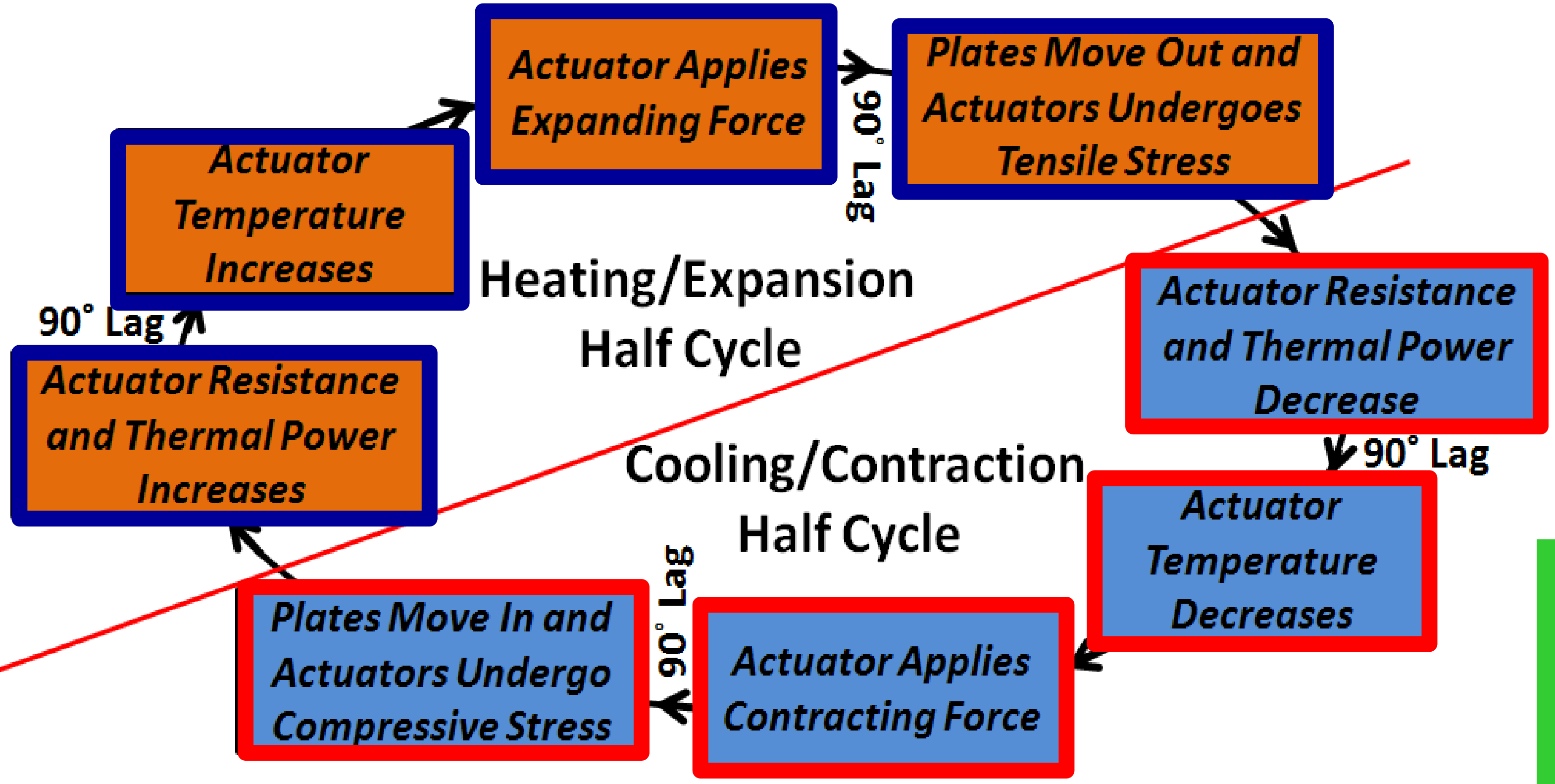


A.A. Barlian, W.-T. Park, J.R. Mallon, A.J. Rastegar, B.L. Pruitt, “Review: Semiconductor piezoresistance for microsystems”, *Proceedings of the IEEE*, vol. 97, no. 3, pp. 513-552, March. 2009.

Thermal-Piezoresistive Oscillation Concept



Thermal-Piezoresistive Oscillation Concept



Actuator Resistance and Thermal Power Increases

90° Lag

Actuator Temperature Increases

Actuator Applies Expanding Force

90° Lag

Plates Move Out and Actuators Undergoes Tensile Stress

Actuator Resistance and Thermal Power Decrease

90° Lag

Actuator Temperature Decreases

Actuator Applies Contracting Force

90° Lag

Plates Move In and Actuators Undergo Compressive Stress

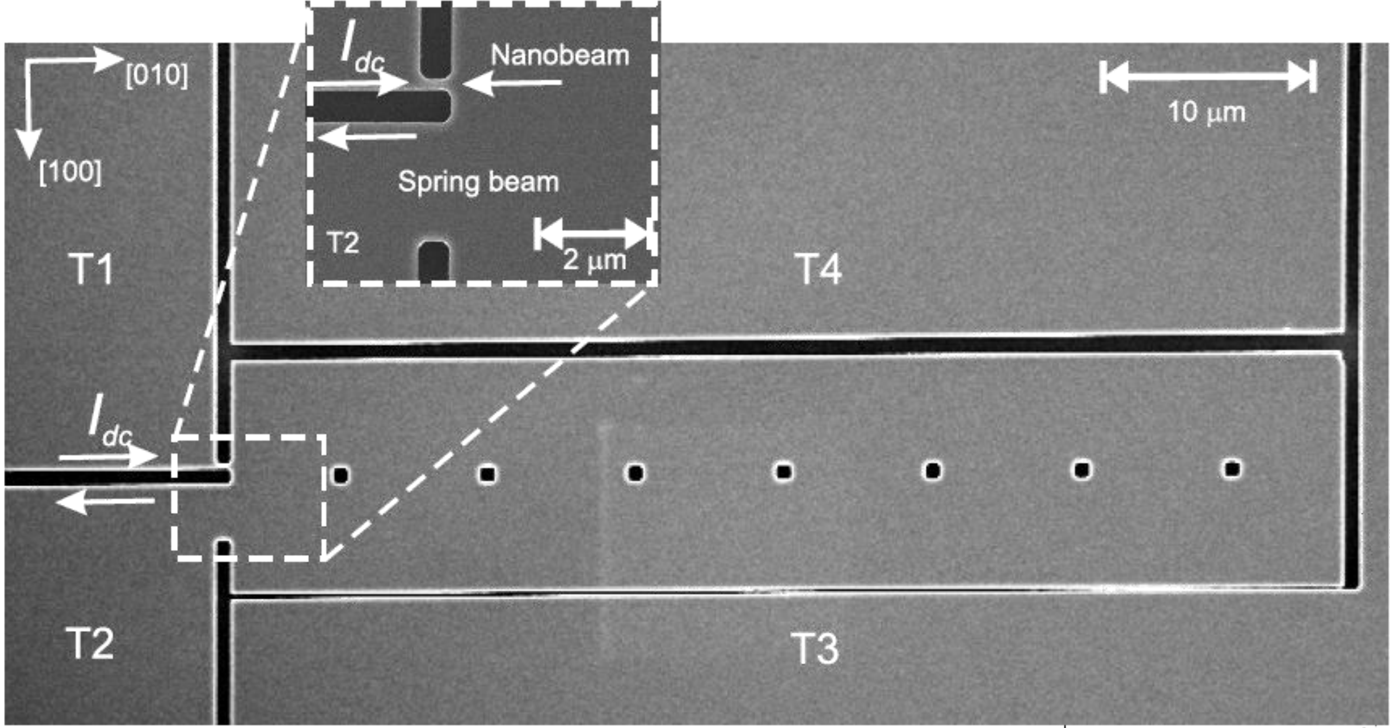
Heating/Expansion Half Cycle

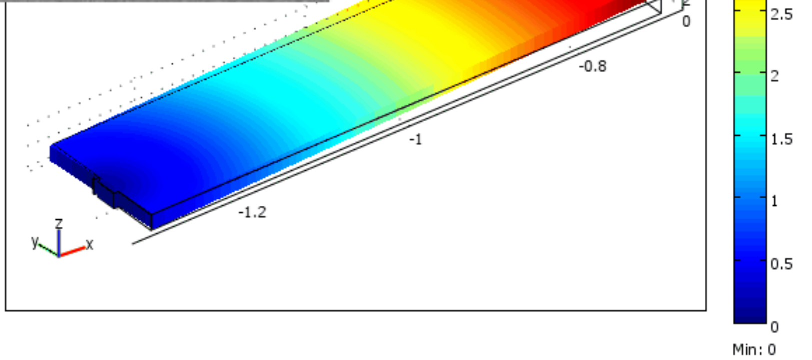
Cooling/Contraction Half Cycle

T

$$P = R\, I_{dc}^{2}$$

Previous Work from NXP SC



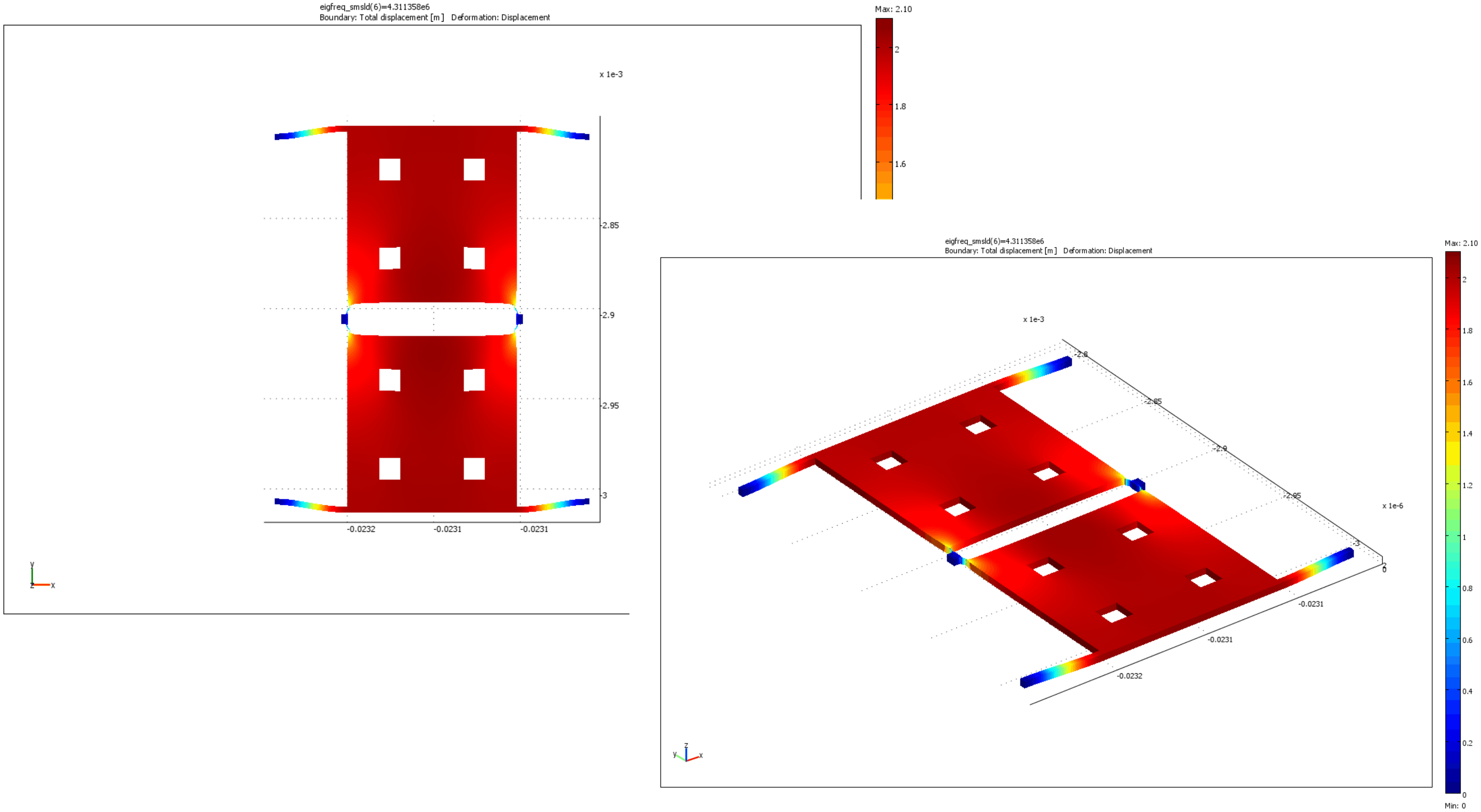


1.26MHz (Vacuum) ***I_{dc}= 1.20 mA***

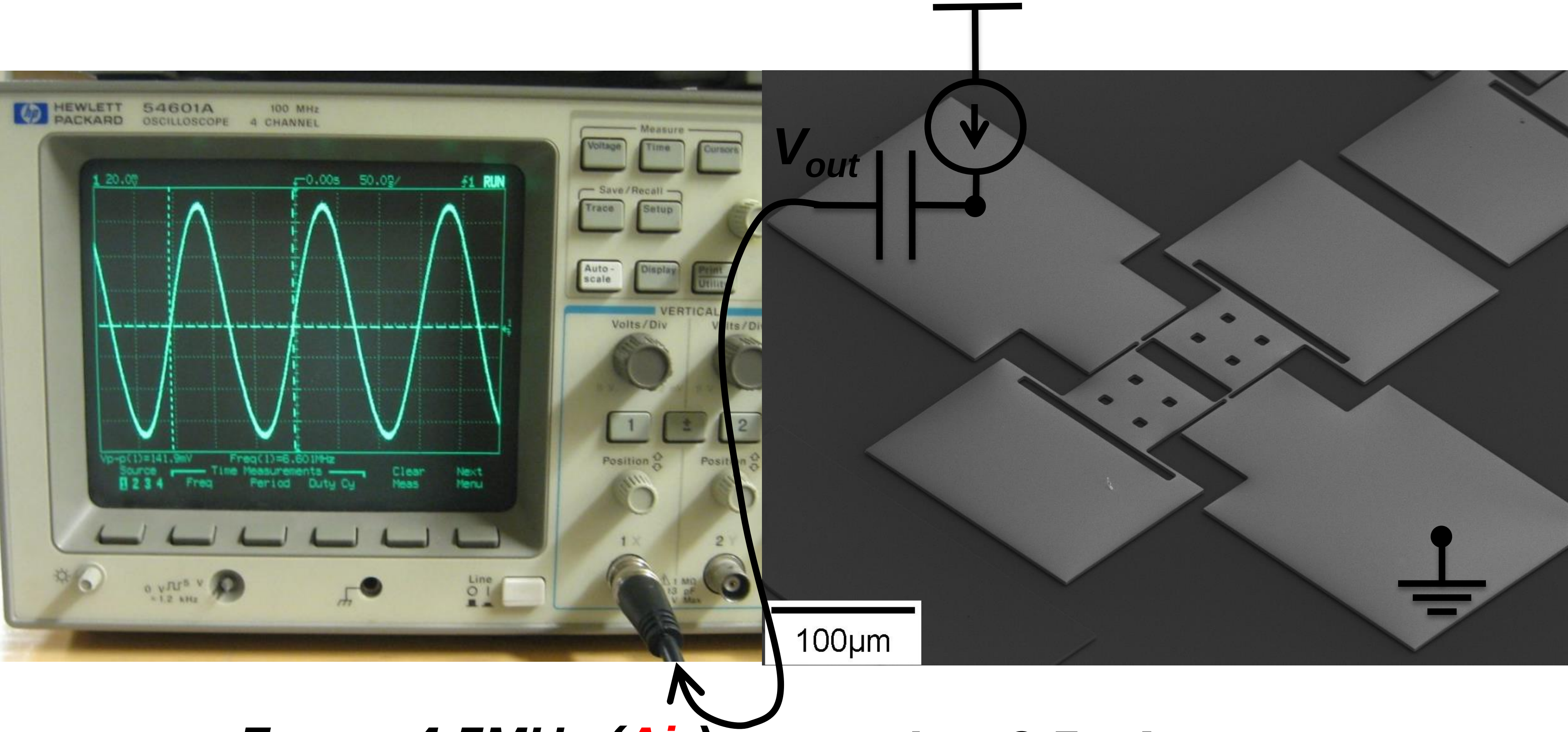
$V_{p\text{-}p}$= 54mV ***P_{dc}= 1.19mW***

K. L. Phan, P. G. Steeneken, M. J. Goossens, G. E.J. Koops, G. J.A.M. Verheijden and J.T.M.v. Beek, "Spontaneous mechanical oscillation of a DC driven single crystal, "to be published, http://arxiv.org/abs/0904.3748 (2009).

Fabricated Thermal-Piezoresistive Resonator



Oscillation Results



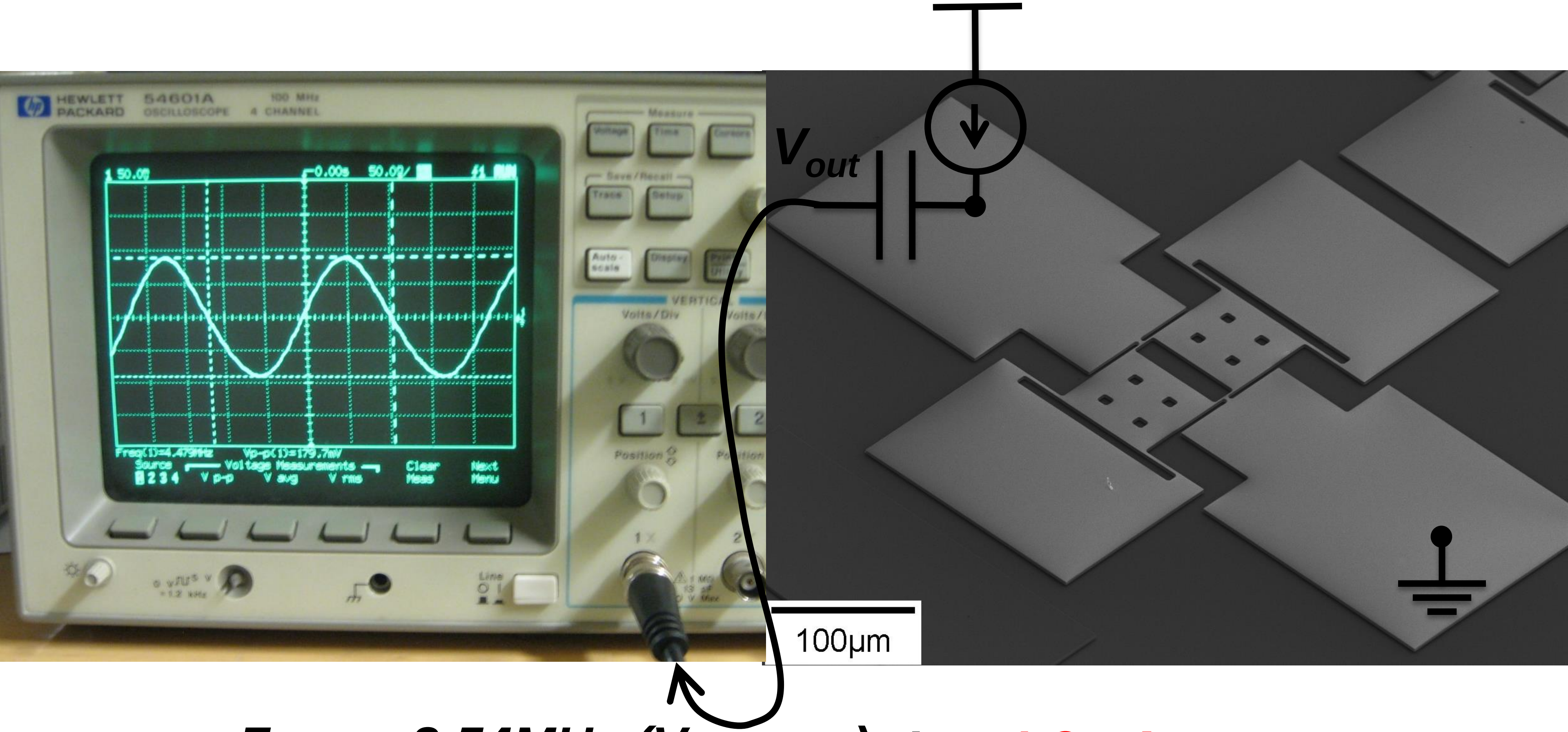
Freq.= 4.5MHz (Air)

$V_{p\text{-}p}$= 400mV

I_{dc}= 3.5mA

P= 23.2mW

Oscillation Results

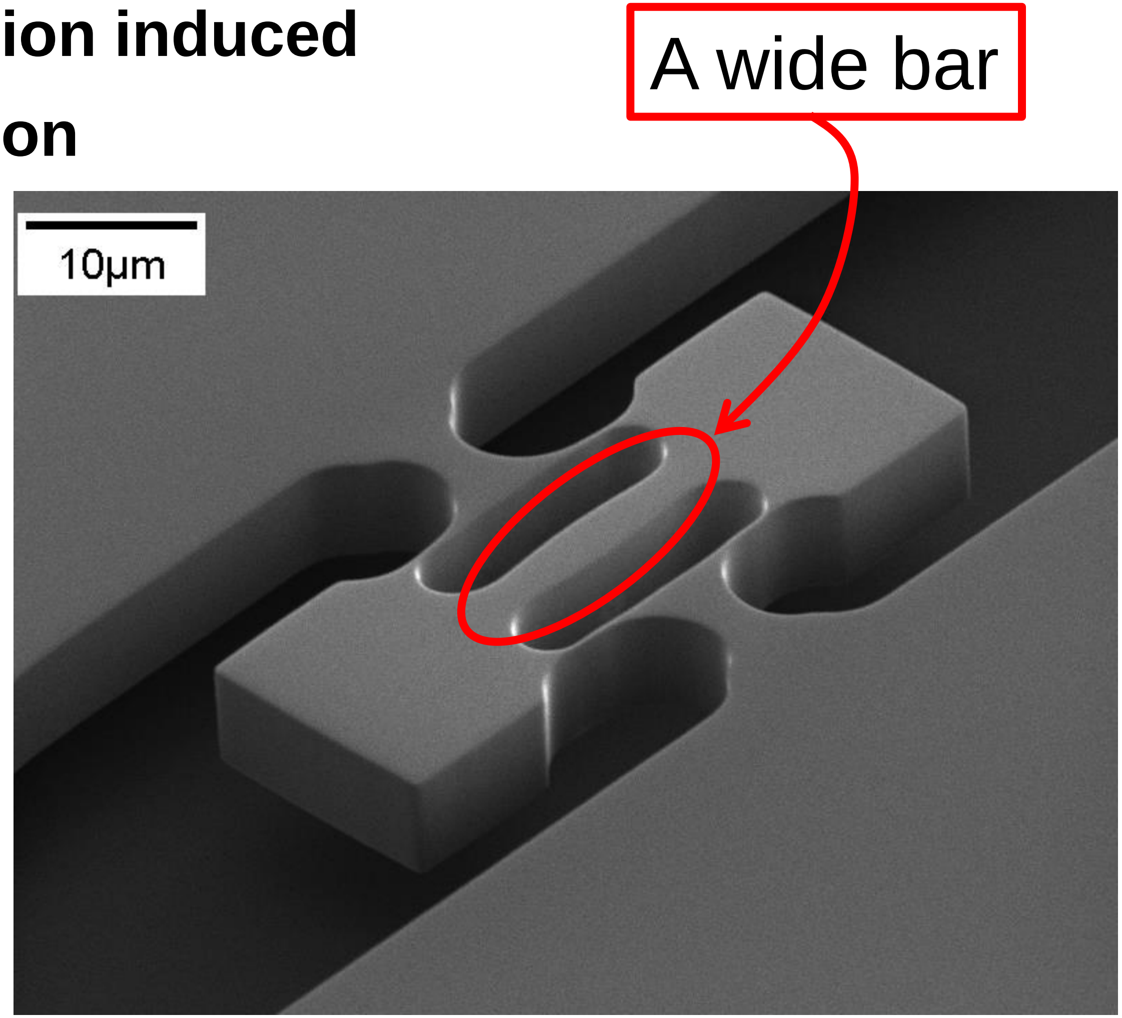


Freq.= 3.54MHz (Vacuum) **I_{dc}= 1.2mA**

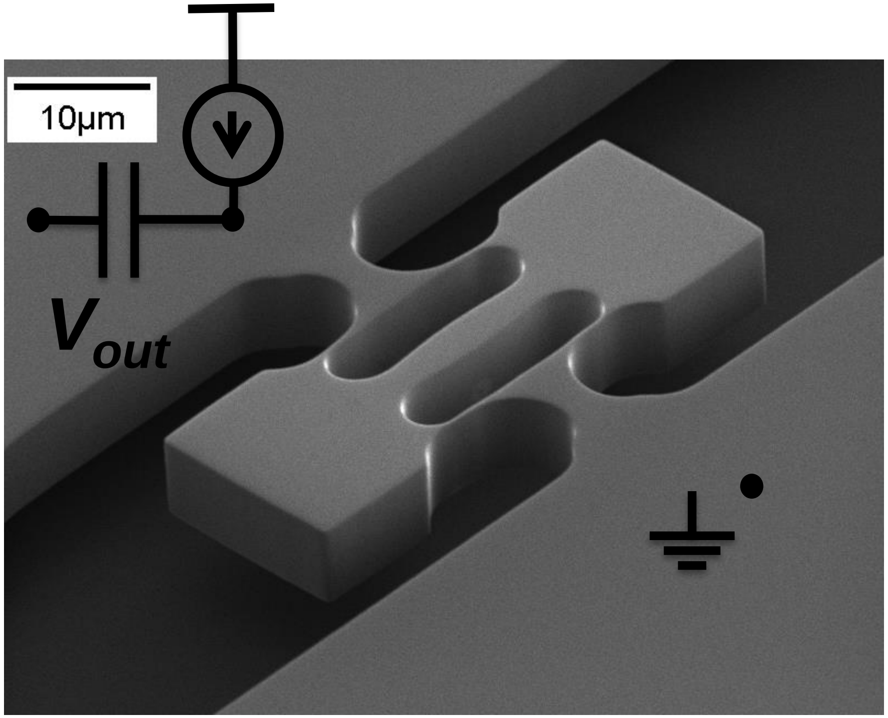
$V_{p\text{-}p}$= 138mV **P= 2.34mW**

Higher Frequency Oscillation

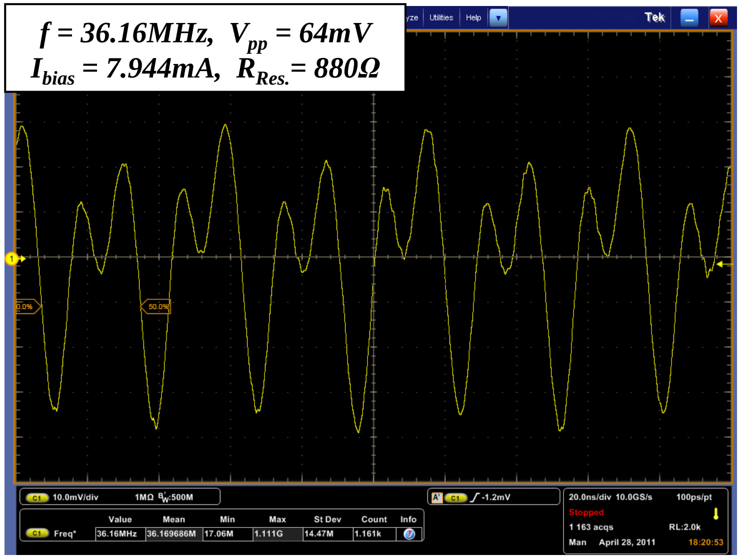
- ☐ **Higher oscillation frequency**
- ☐ **Lower fabrication induced frequency variation**



Oscillation Results



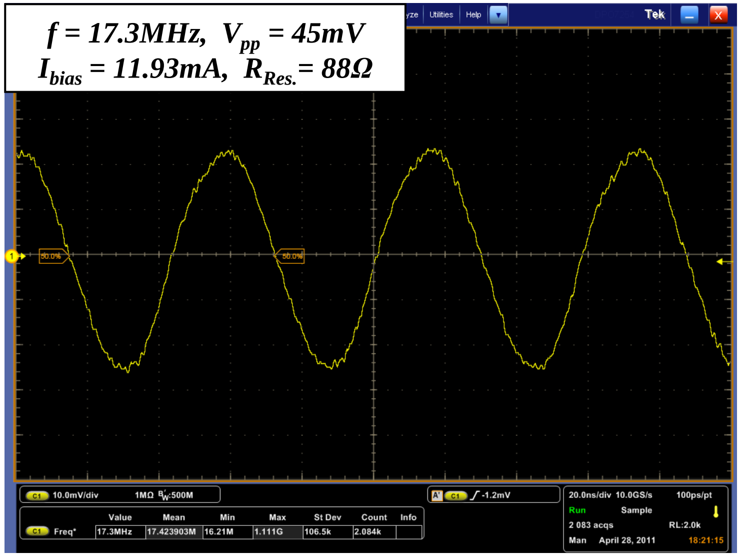
$f = 36.16MHz$, $V_{pp} = 64mV$
$I_{bias} = 7.944mA$, $R_{Res.} = 880\Omega$



	Value	Mean	Min	Max	St Dev	Count	Info
C1 Freq*	36.16MHz	36.169686M	17.06M	1.111G	14.47M	1.161k	

20.0ns/div 10.0GS/s 100ps/pt
Stopped
1 163 acqs RL:2.0k
Man April 28, 2011 18:20:53

$f = 17.3MHz$, $V_{pp} = 45mV$
$I_{bias} = 11.93mA$, $R_{Res.} = 88\Omega$

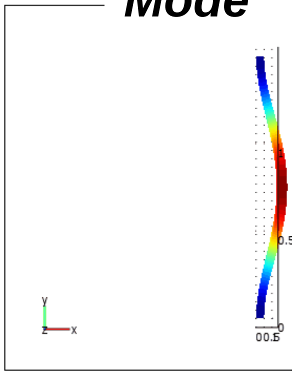


	Value	Mean	Min	Max	St Dev	Count	Info
C1 Freq*	17.3MHz	17.423903M	16.21M	1.111G	106.5k	2.084k	

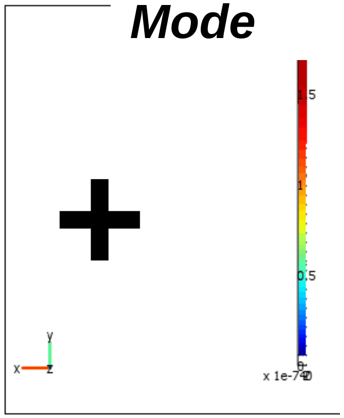
20.0ns/div 10.0GS/s 100ps/pt
Run Sample
2 083 acqs RL:2.0k
Man April 28, 2011 18:21:15

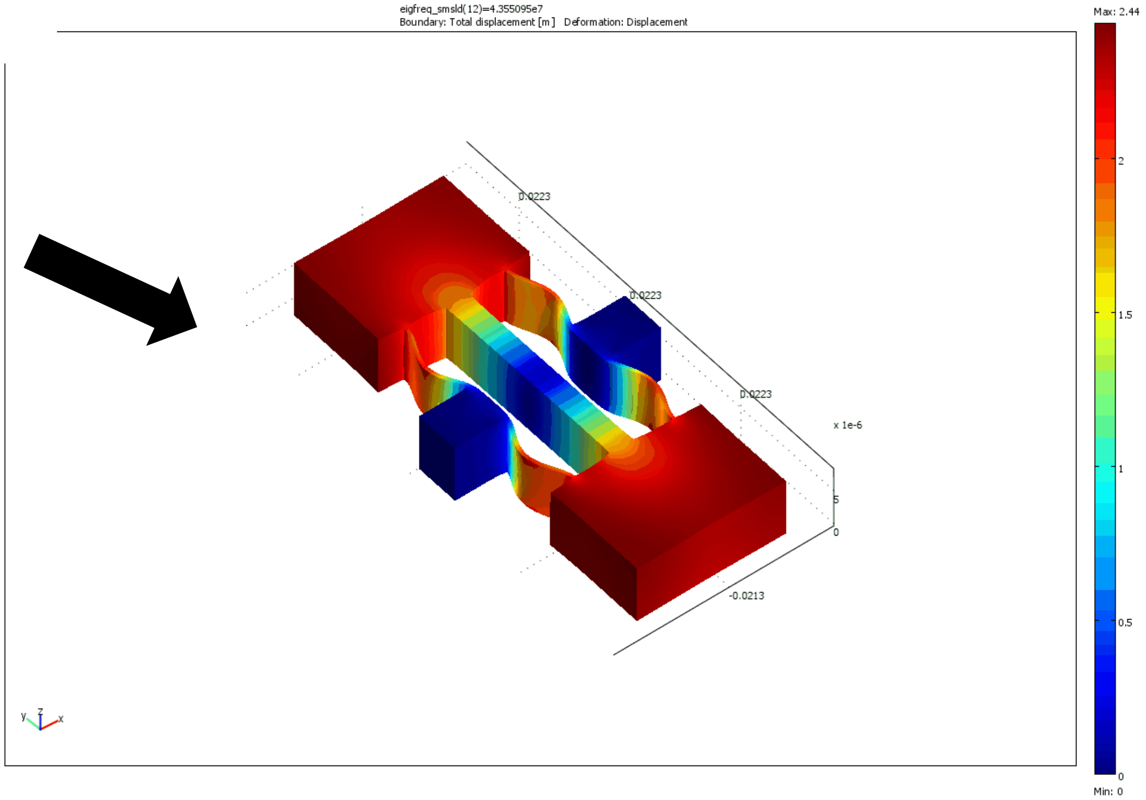
Nonlinear Flexures In Thin Actuators

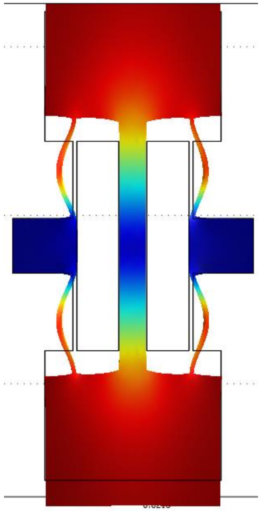
Flexural Mode



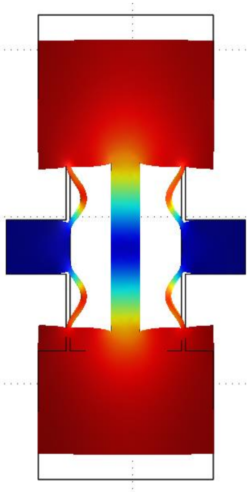
Extensional Mode





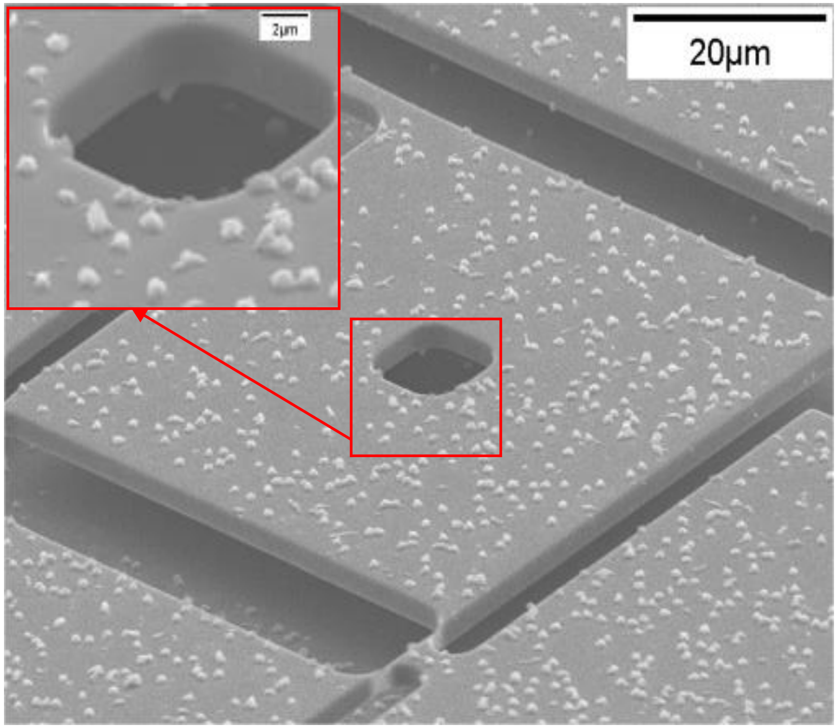


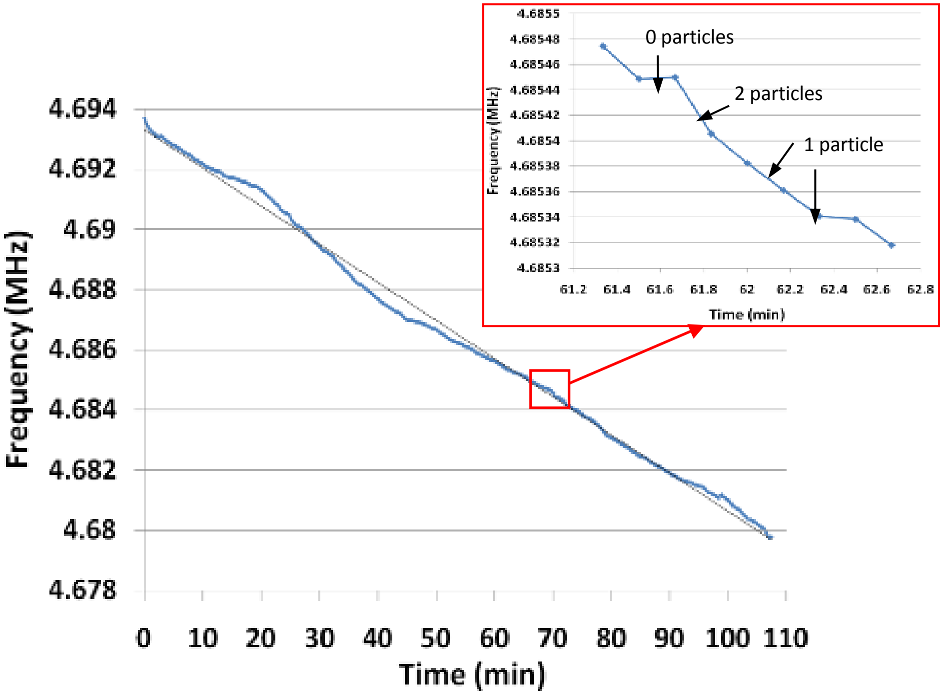
Maximum Elongation



Maximum Compression

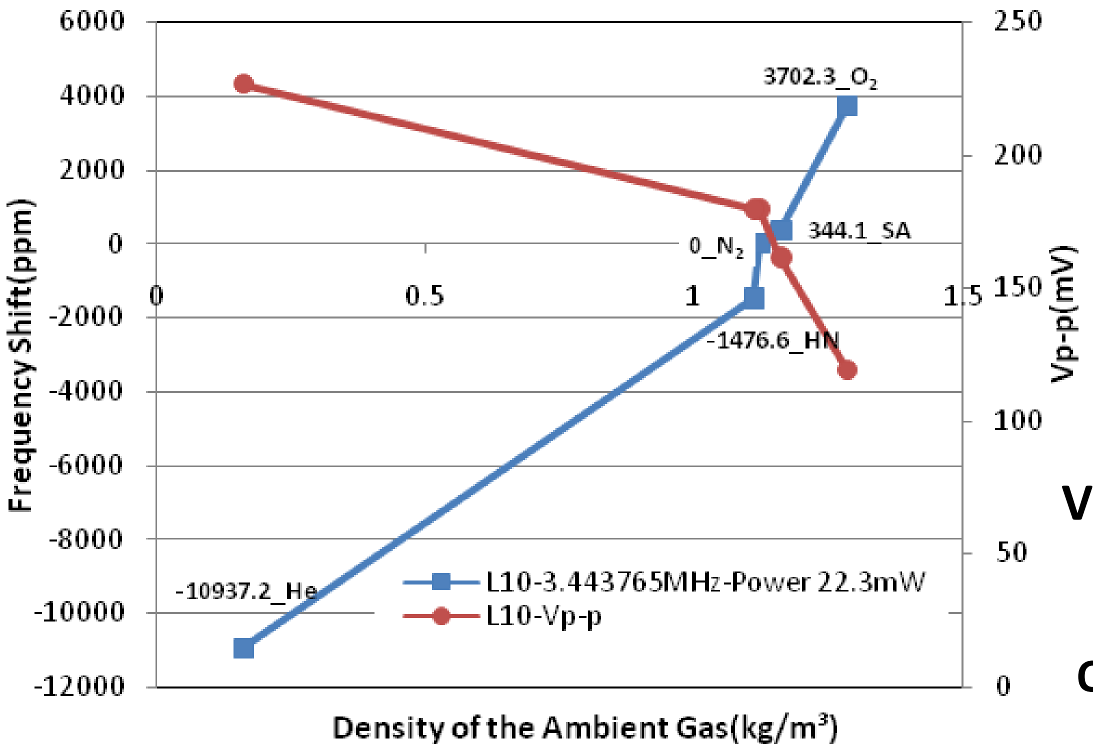
Self-Oscillating Sensor Measurement Results





Overall Quantized Frequency Shift of 14.1kHz (3000 ppm)

Response to Different Gases



Measure the frequency shift of TPO in different gases

Gas Density
(gas damping ‘*c*’) ↑

↓

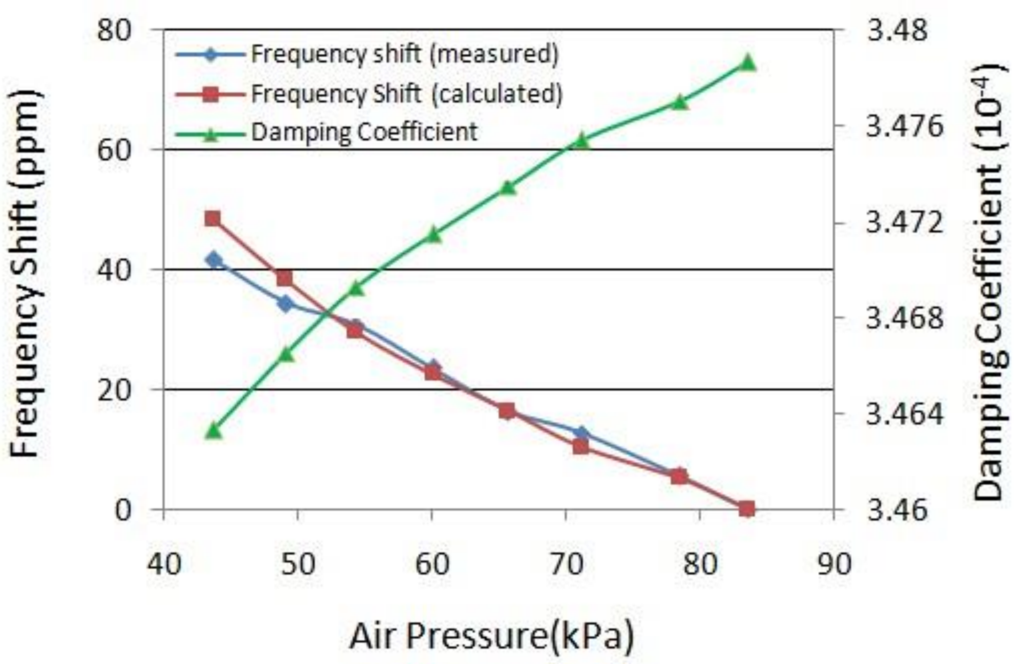
Frequency
‘*f*’ ↑
&
Vp-p /Vibration Amplitude ↓

Opposite trend of *f* vs. *c* !!!

Why?

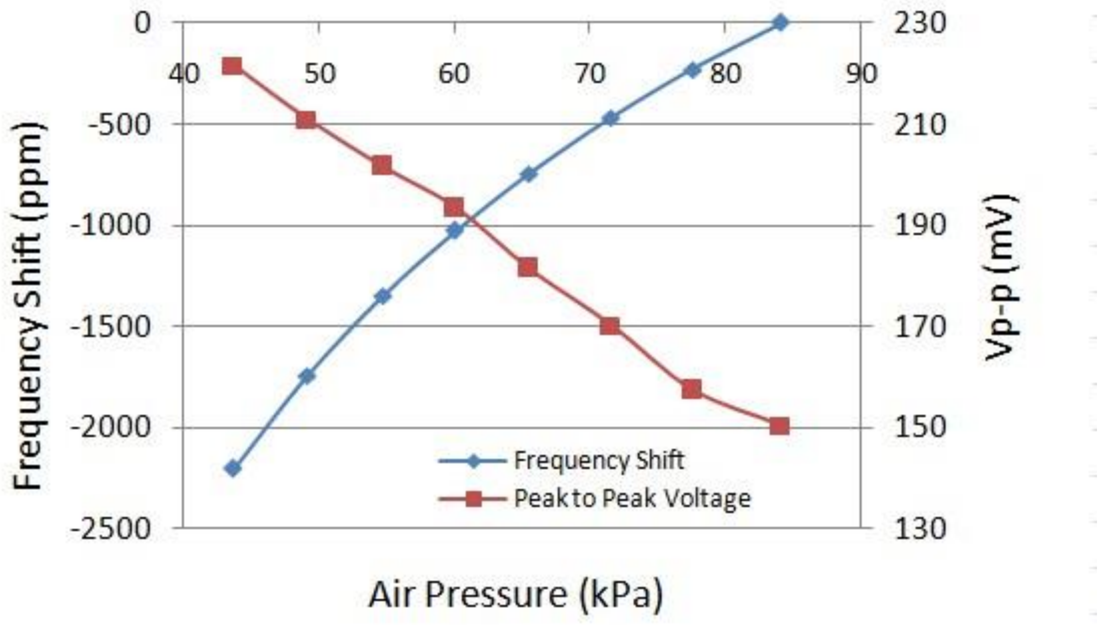
"Gas sensing using thermally actuated dual plate resonators and self-sustained oscillators," Xiaobo Guo, A. Rahafrooz, Yun-bo Yi and S. Pourkamali, 2012 IEEE International Frequency Control Symposium (IFCS 2012).

Measurement Result (TPR)



- Frequency 3.465MHz with power consumption of 0.44mW and a 0.21mA DC
- **Opposite** frequency shift to the TPO under the same pressure change
- Δf **42ppm**, changing the ambient air pressure from 84kPa to 43kPa, **about 50X smaller**
- The damping coefficient in different ambient air pressure is calculated from Eq.(3). They are used to calculate the frequency shift of the TPR.

Pressure Sensing



- Frequency 3.456MHz with power consumption 9.10mW

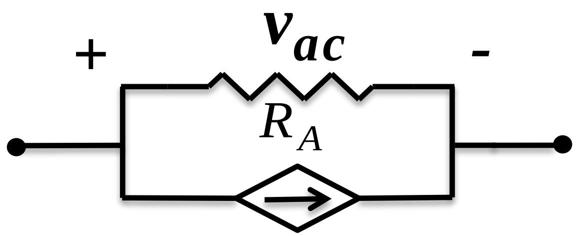
- Higher ambient air pressure, higher damping, lower vibration amplitude (Vp-p) with higher k and higher frequency

- Δf **-2300ppm**, changing the ambient air pressure from **84kPa to 43kPa**

Trans-Conductance Electrical Model

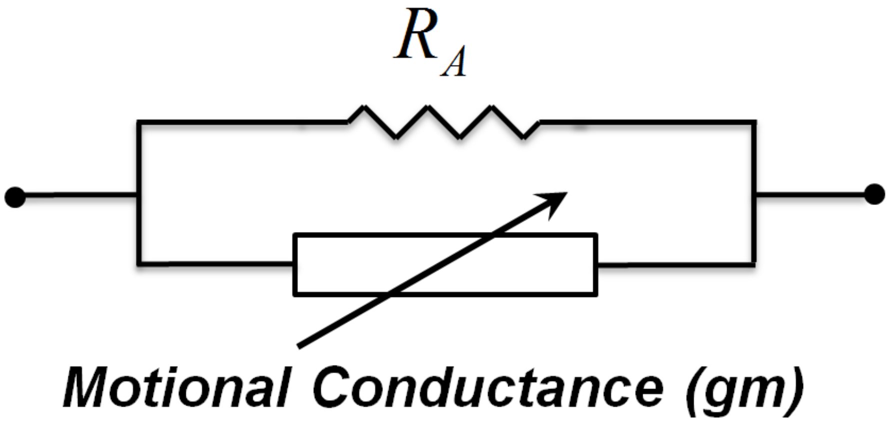
Overall Equivalent Electrical Circuit at resonance

$$H_T\Big|_{s=j\omega_0} = \boxed{g_m} = \frac{i_m}{v_a} = 4\alpha E^2 \boxed{\pi_l} Q \frac{AI_{dc}^2}{KLC_{th}\omega_m}$$



$$i_{ac} = g_m v_{ac}$$

Oscillation Condition in Thermal Resonators



$$g_m = 4\alpha E^2 \pi_l Q \frac{A I_{dc}^2}{K L C_{th} \omega_m}$$

$$g_m + R_A^{-1} < 0 \Rightarrow -g_m R_A > 1 \Rightarrow P_{dc} > -\frac{K L C_{th} \omega_m}{4\alpha E^2 \pi_l Q A}$$

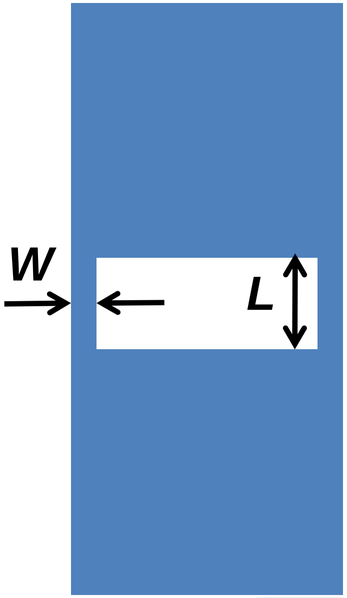
$$\Rightarrow P_{dc_{Min}} = \frac{K L C_{th} \omega_m}{4\alpha E^2 |\pi_l| Q A}$$

Oscillator Optimization

Scaling a Resonator:

$$P_{dc_{Min}} = \frac{\overset{\frac{A}{L}}{\boxed{K}}\, L\, \overset{LA}{\boxed{C_{th}}}\, \overset{\sqrt{\frac{A}{LM}}}{\boxed{\omega_m}}}{4\alpha E^2 \left|\pi_l\right| QA} \propto \frac{\overset{S^3}{A^{\frac{3}{2}}}\, \overset{S^{\frac{1}{2}}}{L^{\frac{1}{2}}}}{\underset{S^{\frac{3}{2}}}{M^{\frac{1}{2}}}} \propto S^2$$

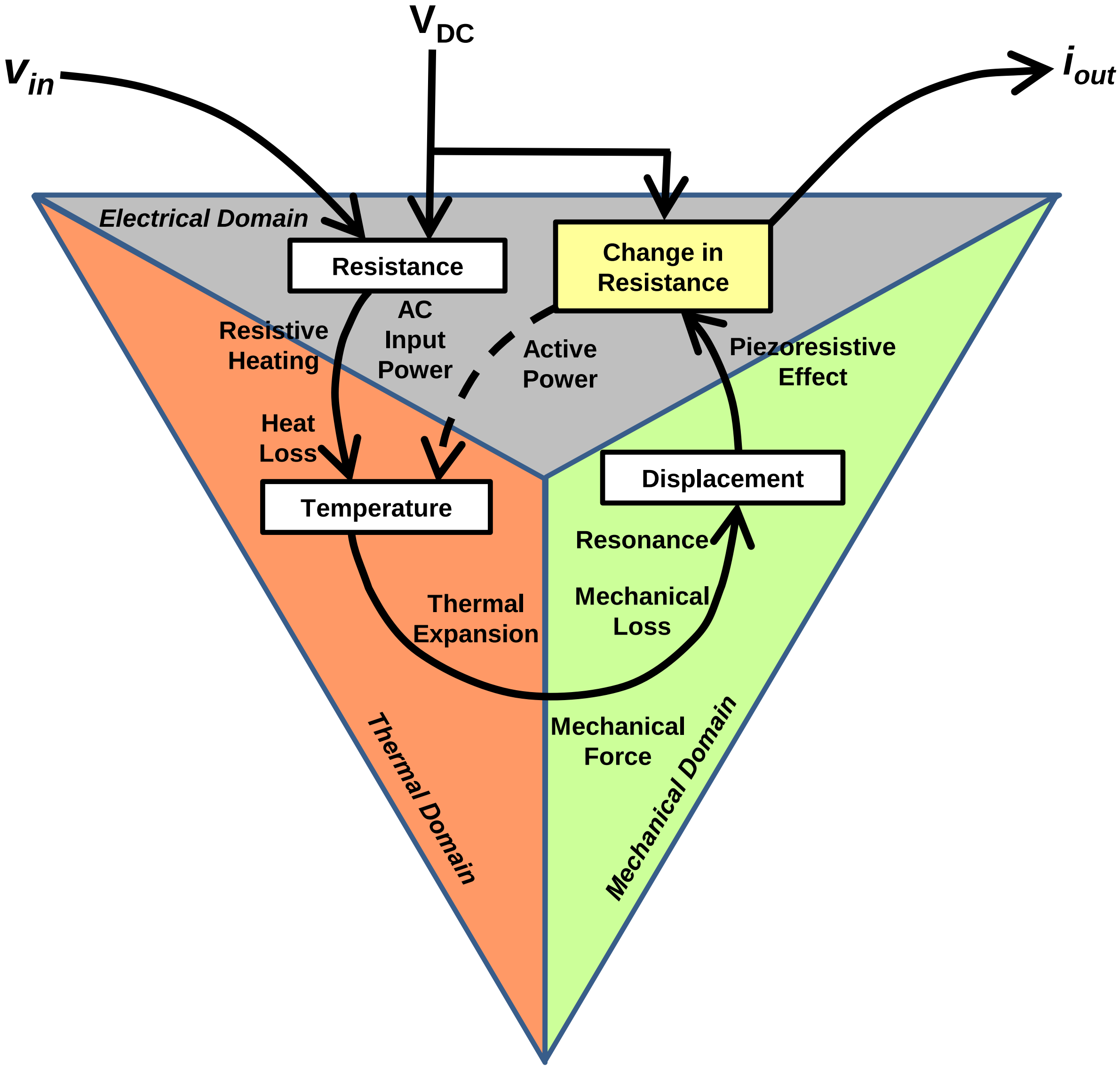
***S*: scaling ratio**



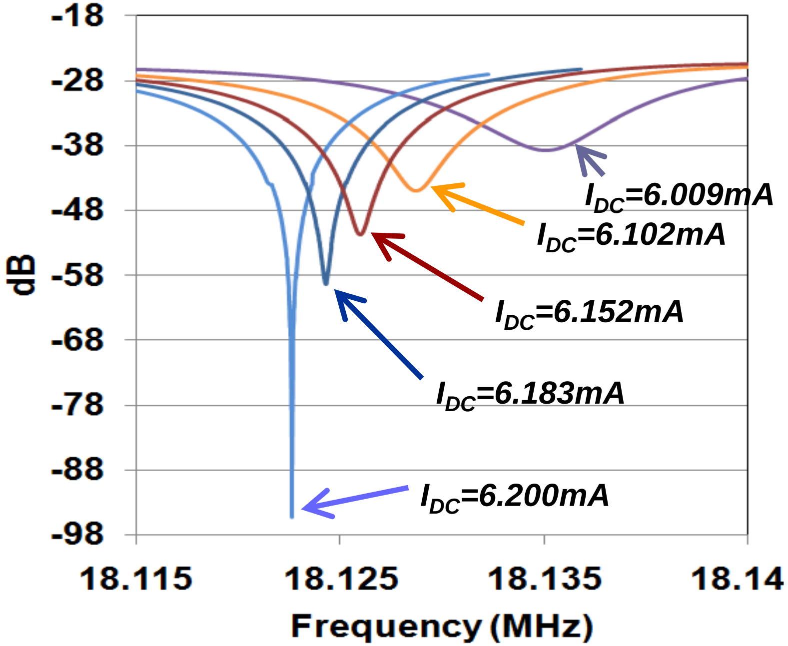
Optimizing at Constant Frequency:

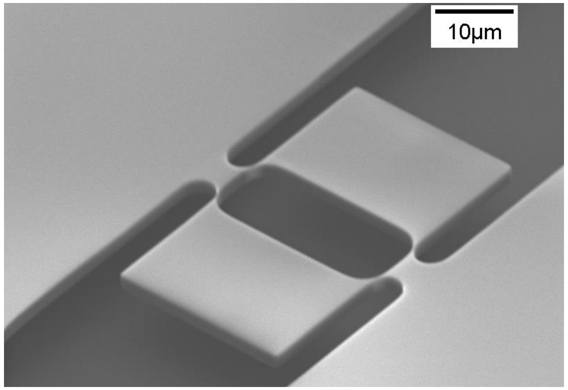
$$P_{dc_{Min}} \propto LA$$

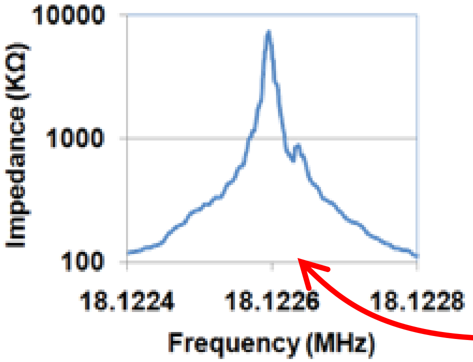
Internal Thermal-Piezoresistive Feedback

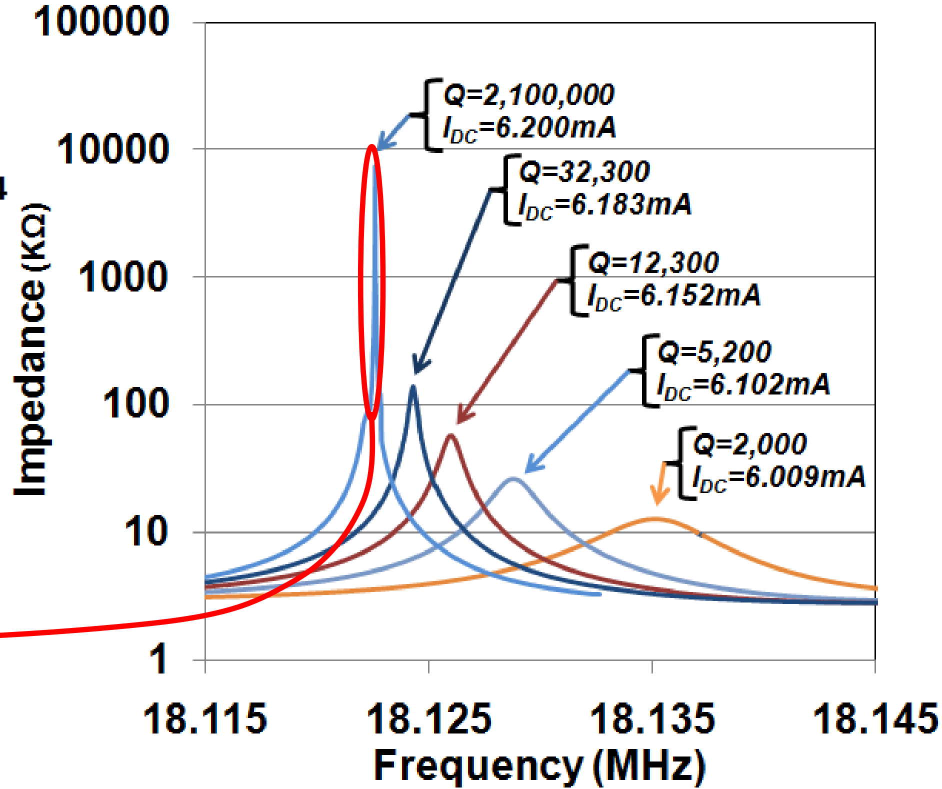


Self-Q-Enhancement



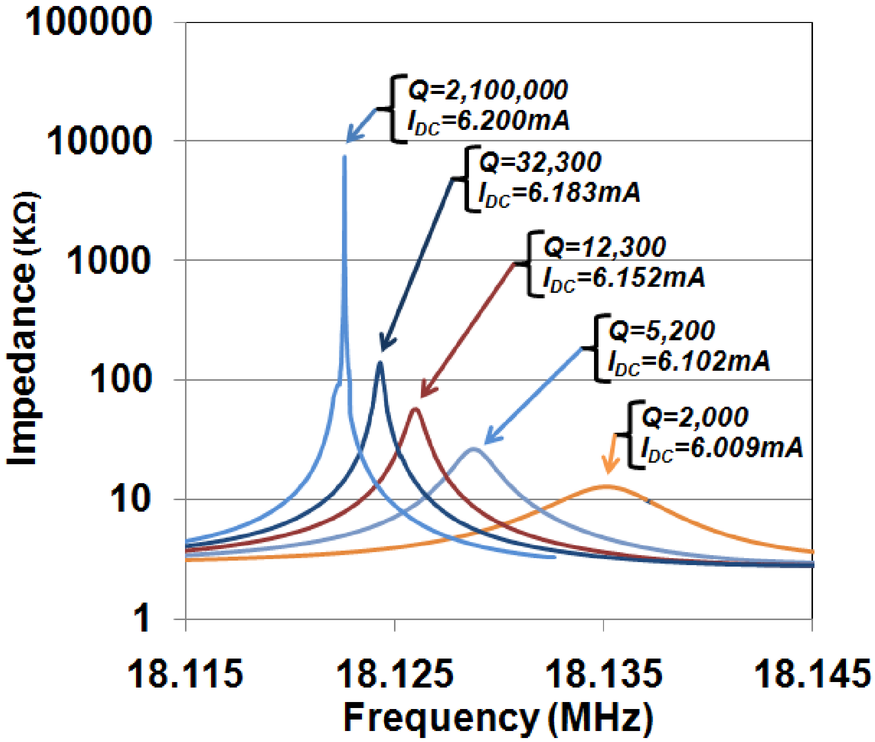


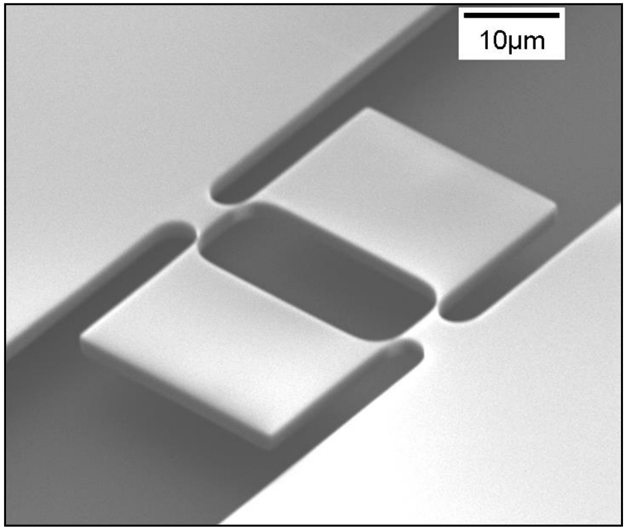


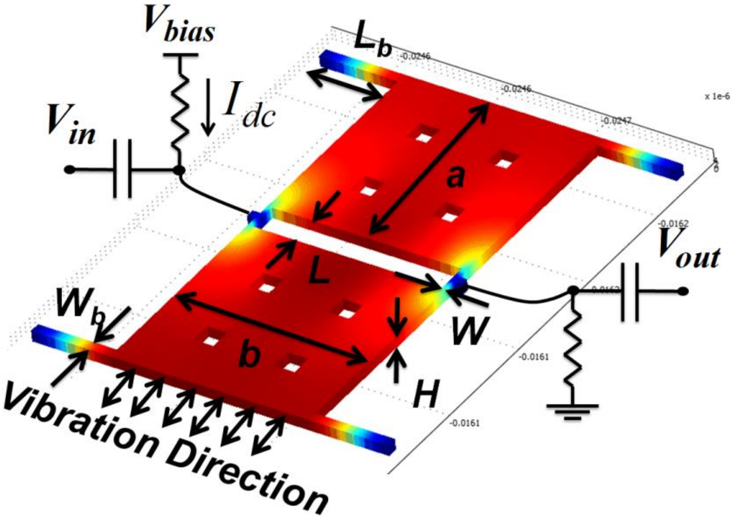


Self-Q-Amplification

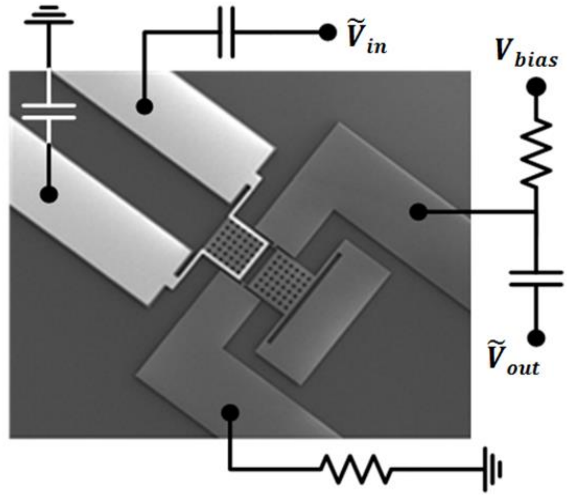
- ❑ Internal self-amplification can also be used for resonator Q-amplification

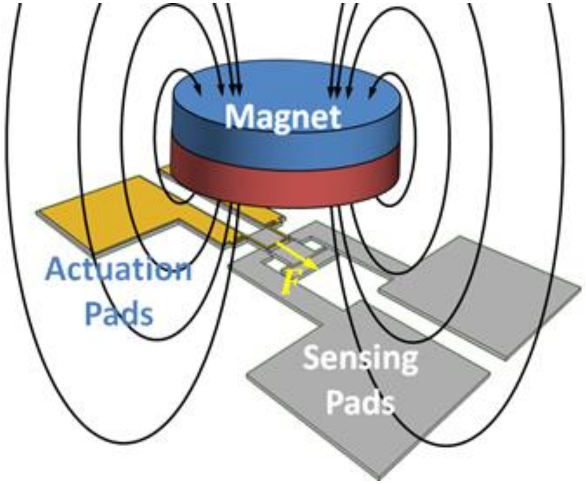


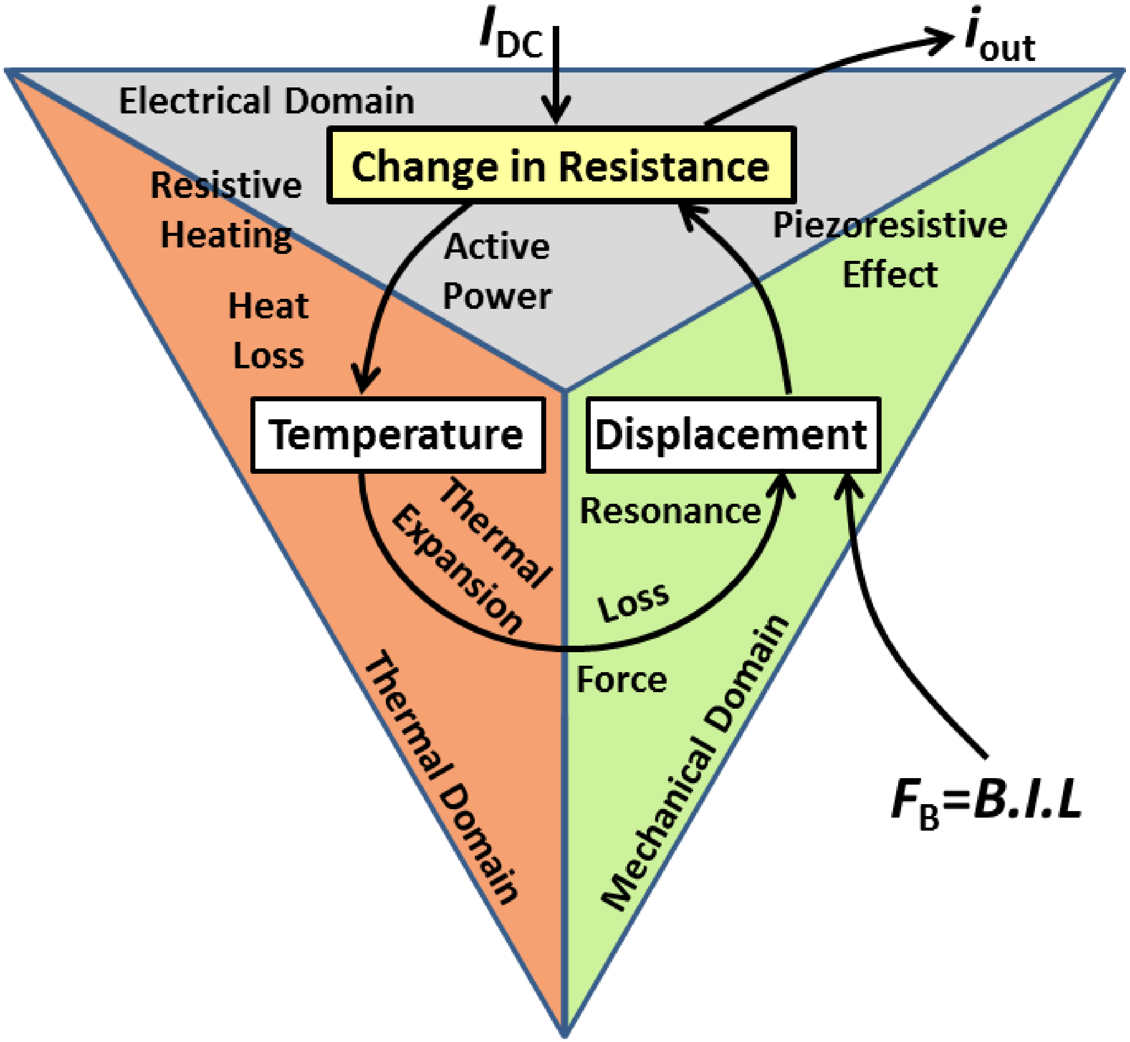




Magnetically Driven Resonator with Internal Amplification







I_{DC}

i_{out}

Electrical Domain

Change in Resistance

Resistive Heating

Active Power

Piezoresistive Effect

Heat Loss

Temperature

Displacement

Thermal Expansion

Resonance

Loss

Force

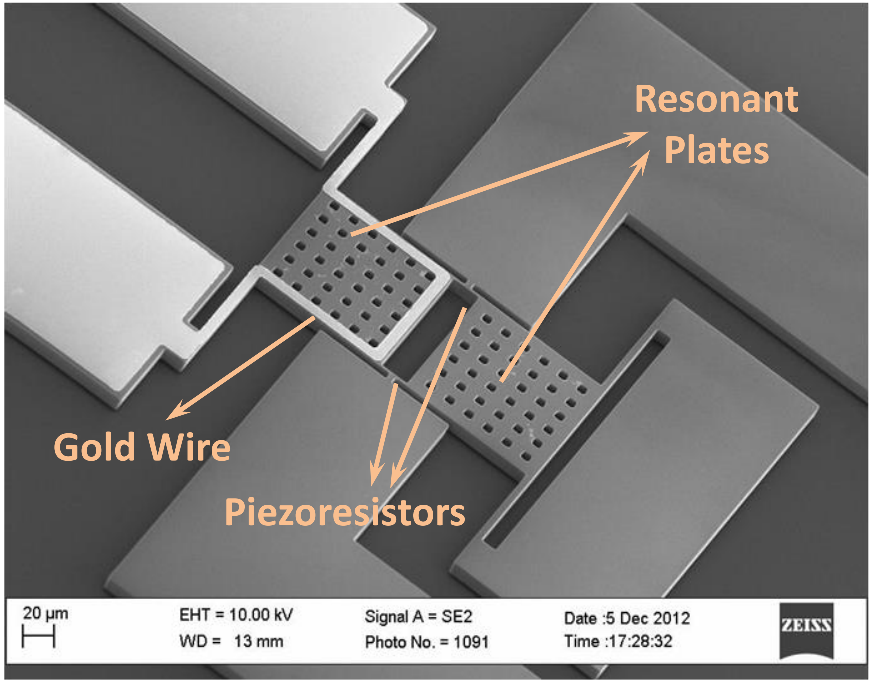
Thermal Domain

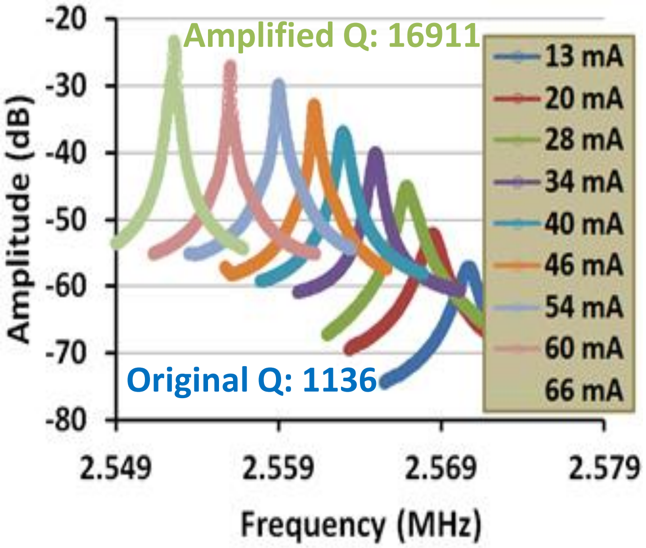
Mechanical Domain

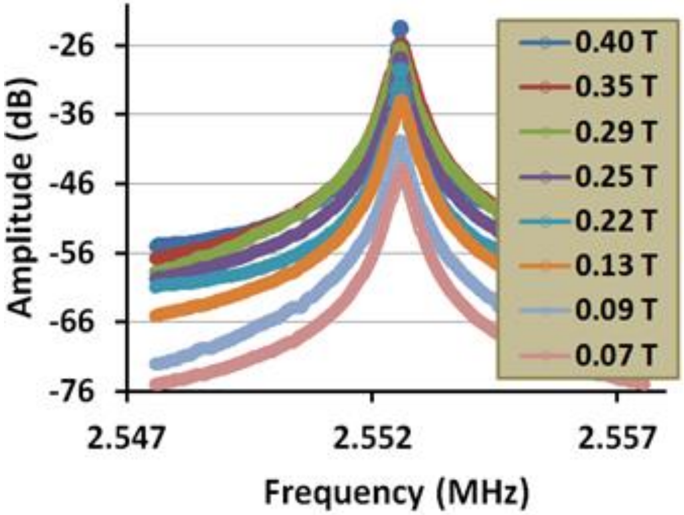
$F_B=B.I.L$

Lorentz Force Magnetometer with Internal Amplification

- Internal Amplification increases vibration amplitude for the same input force leading to a more sensitive sensor
- Sensitivity per bias current increases proportionally with the amplified Q

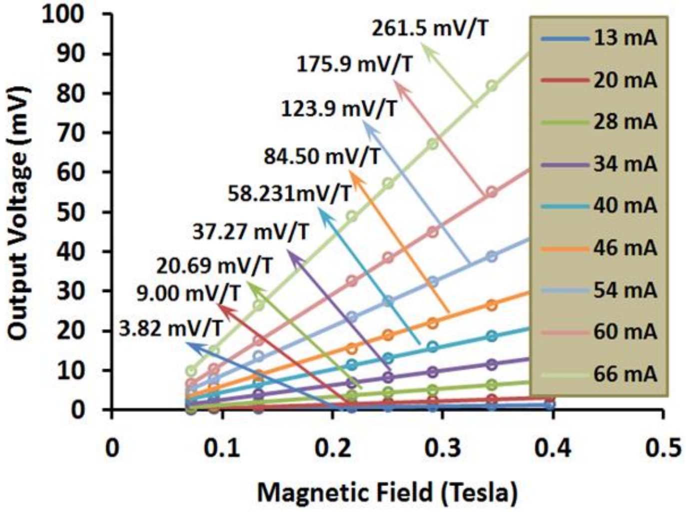


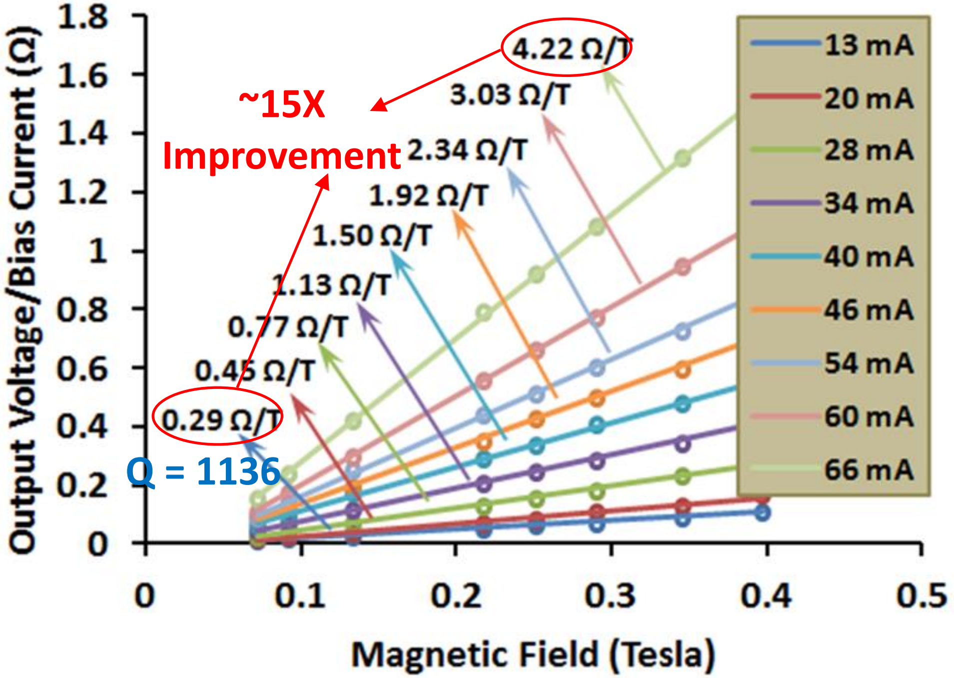


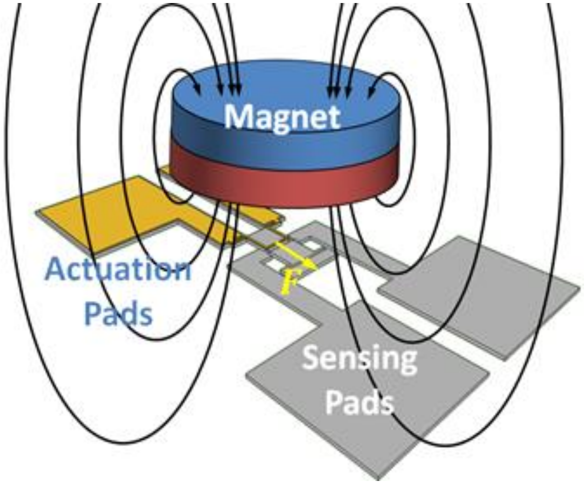


Lorentz Force Magnetometer with Internal Amplification

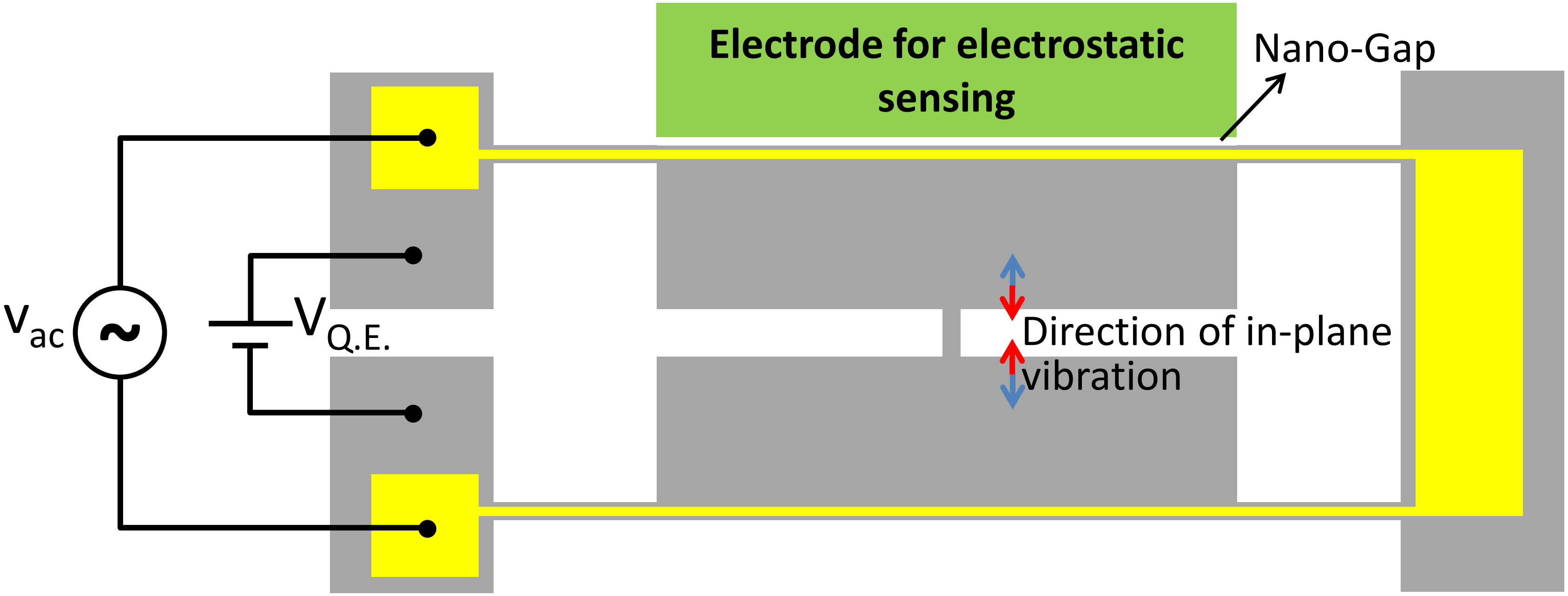
- ☐ Up to **15X** improvement in sensitivity per bias current demonstrated
- ☐ This can potentially be orders of magnitude







Towards Quantum Level Sensitivity?!



- ☐ Use thermal-piezoresistive interactionto amplify resonator Q by 1000-10000X
- ☐ Effective Q up to 40,000,000 already demonstrated for a 4.5MHz resonator
- ☐ This can be done by setting $V_{Q.E.}$ to a value slightly short of self-oscillation
- ☐ An AC current at the exact same frequency can excite the resonant mode in presence of a weak magnetic field
- ☐ Resulting displacement is amplified by the effective Q factor
- ☐ A nano-gap and electrostatic sensing can then pick up the resonator vibrations

Acknowledgements

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- **My colleagues and collaborators: Professors Wilson, Voyles, Yi, Purse (DU), Abdolvand (Oklahoma State Univ.), Bright (CU Boulder), Tabib-Azar (U. of Utah)**
- **My former/current graduate students: Amir Rahafrooz, Arash Hajjam, Babak Tousifar, Xiaobo Guo, Emad Mehdizadeh, Ayesha Iqbal, etc.**

Colorado
Office of Economic Development
and International Trade

Thank You for Your Attention

Operation Mechanism of Resonator

I

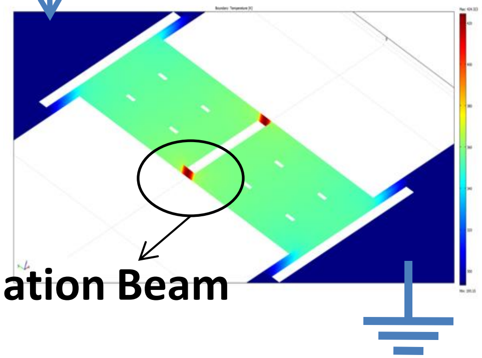
AC+ small DC ***TPR***[*1]

Resonance frequency $\downarrow f = \frac{1}{2\pi}\sqrt{\frac{k(1-2\zeta^2)}{m}}$

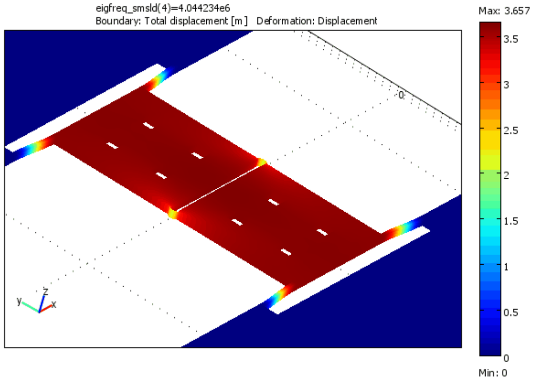
Damping ratio $\zeta = \frac{c\uparrow}{2\sqrt{km}}.$

Large DC ***TPO***[*2]

f=g(c) ?



Actuation Beam



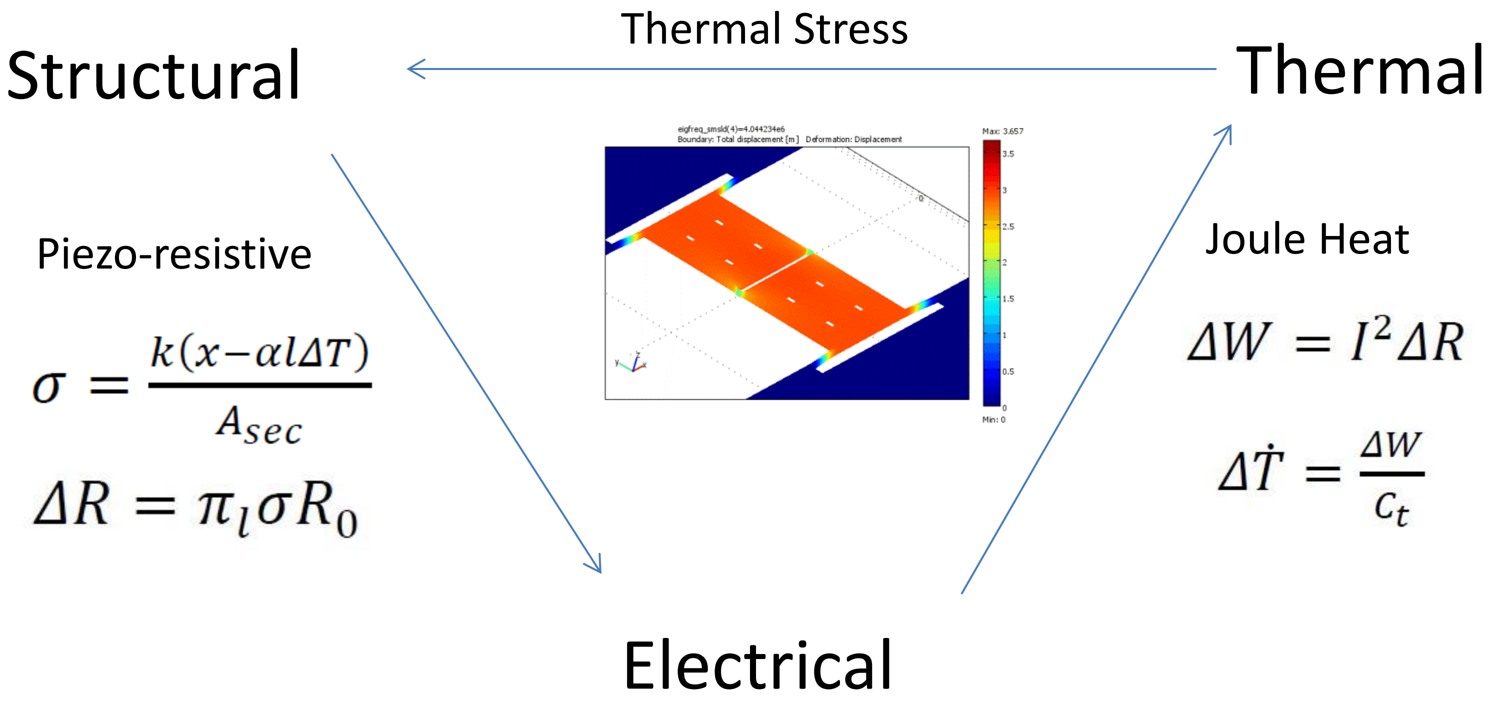
In plane mode vibration & Piezo-resistive Readout

*1. "High frequency thermally actuated electromechanical resonators with piezoresistive readout," A. Rahafrooz, and S. Pourkamali, IEEE Transactions on Electron Devices, 58,4(2011).

*2. "Fully Micromechanical Piezo-Thermal Oscillators," A. Rahafrooz, and S. Pourkamali, IEEE International Electron Device Meeting (IEDM), Dec.(2010).

Coupled Equations

$$m\ddot{x} + c\dot{x} + k(x - \alpha l \Delta T) = 0$$



Thermal Stress

Structural

Thermal

Piezo-resistive

$$\sigma = \frac{k(x - \alpha l \Delta T)}{A_{sec}}$$

$$\Delta R = \pi_l \sigma R_0$$

Joule Heat

$$\Delta W = I^2 \Delta R$$

$$\Delta \dot{T} = \frac{\Delta W}{c_t}$$

Electrical

Final Solution

Combine these equations together, resulting:

$$\Delta\dddot{T} + \left(Nk\alpha l + \frac{c}{m}\right)\Delta\ddot{T} + \frac{(cNk\alpha l+k)\Delta\dot{T}}{m} = 0 \qquad (1)$$

Where $N = I^2\pi_l R_0/(c_t A_{sec})$.

Assume $\Delta T = \Delta T_0 e^{i\omega t}$. Eq. (7) becomes

$$-i\omega^3 - \left(Nk\alpha l + \frac{c}{m}\right)\omega^2 + (cNk\alpha l + k)\frac{i\omega}{m} = 0 \qquad (2)$$

Solution – part 1

$$-i\omega^3 \boxed{-\left(Nk\alpha l + \frac{c}{m}\right)} \omega^2 + (cNk\alpha l + k)\frac{i\omega}{m} = 0 \qquad (2)$$

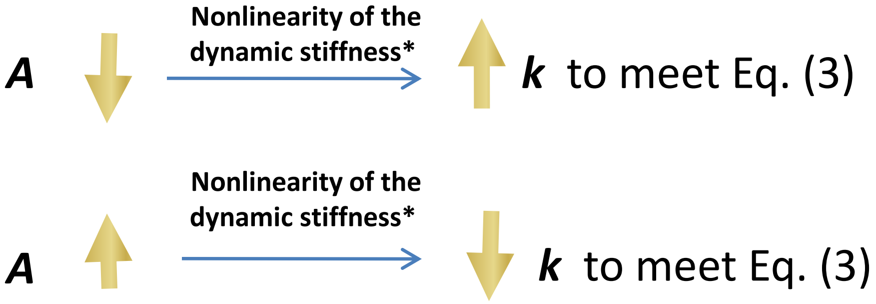
For Eq. (9) to be satisfied, **the real part** of it should be equal to zero, resulting in:

$$c = -mNk\alpha l \qquad (3)$$

The damping c is compensated by the term "***-mNkαl***"

If the real part > 0,

If the real part < 0,



*Nonlinearity of the dynamic stiffness $F = k_1x - k_2x^3$

Solution – part 2

$$\boxed{-i\omega^3} - \left(Nk\alpha l + \frac{c}{m}\right)\omega^2 + \boxed{(cNk\alpha l + k)\frac{i\omega}{m}} = 0$$ (2)

For Eq. (9) to be satisfied, the imaginary part of it should be equal to zero, resulting in:

$$\omega^2 = \frac{(cM\alpha l+1)k}{m}$$ (4)

Since $cM\alpha l << 1$ Eq. (4) can be simplified to

$$\omega^2 \approx \frac{k}{m}$$ (5)

Can it Catch up with SQUIDs?

- Magnetic Force: $F = 2.B.I.L$
  - $B = 10^{-12}T$, $I_{ac} = 100mA$, $L = 500\mu m$ → $F = 10^{-15}N$

- For resonator mechanical stiffness of $K = 400N/m$,

displacement amplitude: $x = Q_{eff} \, . \, F / K$, Assuming $Q_{eff} = 40{,}000{,}000$,

$x = 10^{-11}m$

- For a capacitive gap of $g=100nm$, electrostatic bias voltage of 5V, device thickness of 10µm, and resonant frequency of 1MHz:

$i_{out} = 2\varepsilon_0 AV\omega x/g^2 = 2.8nA$

- 28pA is within the detectable range for output of low frequency resonators (e.g. gyroscopes have output signals in the same range)

- For example a Trans-Impedance Amplifier with trans-resistance of 1MΩ turns this into a 2.8mV signal

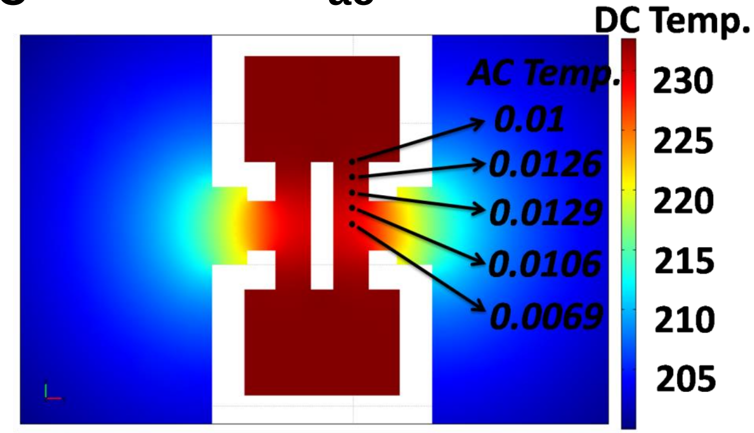
Calculation of Actuator Thermal Capacitance

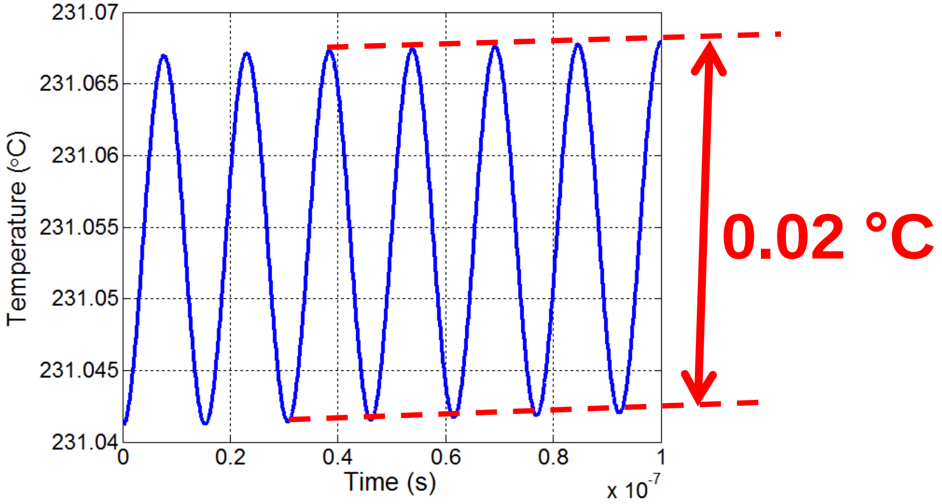
$$g_m = 4\alpha E^2 \pi_l Q \frac{A I_{dc}^2}{K L \boxed{C_{th}} \omega_m}$$

To calculate the g_m , all the parameters except the effective thermal capacitance of the actuators (C_{th}) are known.

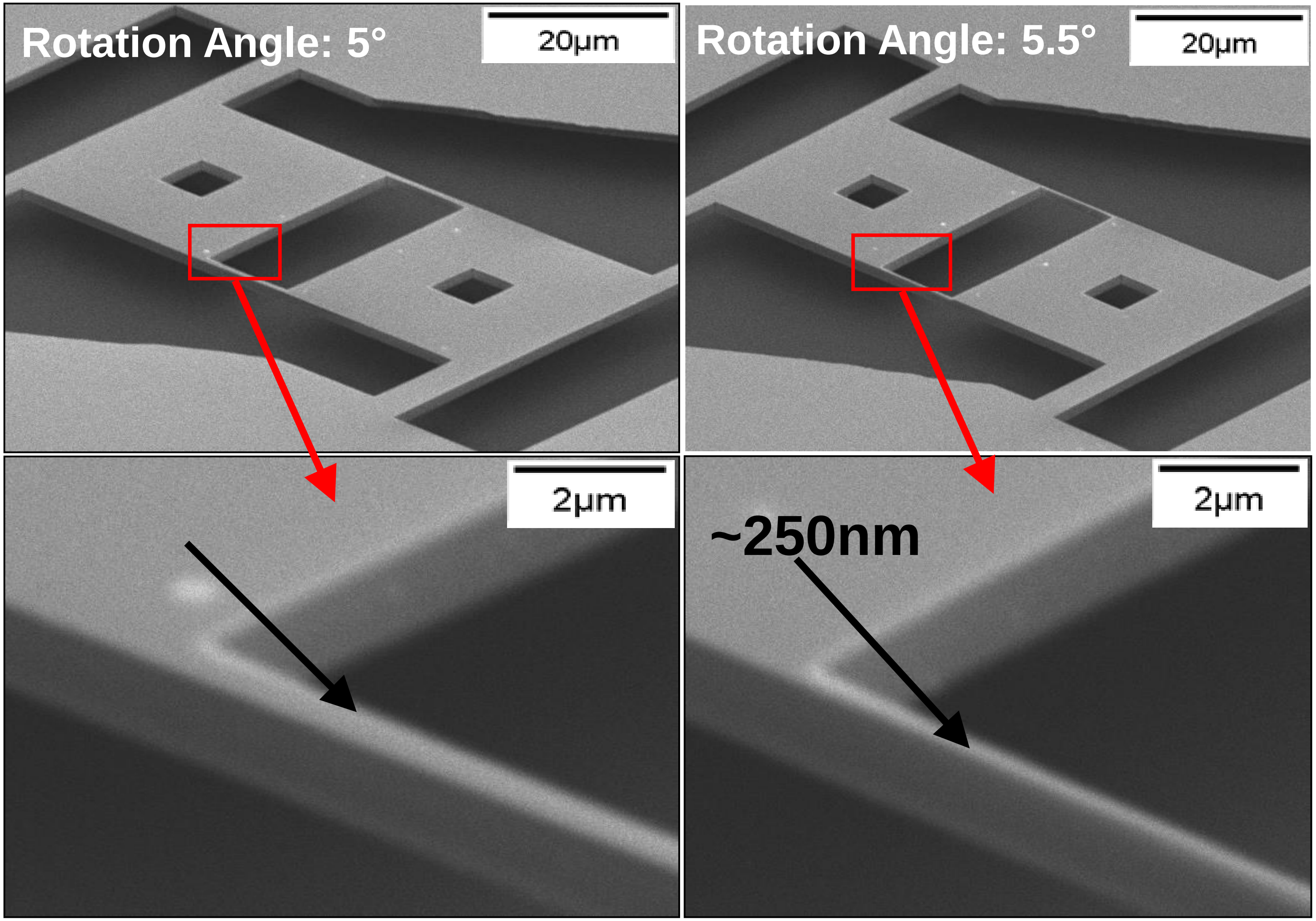
$$C_{th} = \frac{I_{dc} i_{ac} R_A}{T_{ac} \omega_m}$$

I_{DC} = 60mA, i_{ac}= 5mA @ 61MHz



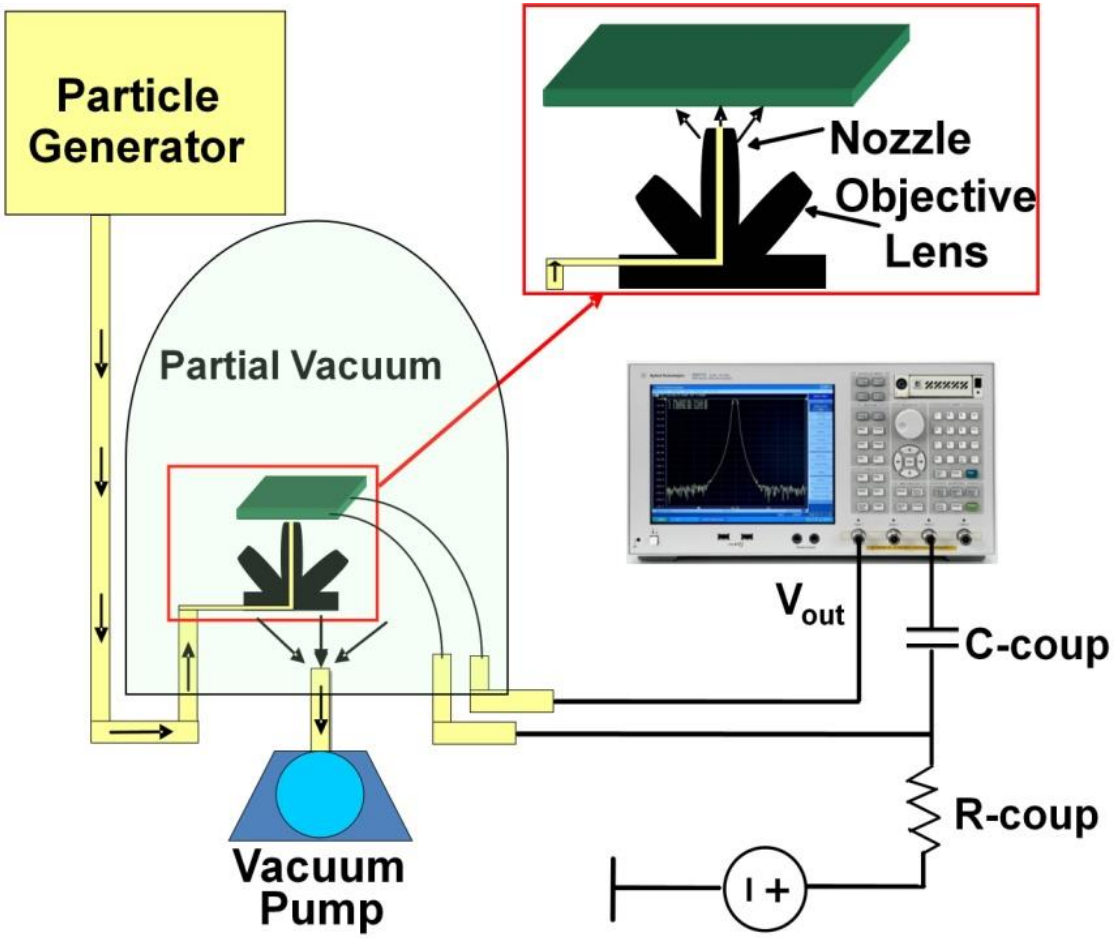


Fabrication Results



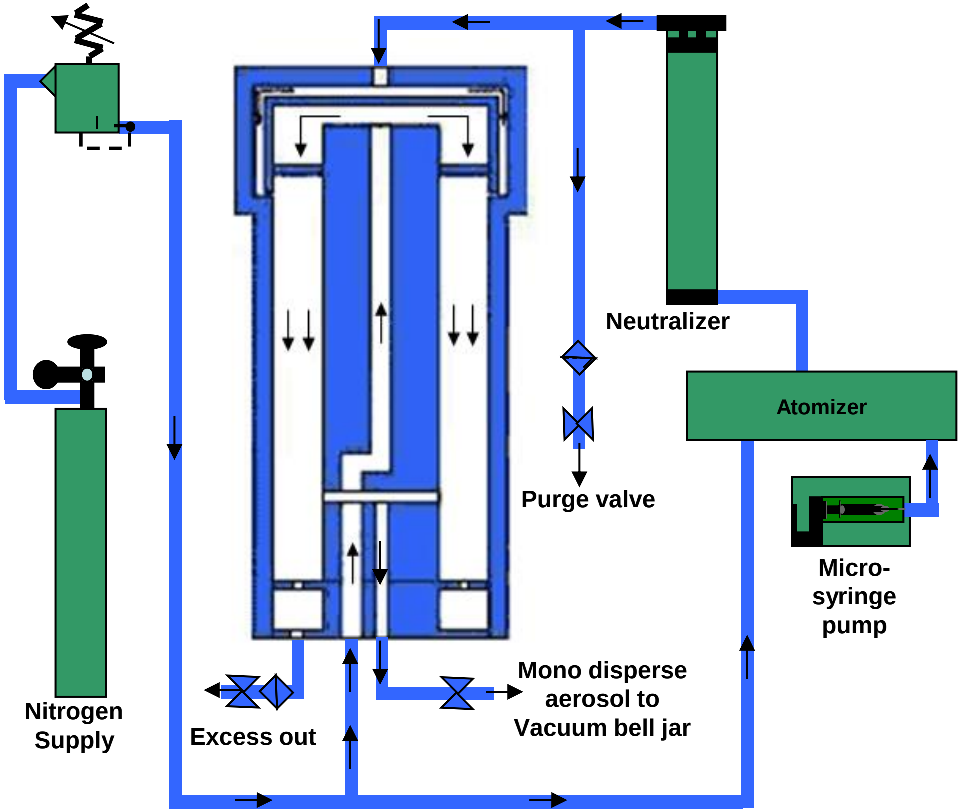
Test Setup for Mass Sensitivity Characterization

Particles deposited on the resonators while monitoring their frequency shift

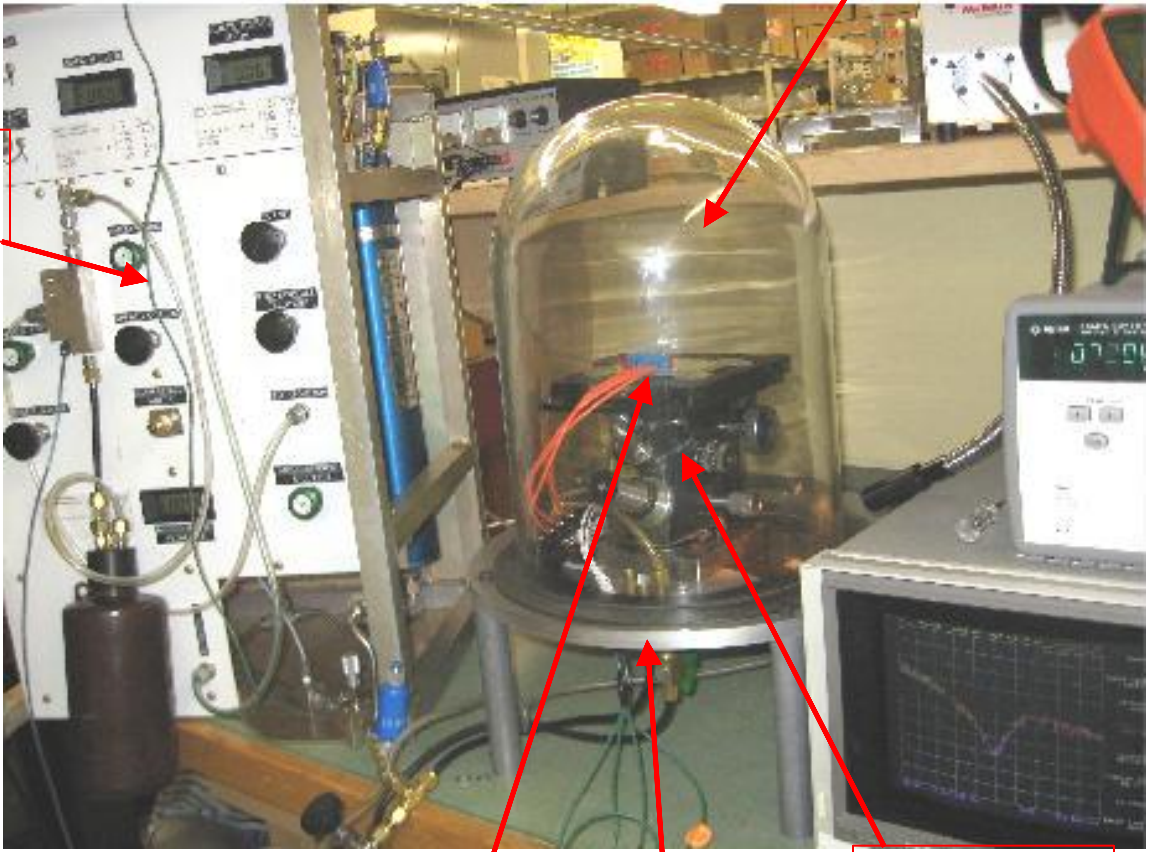


Generation of Artificial Particles

- ❑ Aerosol particles with known size and composition generated



Test Setup



Vacuum chamber

Particle generator

MEMS device

Feed-through connections

Alignment apparatus

Cause of Negative TCF

- Main cause is negative temperature coefficient of Young’s modulus (TCE)

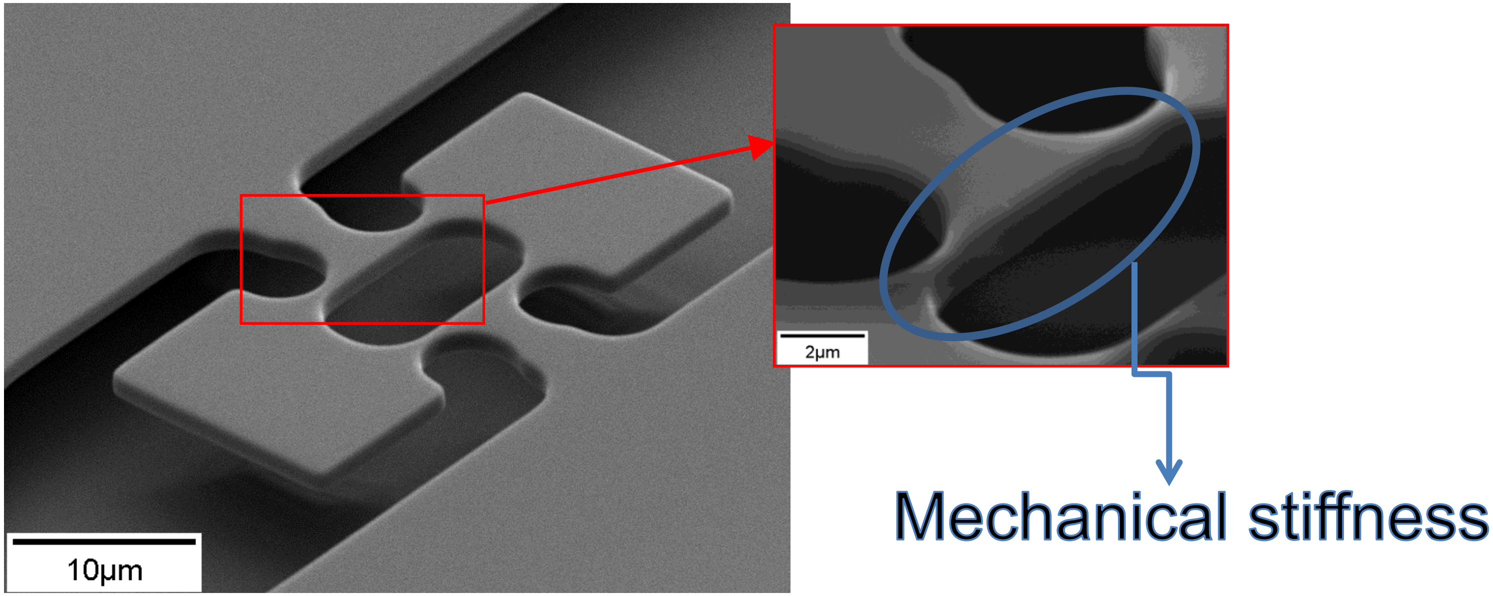
$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

K is stiffness and m is mass

$$T \Uparrow \longrightarrow k \Downarrow \longrightarrow f \Downarrow$$

High Concentration N-type Doping

- ❑ Effect of high concentration N-type doping on the temperature drift



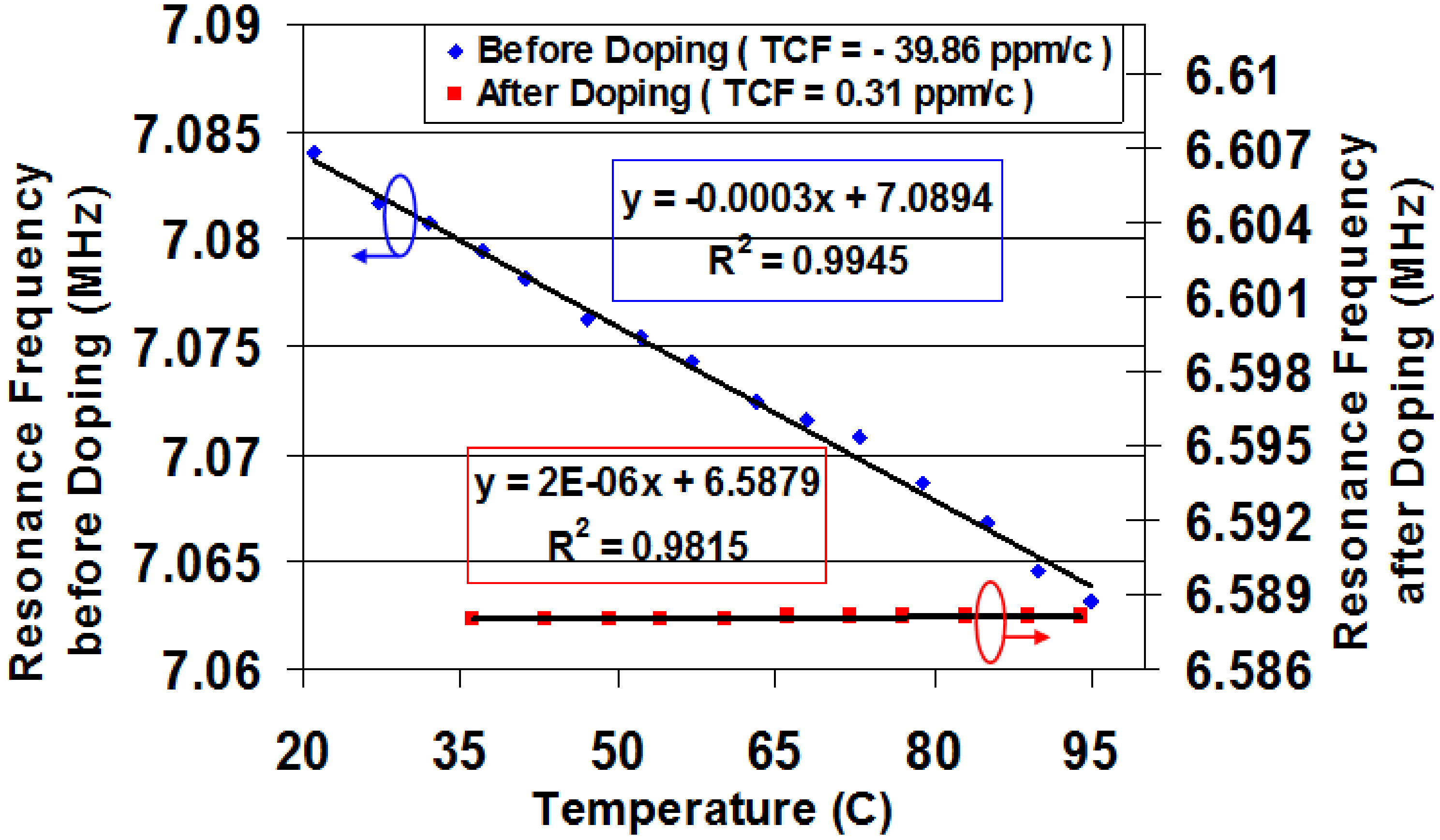
Mechanical stiffness

- ❑ Only short doping and drive-in steps were required for reaching high concentrate dopant levels

Measurement Results

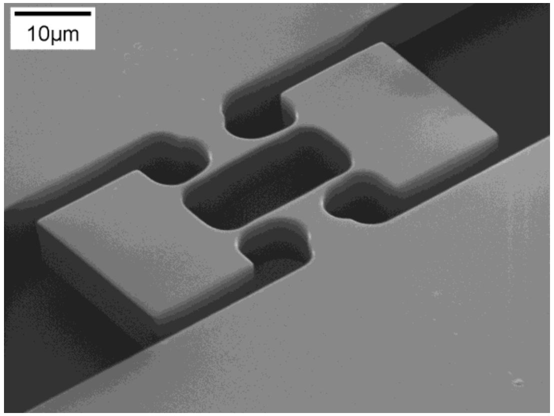
TCF **before** doping = **-39.86ppm/ºC**

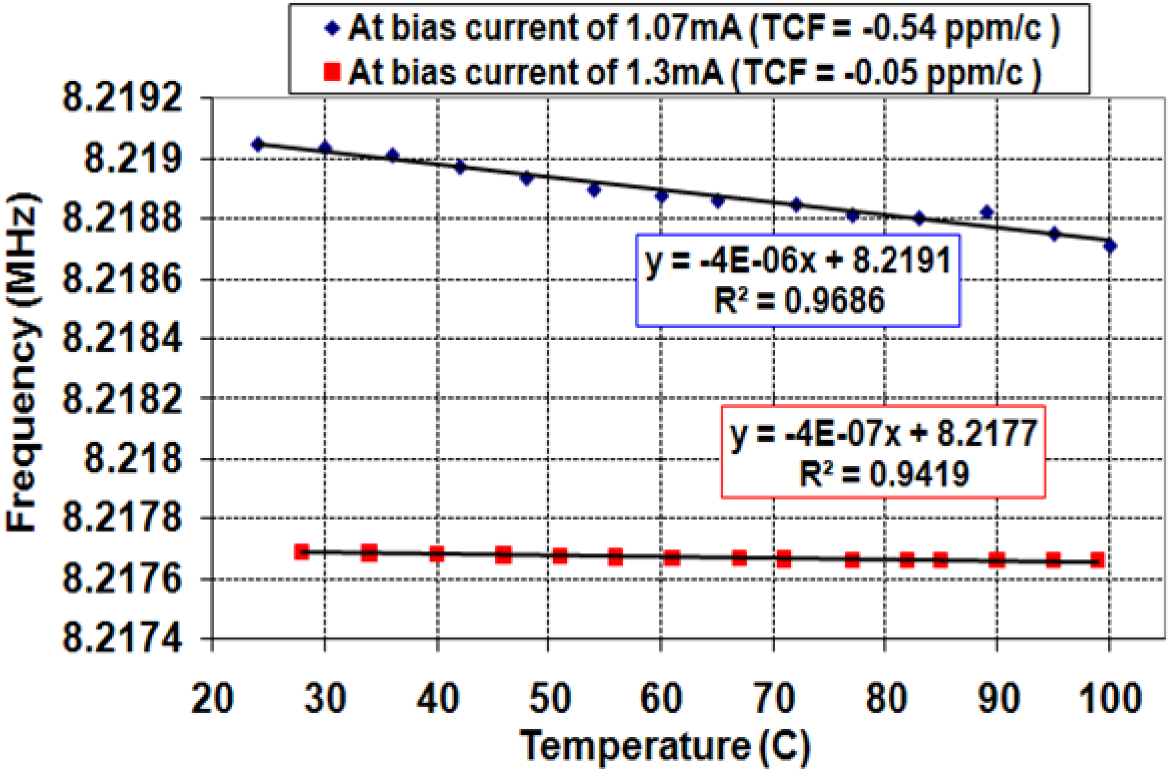
TCF **after** doping = **0.31ppm/ºC** (Positive TCF)



TCF Dependence on Bias Current

- ☐ TCF as low as: **-0.05ppm/°C**





PLL (lysine units in kg/mol)-g(grafting ratio: PEG chains per lysine unit)-PEG (mass of PEG in kg/mol)

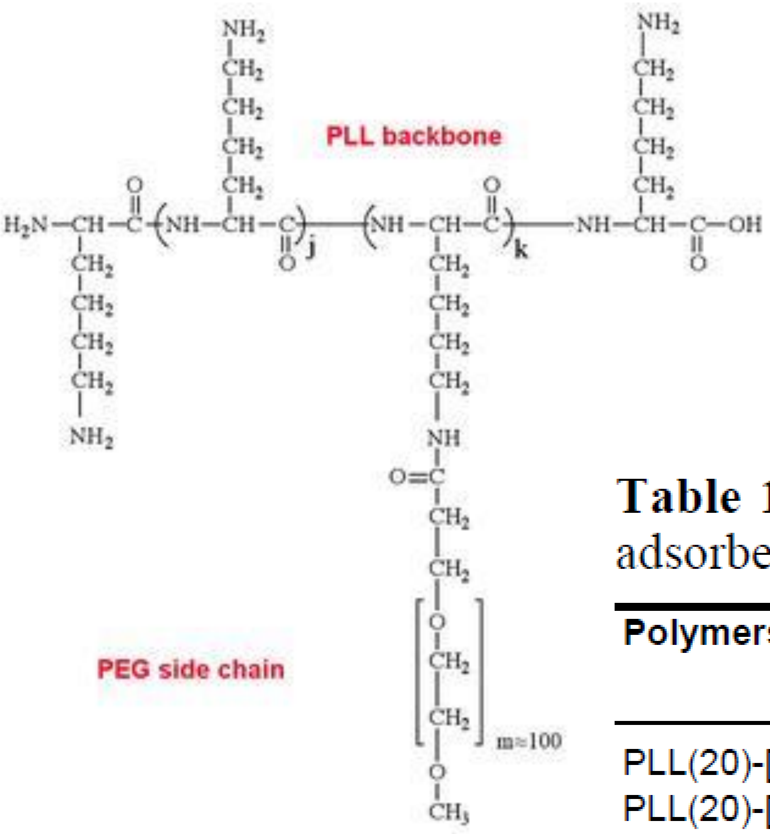
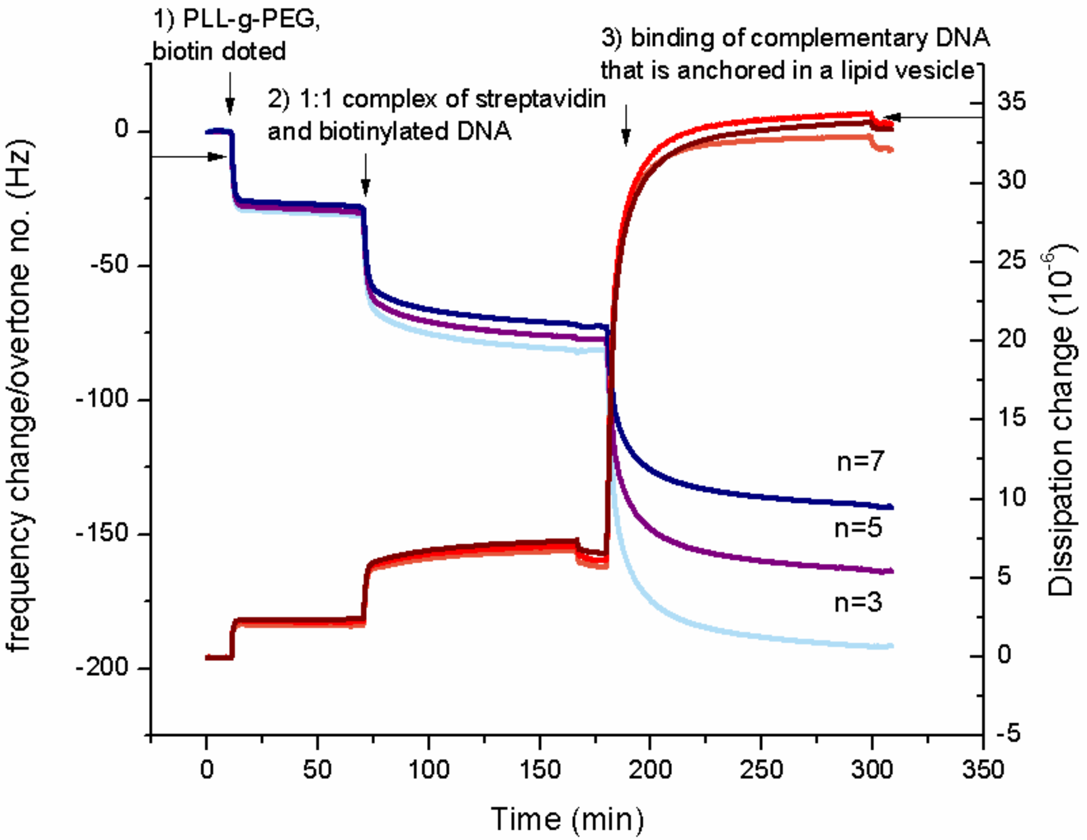


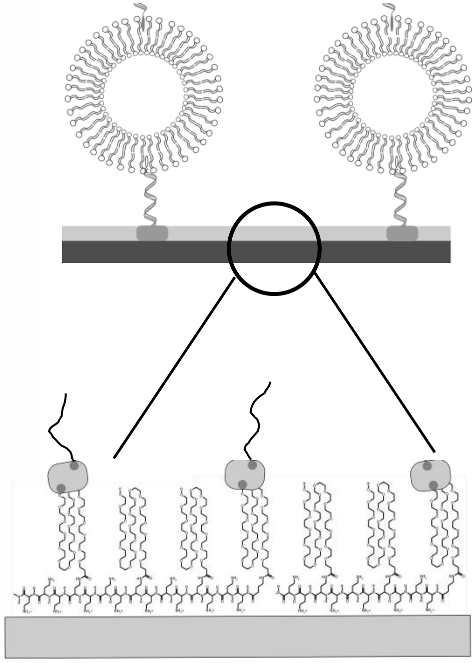
Table 1: Thickness d and hydration of PLL-*g*-PEG layers adsorbed on SiO_2. .

Polymers	salt [mM]	d [Å]	SLD [$Å^{-2}$]	hydration [vol.-%]	χ^2 -
PLL(20)-[3.5]-PEG(2)	10	38.6	5.05E-06	82	0.053
PLL(20)-[3.5]-PEG(2)	1	39.7	5.48E-06	90	0.052
PLL(300)-[2.1]-PEG(2)	10	46.3	5.33E-06	87	0.062
PLL(300)-[3.2]-PEG(2)	10	49.1	5.56E-06	91	0.060
PLL(300)-[3.2]-PEG(2)	1	50.6	5.59E-06	92	0.082
PLL(300)-[2.1]-PEG(5)	10	38.2	5.44E-06	89	0.068

Numbers derived from neutron scattering experiments.

QCM-D response at three overtones for stepwise build up of depicted surface architecture





3: vesicles with complementary DNA

2: streptavidin + biotin DNA

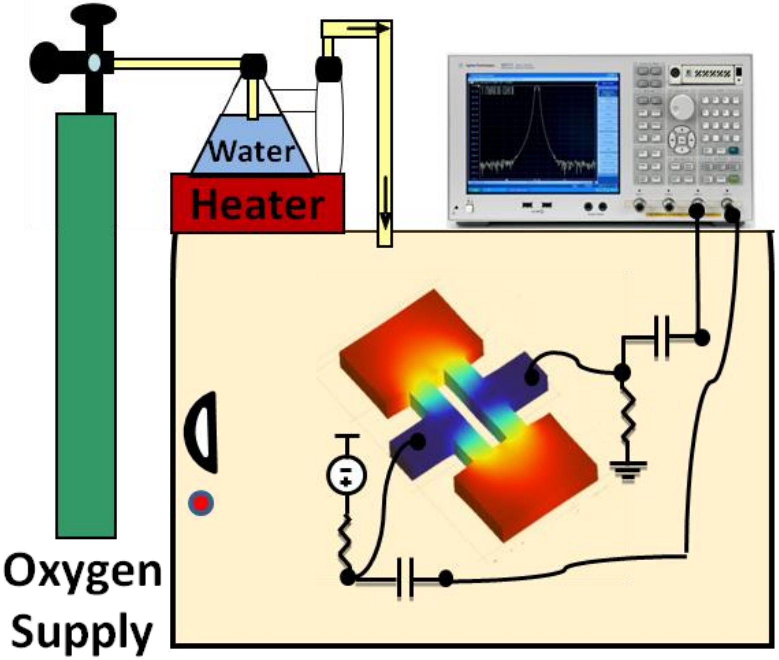
1: biotin-PLL-PEG

SiO_2 surface

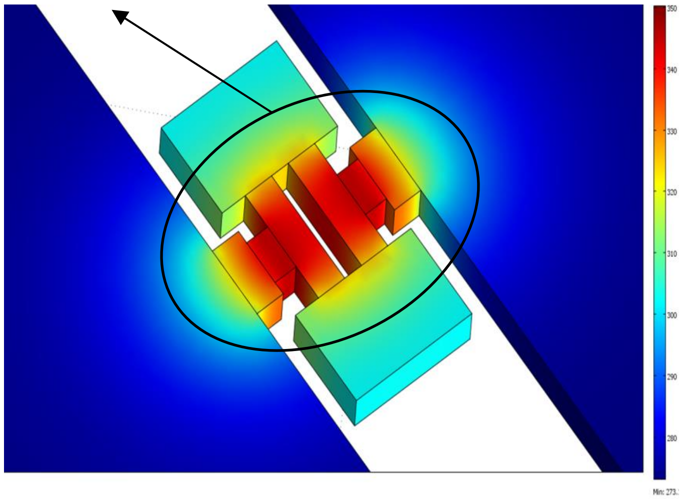
Localized Thermal Oxidation for Frequency Trimming and Temperature Compensation of Micromechanical Resonators

- Resonance frequency of silicon MEMS resonators is dependent on physical dimensions of the resonating structure
- Post-fabrication frequency trimming via pulsed-laser-deposition, material diffusion and electrostatic frequency trimming → Deficiencies such as frequency inaccuracy
- Presented approach based on thermal oxidation of the surface of the beams

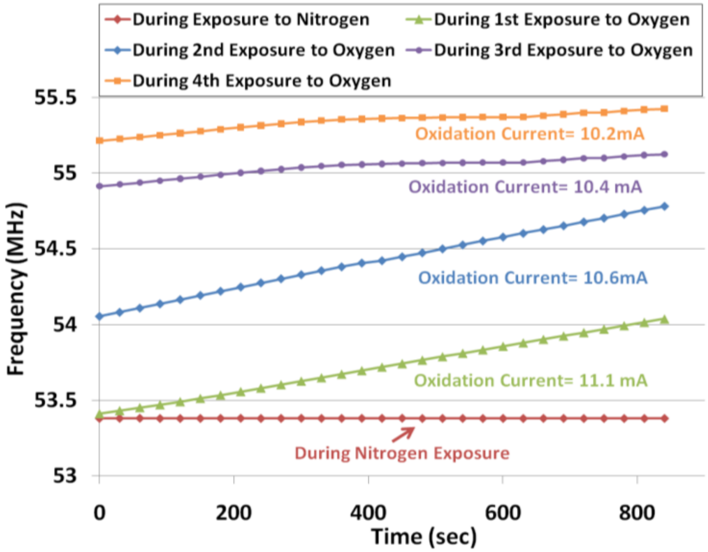
Presentation in MEMS 2012 Conference:

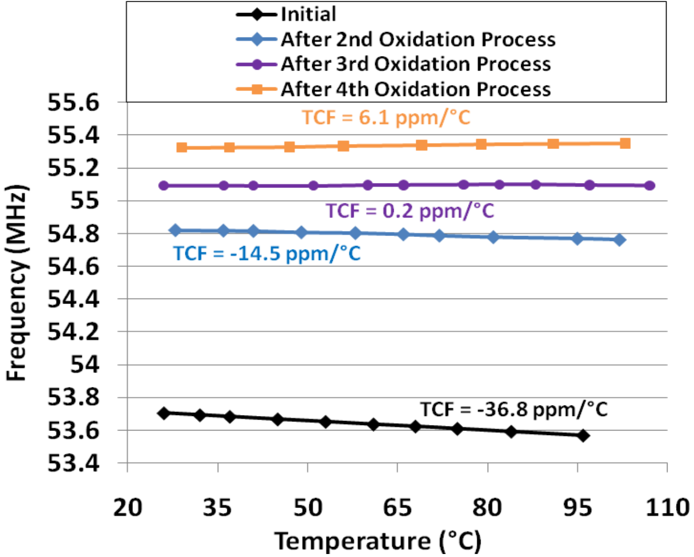


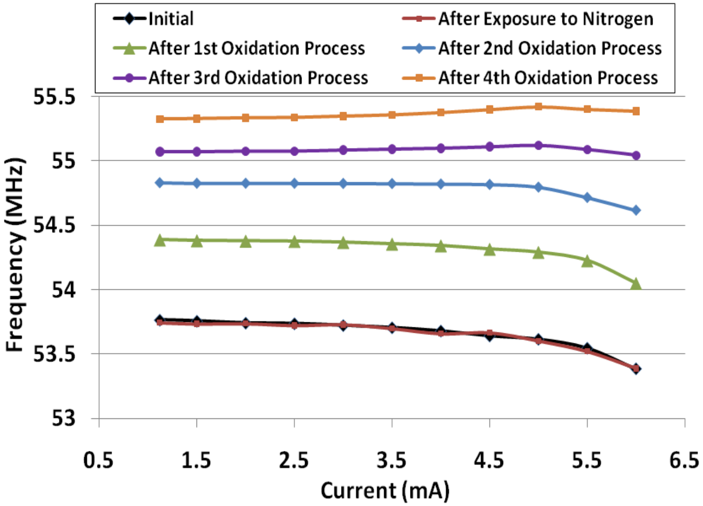
Silicon dioxide forming on the hot surfaces

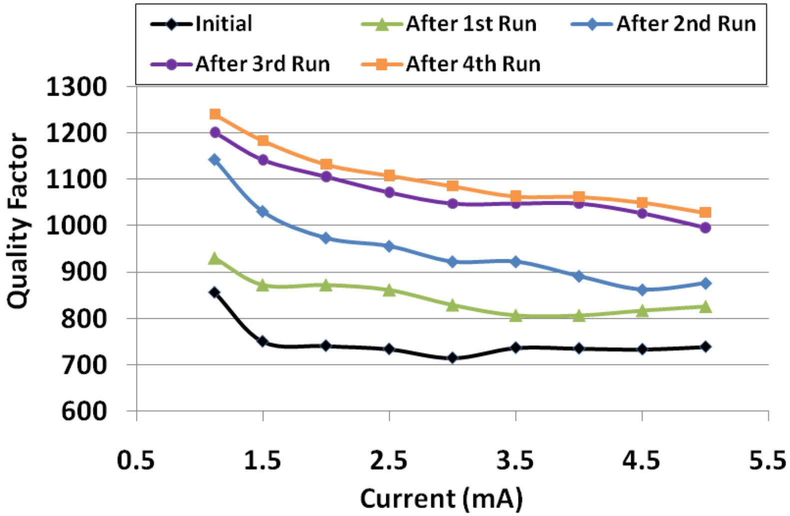


Measurement Results







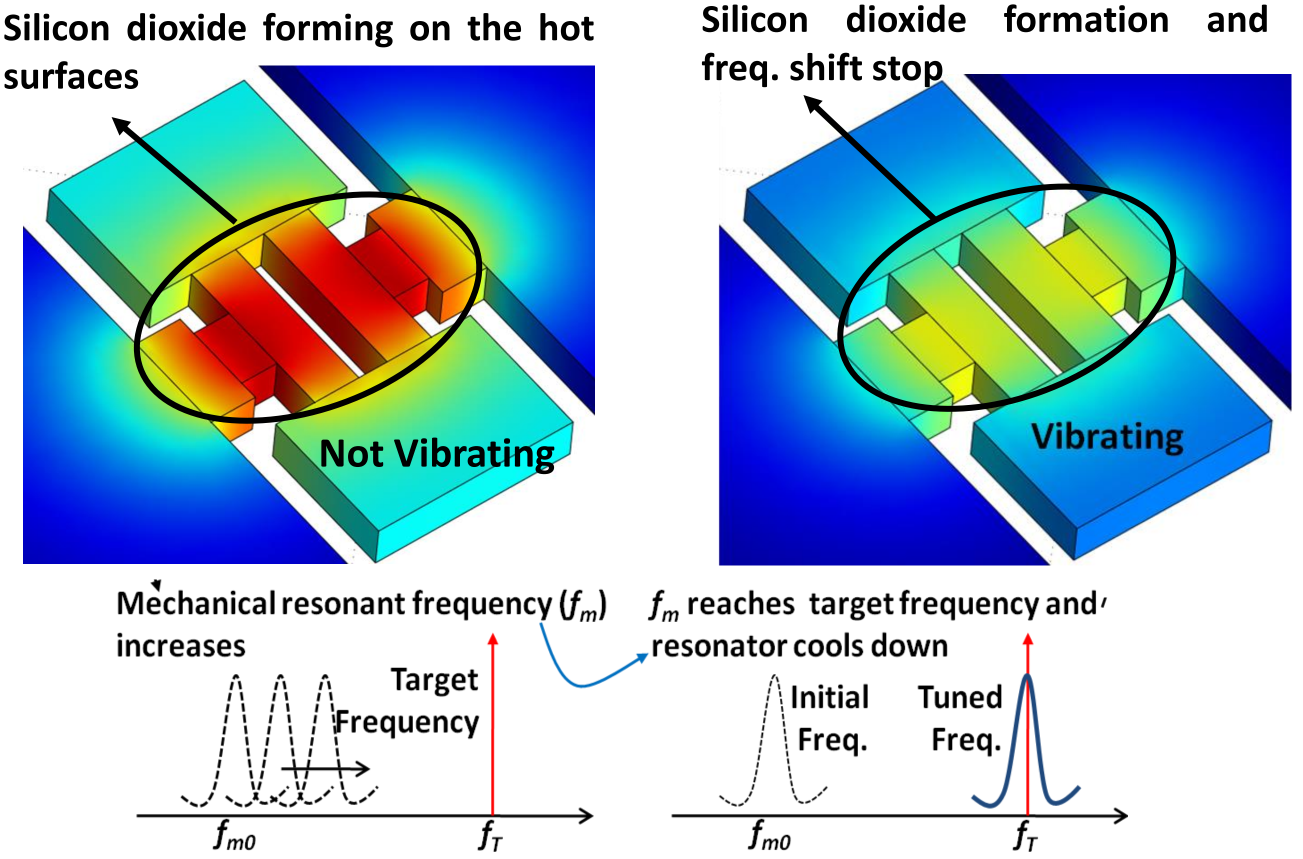


Self-controlled Frequency Trimming Technique for Micromechanical Resonators

Presentation in Hilton Head 2012 workshop:

Schematic demo of the autonomous frequency trimming technique

- The cooling effect at resonance, allows the localized oxidation to stop automatically as soon as the resonator frequency reaches the targeted actuation frequency



Silicon dioxide forming on the hot surfaces

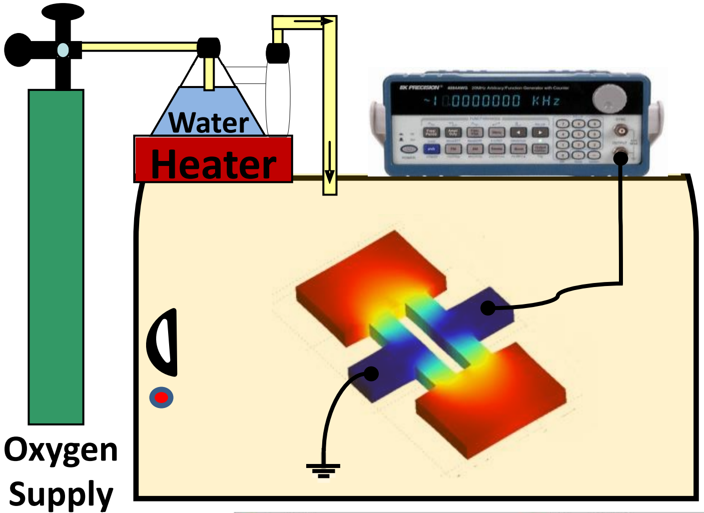
Silicon dioxide formation and freq. shift stop

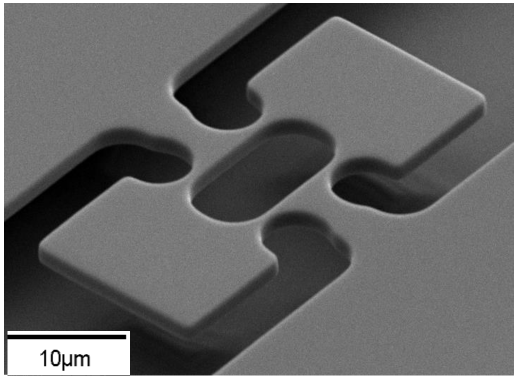
Mechanical resonant frequency (f_m) increases

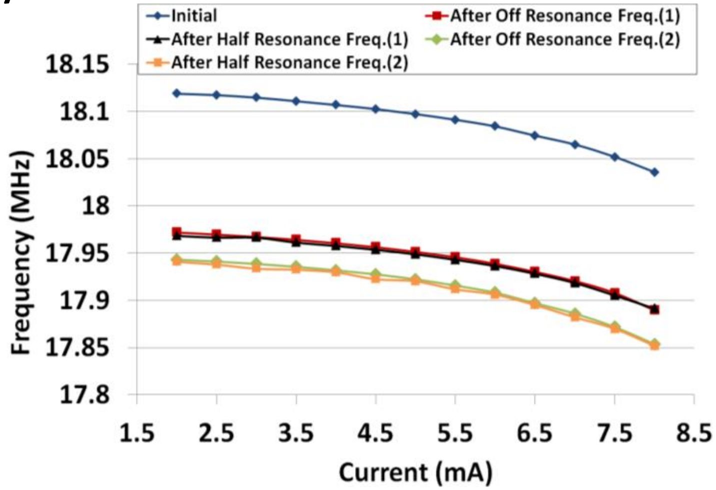
f_m reaches target frequency and resonator cools down

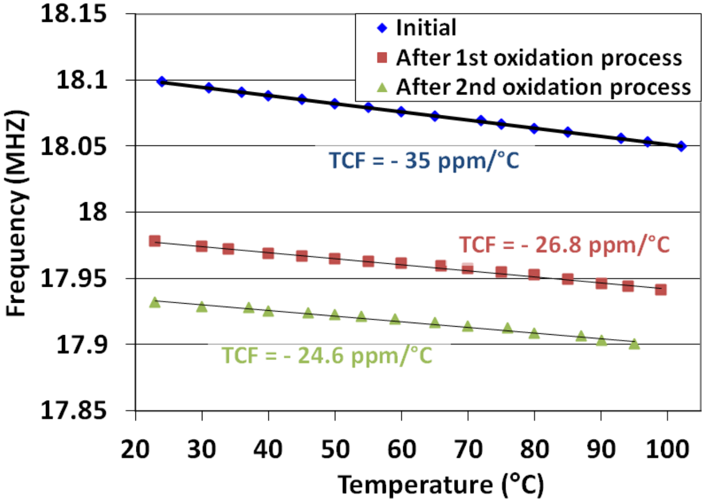
Measurement Setup and Results

- Changes in dimensions and Young’s modulus as well as internal stress caused by oxidation results in a permanent change in the resonant frequency of the device





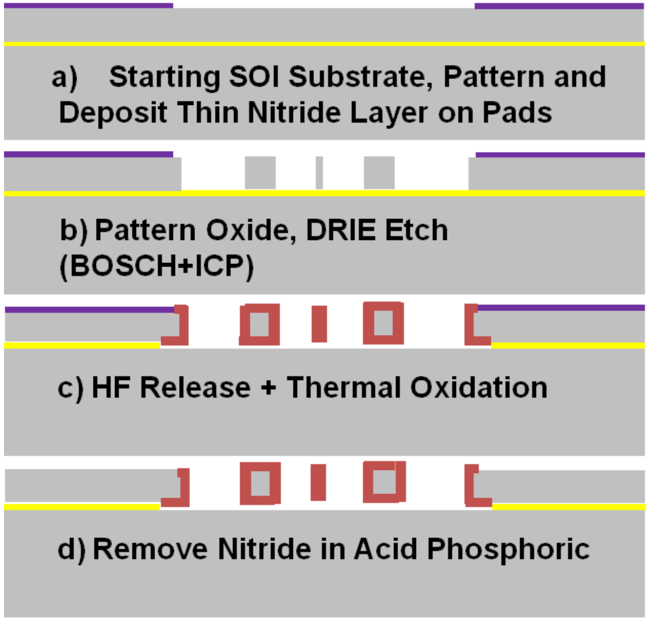




Input-Output Insulation in Thermal-Piezoresisitive Resonant Microsctructures using Embedded Oxide Beams

Presentation in International Frequency Control Symposium 2012:

- Thermally actuated MEMS resonators with electrically insulated input and output ports
- Significantly reduced feed through current makes it possible to use such resonators in electronic circuits as frequency selective components
- Eliminates the data processing required to extract the motional conductance and Q factor of such resonators from measurements

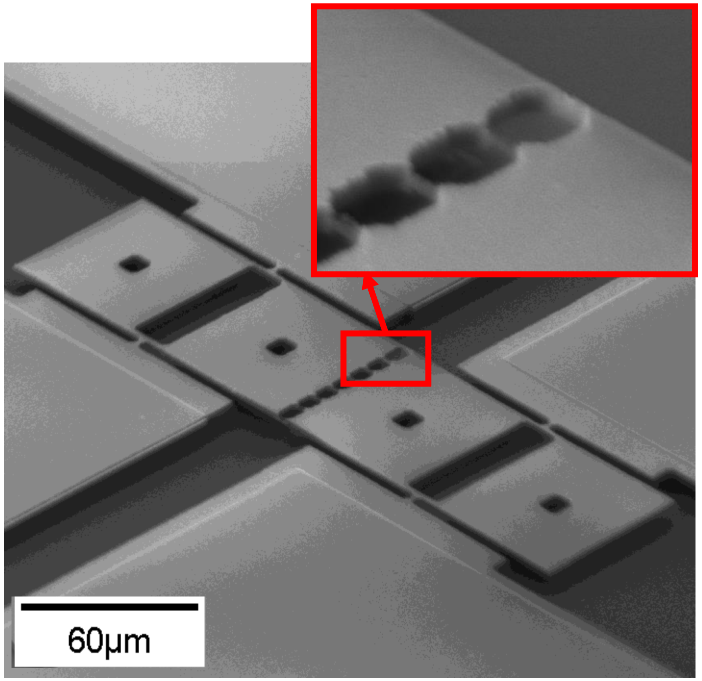


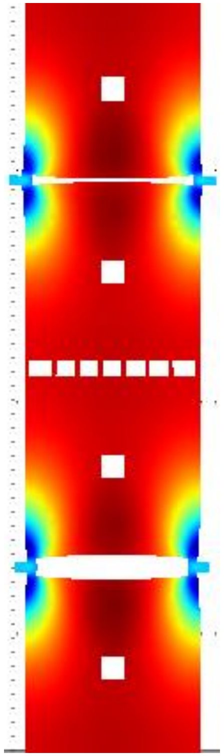
a) Starting SOI Substrate, Pattern and Deposit Thin Nitride Layer on Pads

b) Pattern Oxide, DRIE Etch (BOSCH+ICP)

c) HF Release + Thermal Oxidation

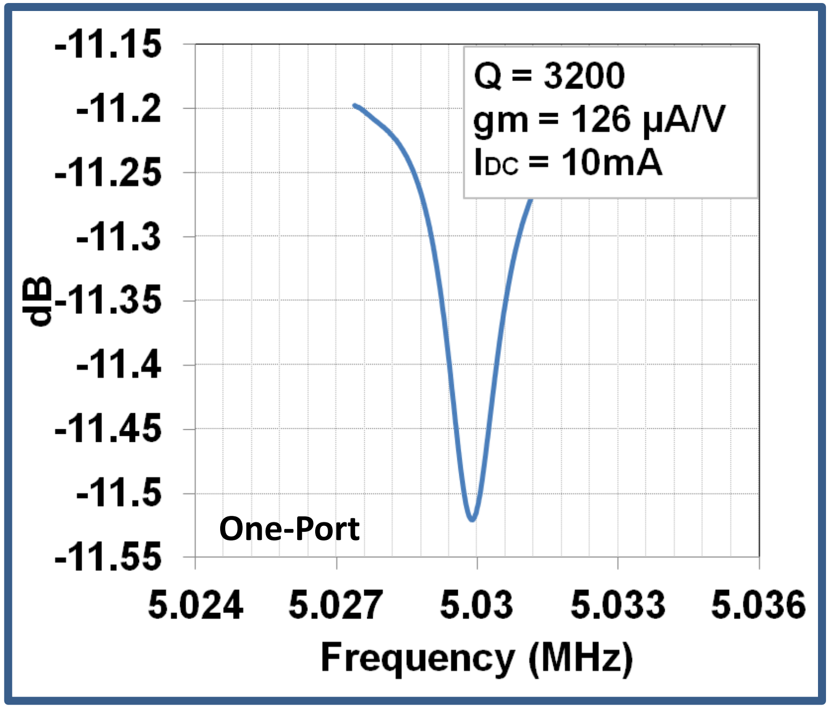
d) Remove Nitride in Acid Phosphoric

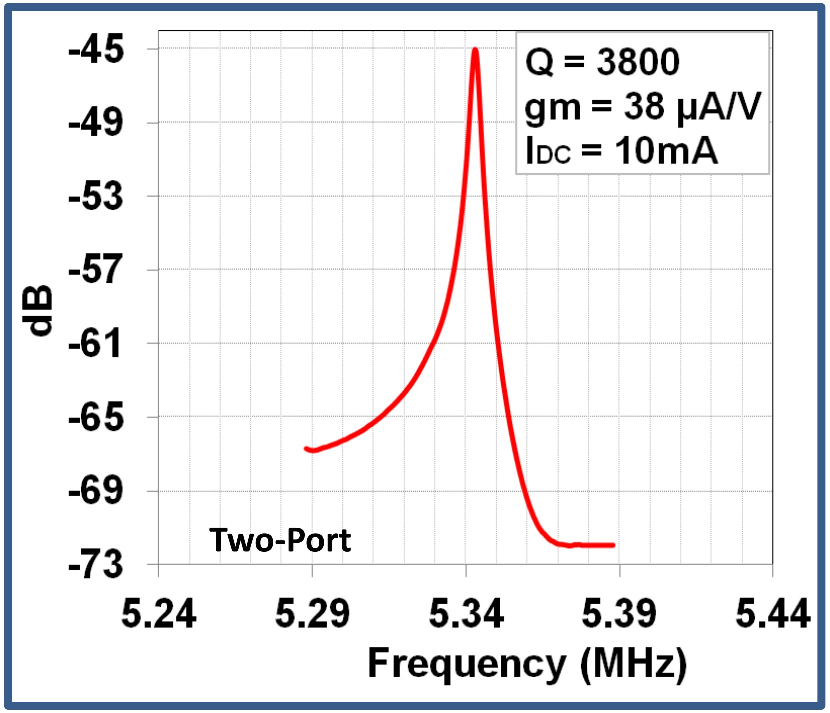




Measurement Results

- The downward resonance peak in the one-port device is due to the negative piezoresistive coefficient of the structural material (N-type Si), while the out of phase motion of the two sections in the two-port device results in an upward resonance peak
- The resonance peak for the two port resonator has much larger amplitude due to elimination of feed-through





Silicon Nonowire Fabrication Technique

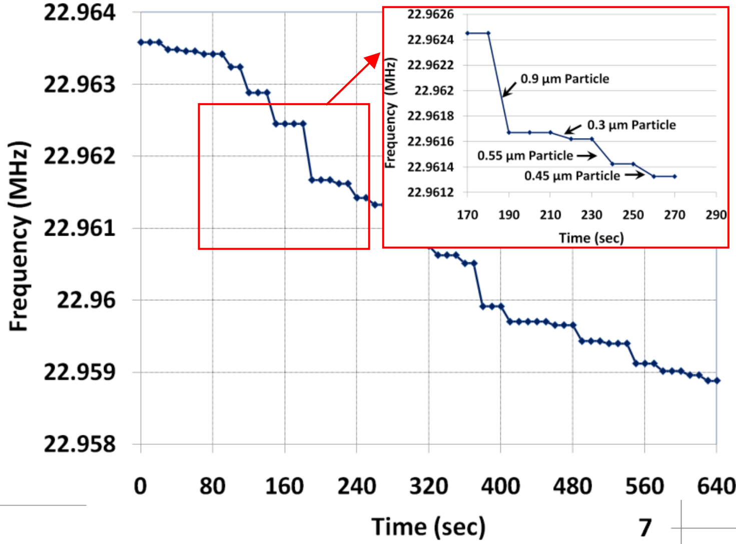
❑ **Silicon nanowires have great potentials in nanoelectronics and nano-electro-mechanical systems:**

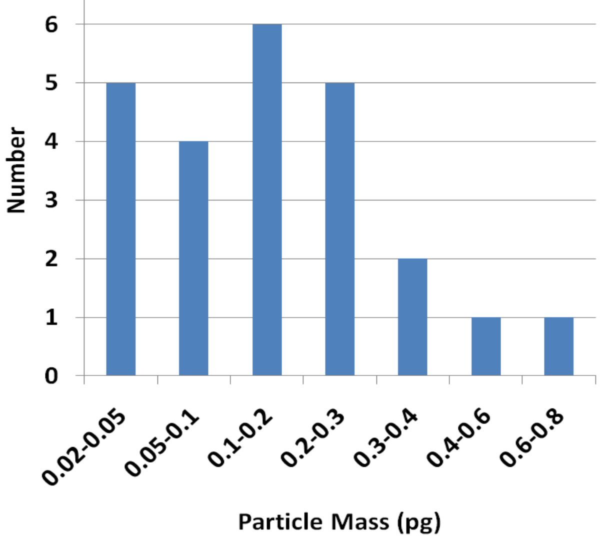
- **Huge piezoresistive coefficients**
- **Large dependence of electrical conductivity to molecular adsorption**
- **Extremely high mass sensitivity of nanowire resonators**

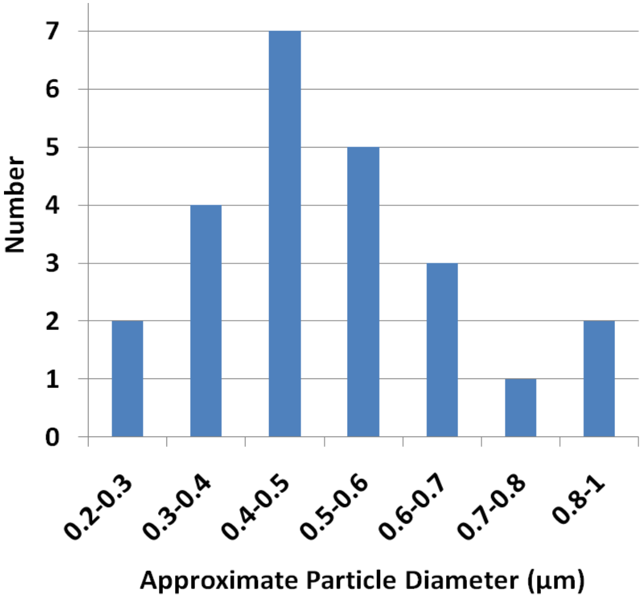
❑ **Costly and time consuming processes: no controlled batch-fabrication capability in any of the proposed fabrication methods**

❑ **Our Method: low cost, controllable process, the ability to be integrated in N/MEMS structures such as high frequency thermal-piezoresistive resonators**

Arbitrary Airborne Particle Measurements

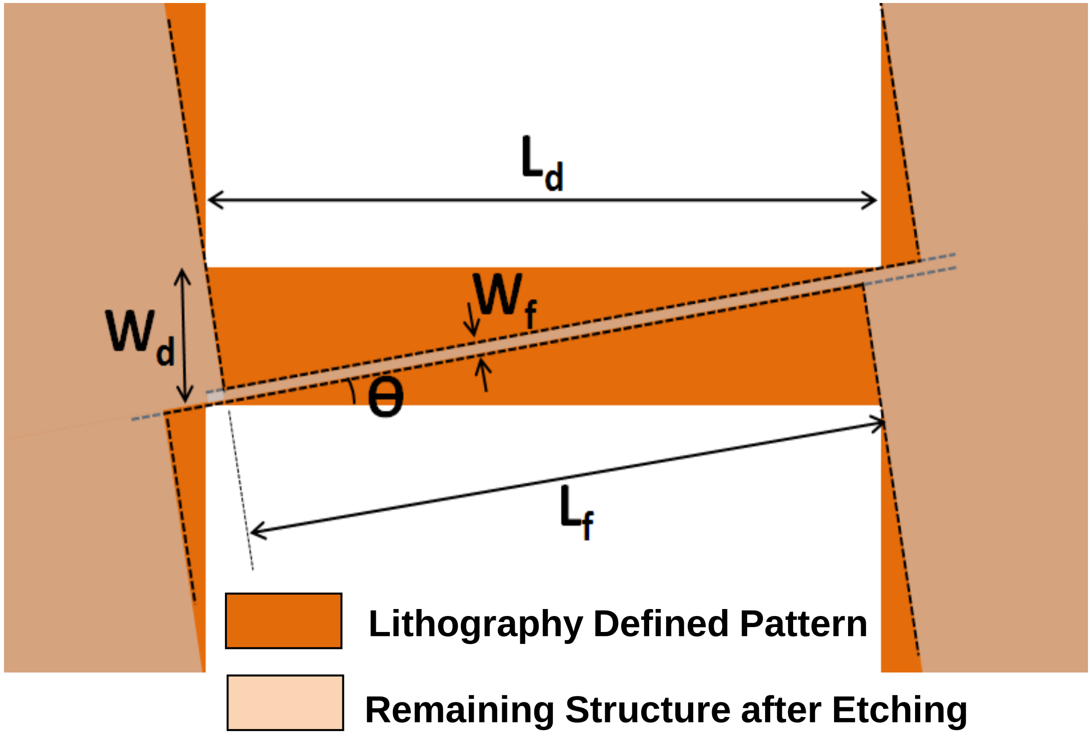




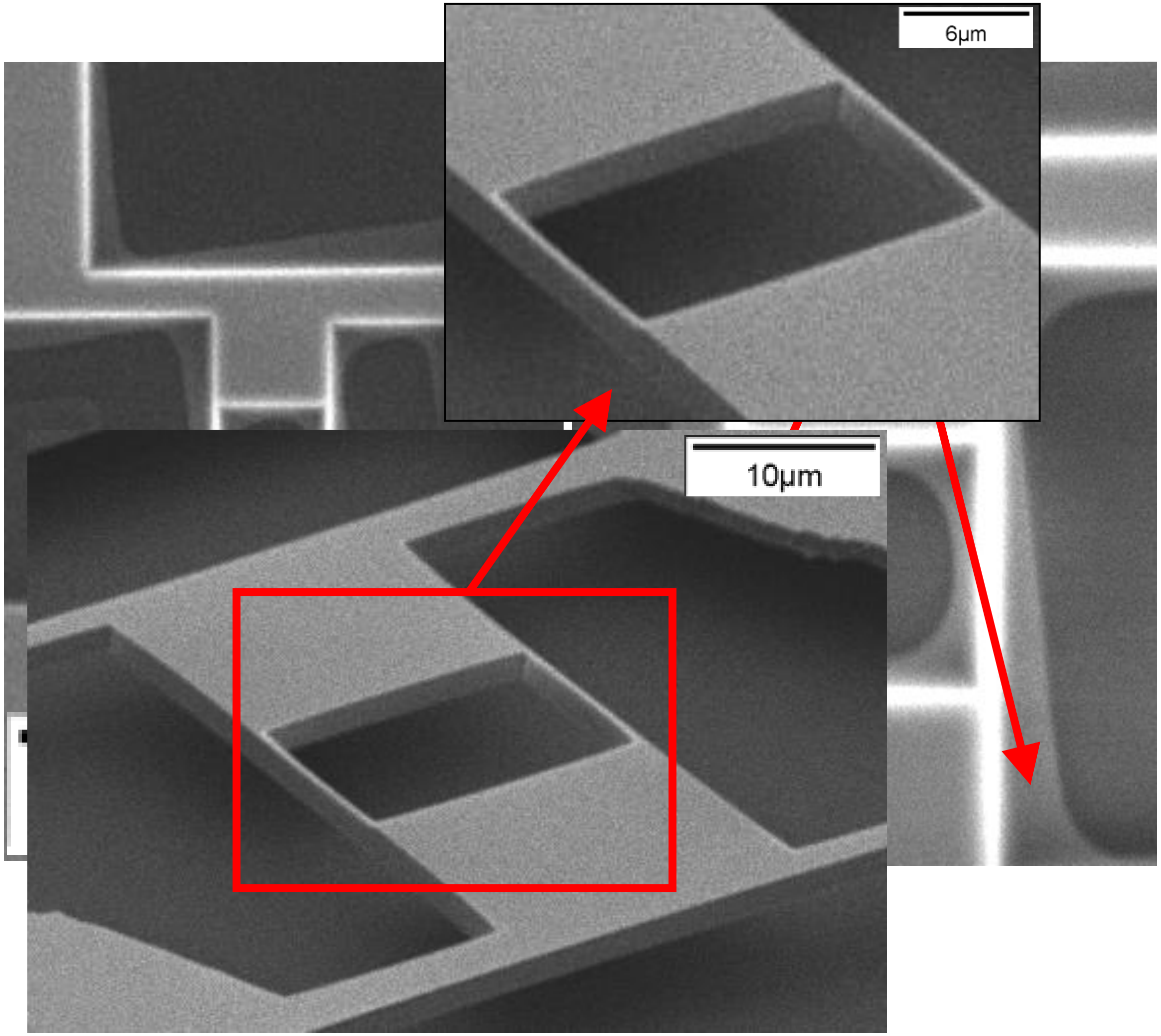


Controlled Batch Fabrication Of Crystalline Silicon Nonowires

- ❑ Using the Anisotropic wet etching of silicon in alkaline solutions (e.g. KOH or TMAH)
- ❑ Rotational misalignment between the photo-lithography defined patterns and the crystalline orientation of silicon



Fabrication Results



Fabrication Results