Status Update on High-Frequency Cantilever Design for Fluid Operation

Joey Doll, June 2008

Overview

- **Cantilevers in Fluid**
  - Analytical modeling
  - Implications for design
- Numerical optimization of epitaxial cantilevers
  - Comparison with Previous Approaches
  - Numerical model
  - Comparison with experimental data (Harley)
  - Implementation
  - Results
- Piezoelectric Actuation Model
- Summer and Future Work

Fluid Modeling

- Oscillations of a thin blade on fluid
  - W. Chu, 1963
- Extended to cantilevers for AFM
  - J. Sader, 1993 - Ongoing
- Analytical approximations for frequency spectra of cantilevers in fluid

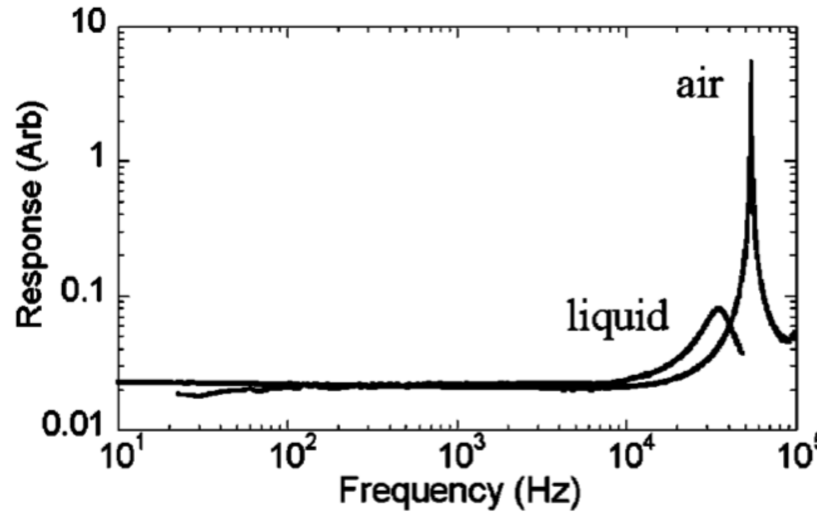
Fluid Modeling

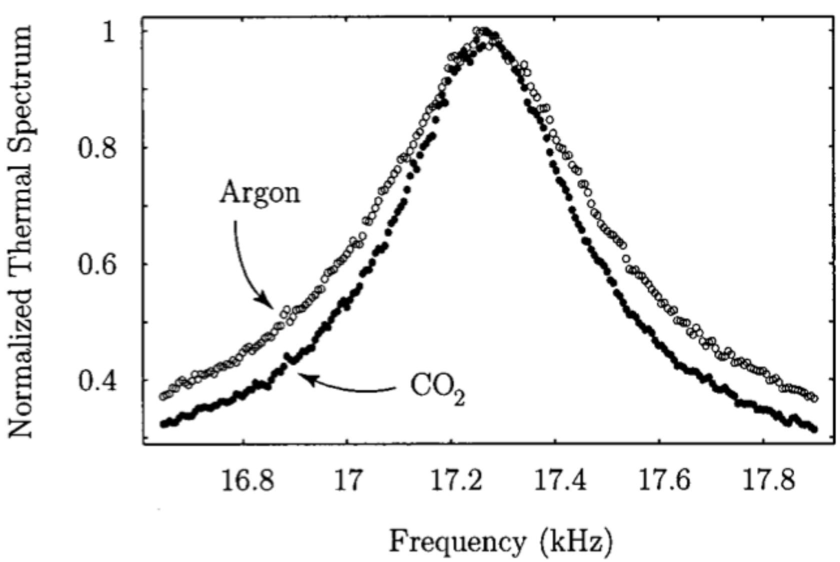
- Assumptions
  - t << w << L
  - Rectangular, uniform cross-section
  - Vibrations smaller than any dimensions
  - Fluid damping dominates internal dissipation
  - Incompressible, infinite viscous fluid
- Variations on this analysis exist (e.g. inviscid)

Frequency response of cantilever beams immersed in viscous fluids with applications to the atomic force microscope: Arbitrary mode order. Eysden and Sader (2007)

Fluid Modeling

High-speed atomic force microscopy in liquid, Sulcheck, Hsieh, Adams, Minne, Quate, Adderton, Rev. Sci. Instr. (2000)





Rheological measurements using microcantilevers, Boskovic, Chon, Mulvaney, Sader, Soc. Of Rheology (2002)

Fluid Modeling

$$\mathrm{Re} = \frac{\rho \omega w^2}{\eta} \qquad \kappa = C_n \frac{w}{L}$$

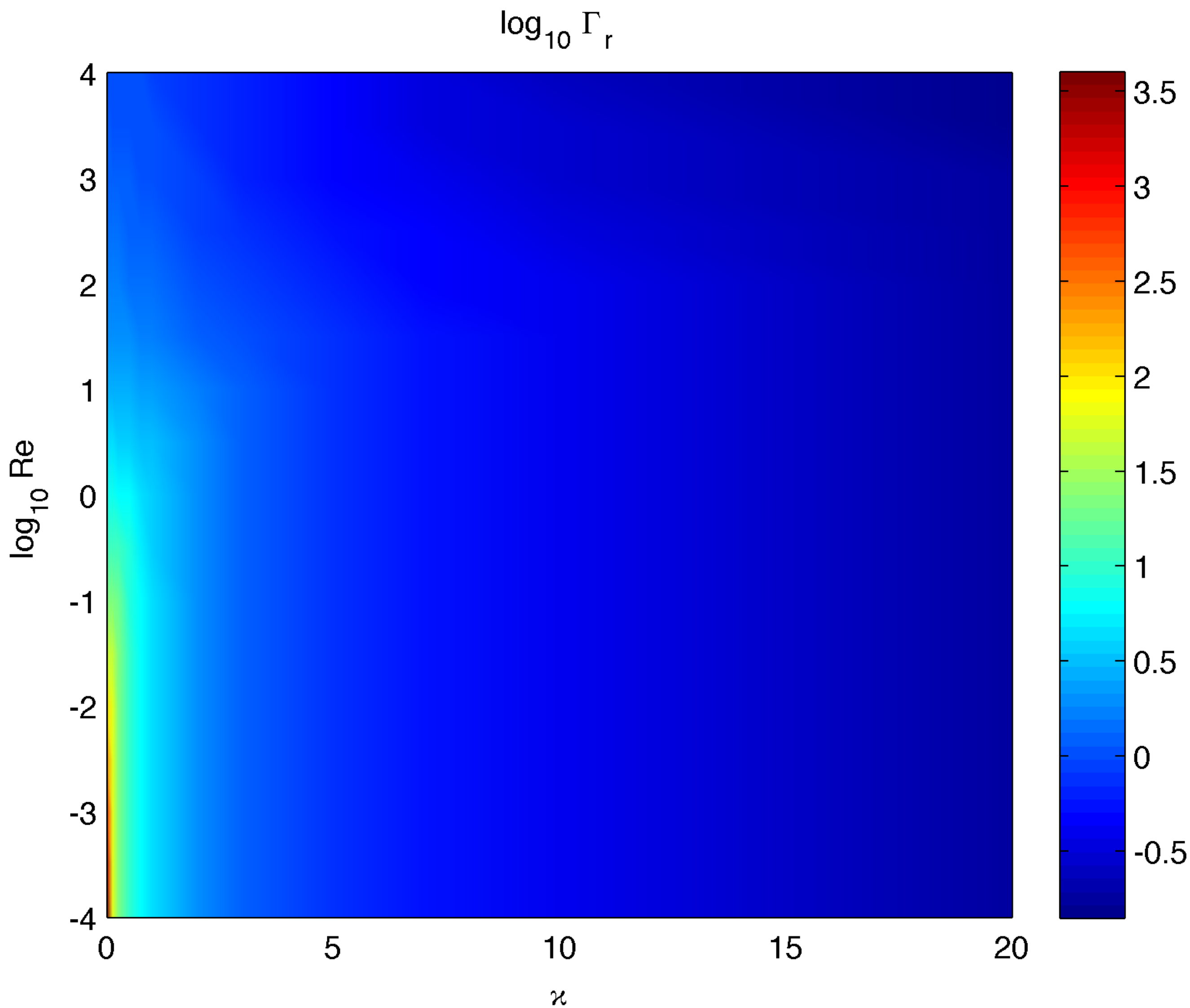
$$\omega_{damped} = \omega_{vac} \left[1 + \frac{\pi \rho_f w}{4 \rho_c h} \Gamma_r(\omega_{damped}, n) \right]^{-1/2}$$

$$Q_n = \frac{\frac{4\rho_c h}{\pi \rho_f w} + \Gamma_r(\omega_{damped}, n)}{\Gamma_i(\omega_{damped}, n)}$$

Frequency response of cantilever beams immersed in viscous fluids with applications to the atomic force microscope: Arbitrary mode order. Eysden and Sader (2007)

Valid for Q >> 1 or Re << 1

Hydrodynamic Function

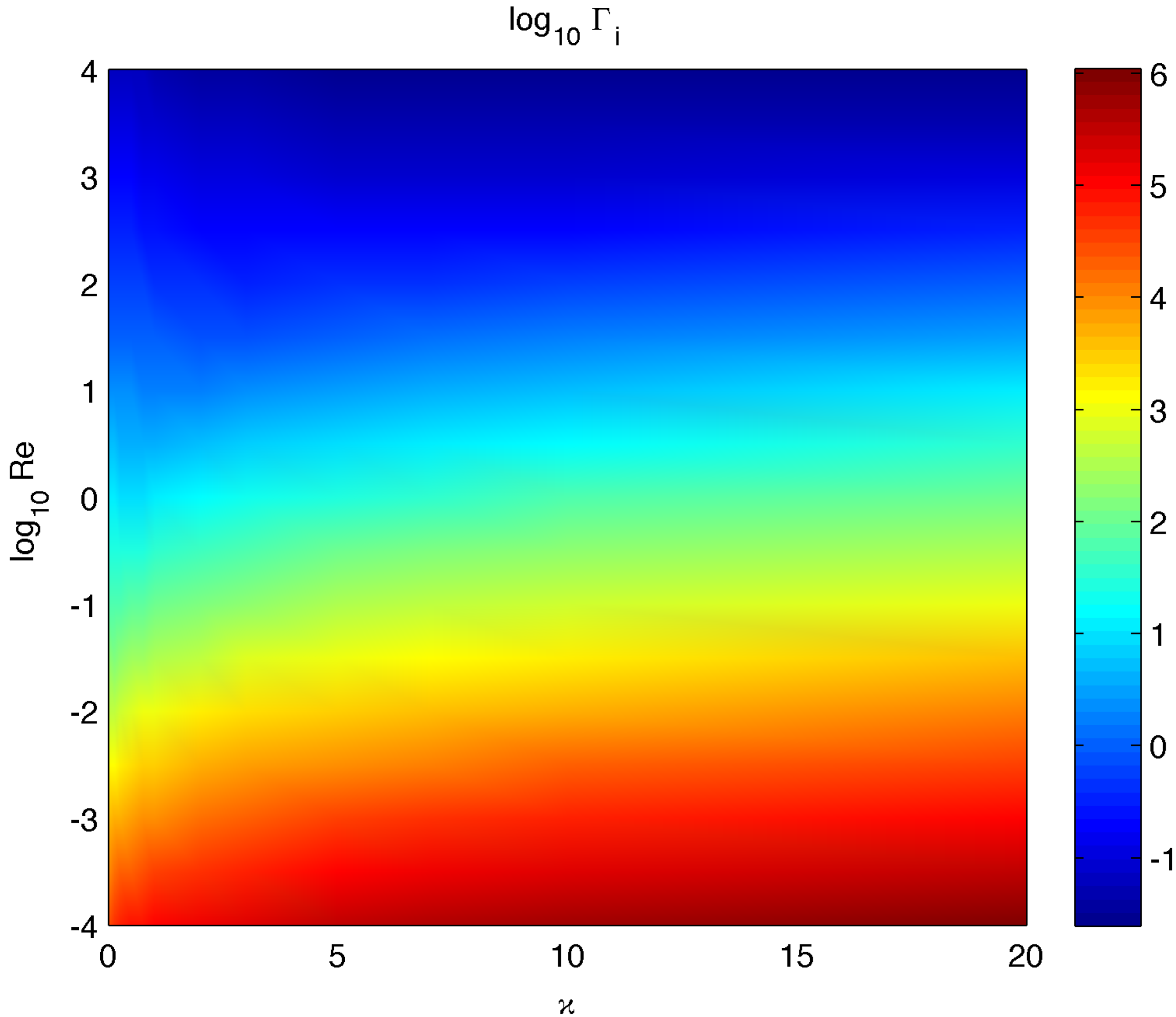


$$\Gamma = f(\kappa, \mathrm{Re})$$

$$\mathrm{Re} = \frac{\rho \omega w^2}{\eta}$$

$$\kappa = C_n \frac{w}{L}$$

Hydrodynamic Function



$$\Gamma = f(\kappa, \mathrm{Re})$$

$$\mathrm{Re} = \frac{\rho \omega w^2}{\eta}$$

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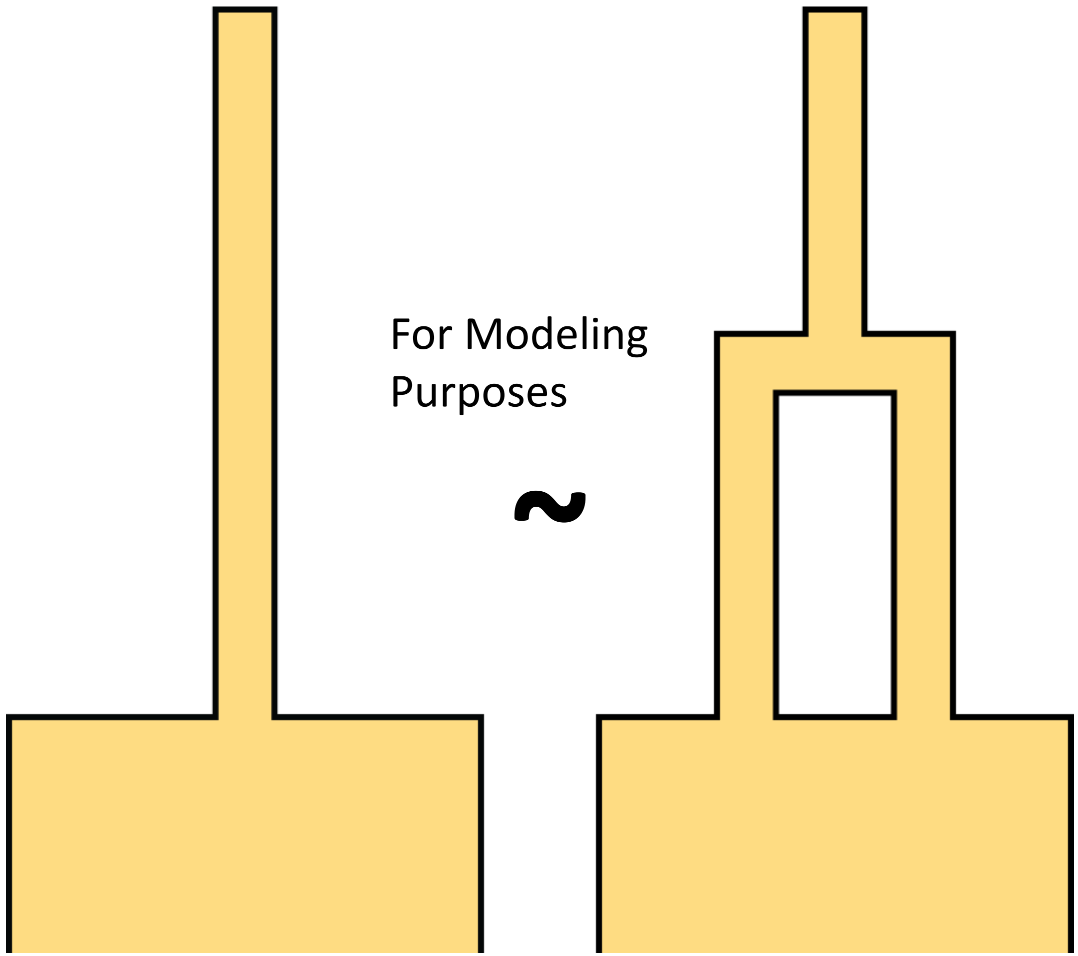
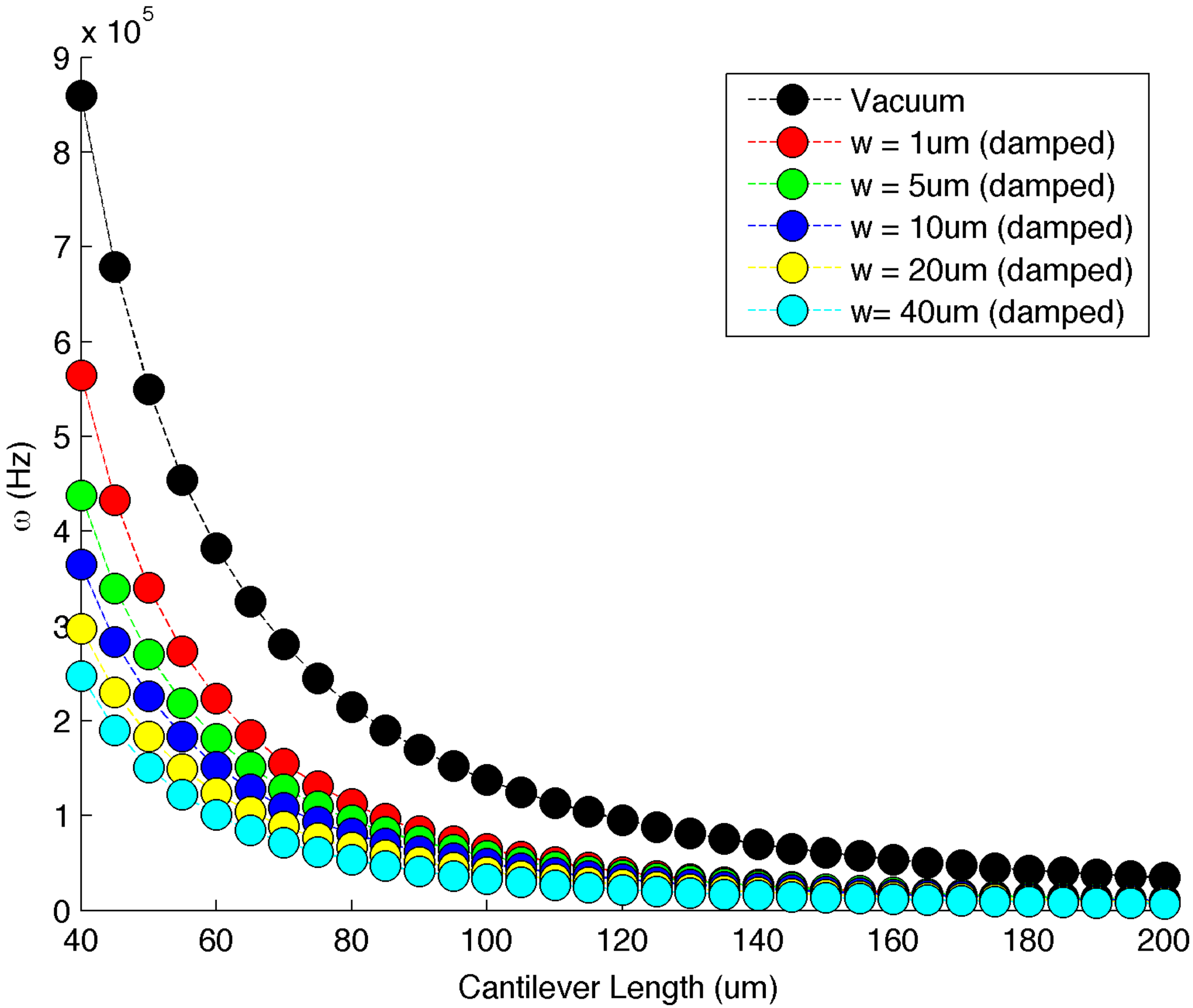
Fluid Modeling

L, w, t

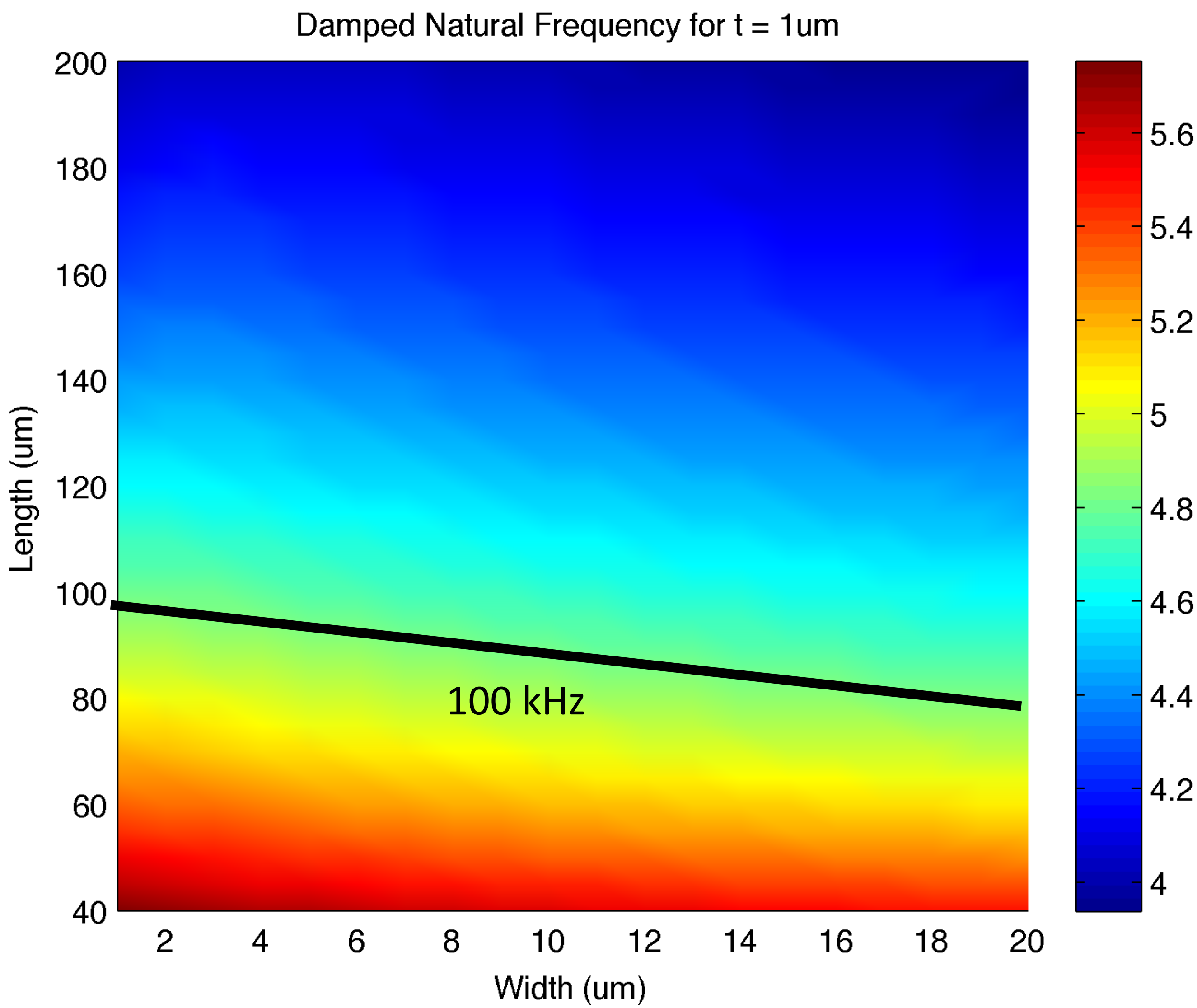
Damping ~ w^2



Vacuum vs. Liquid Frequencies



Damped Natural Frequency



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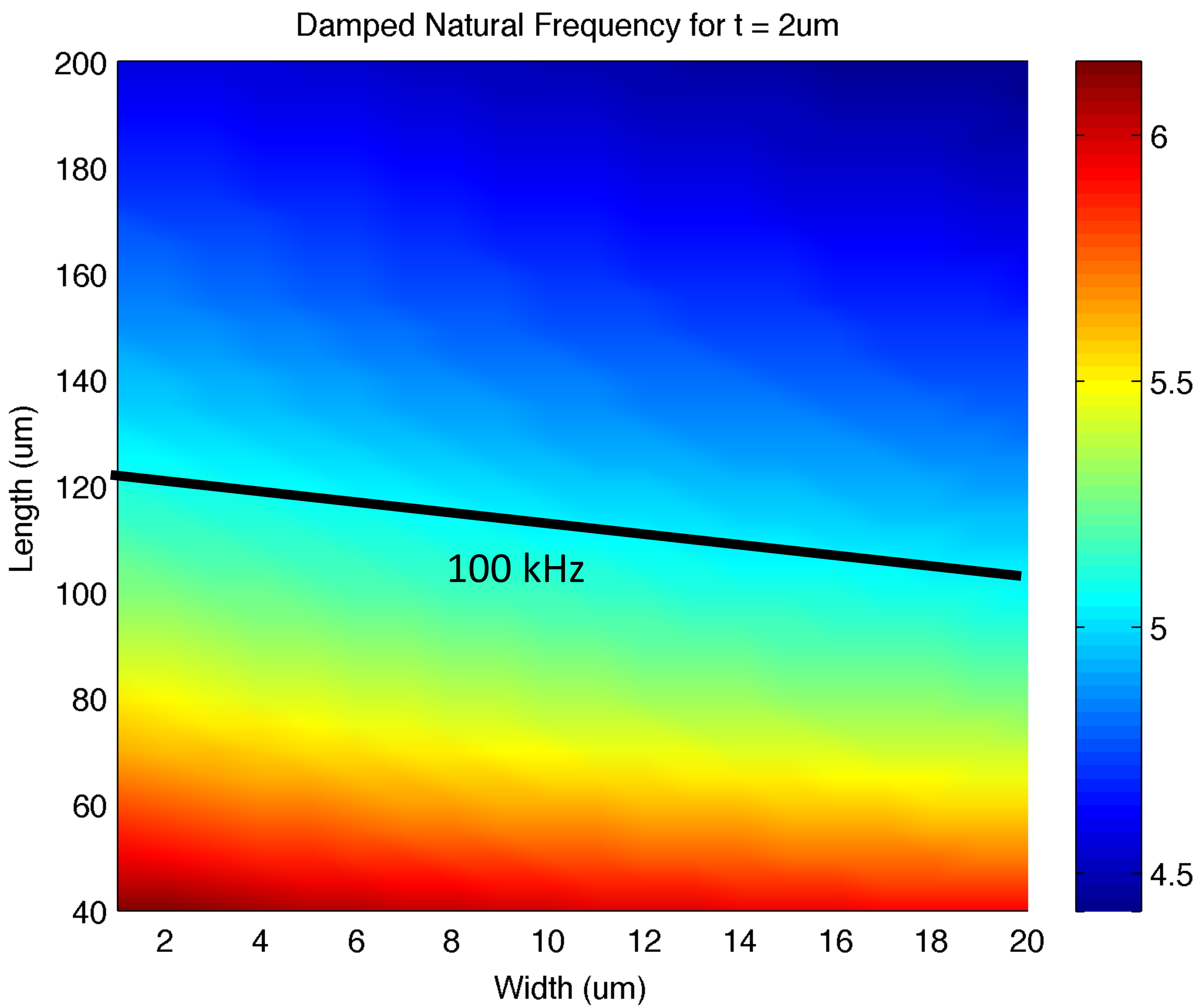
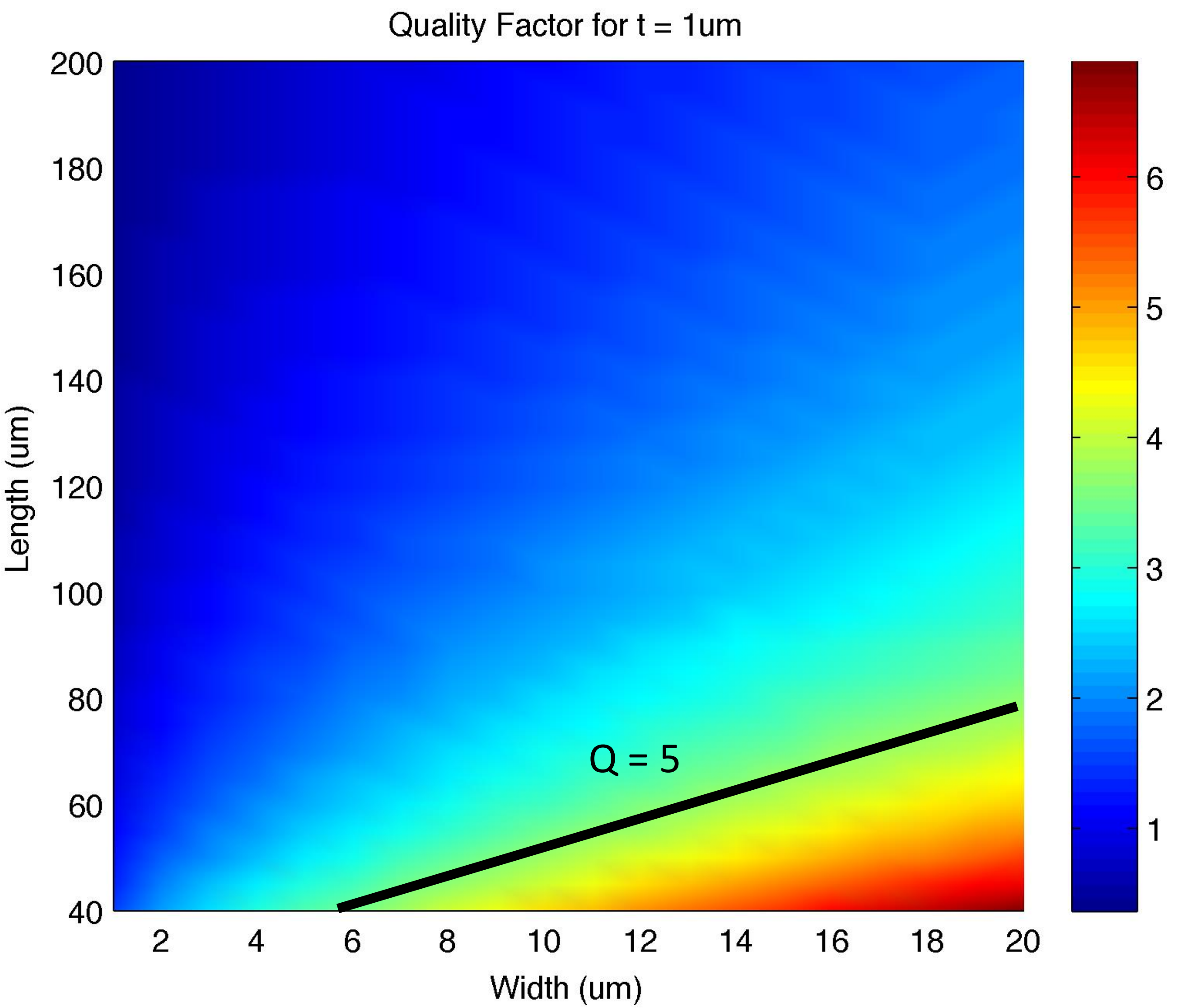


Quality Factor



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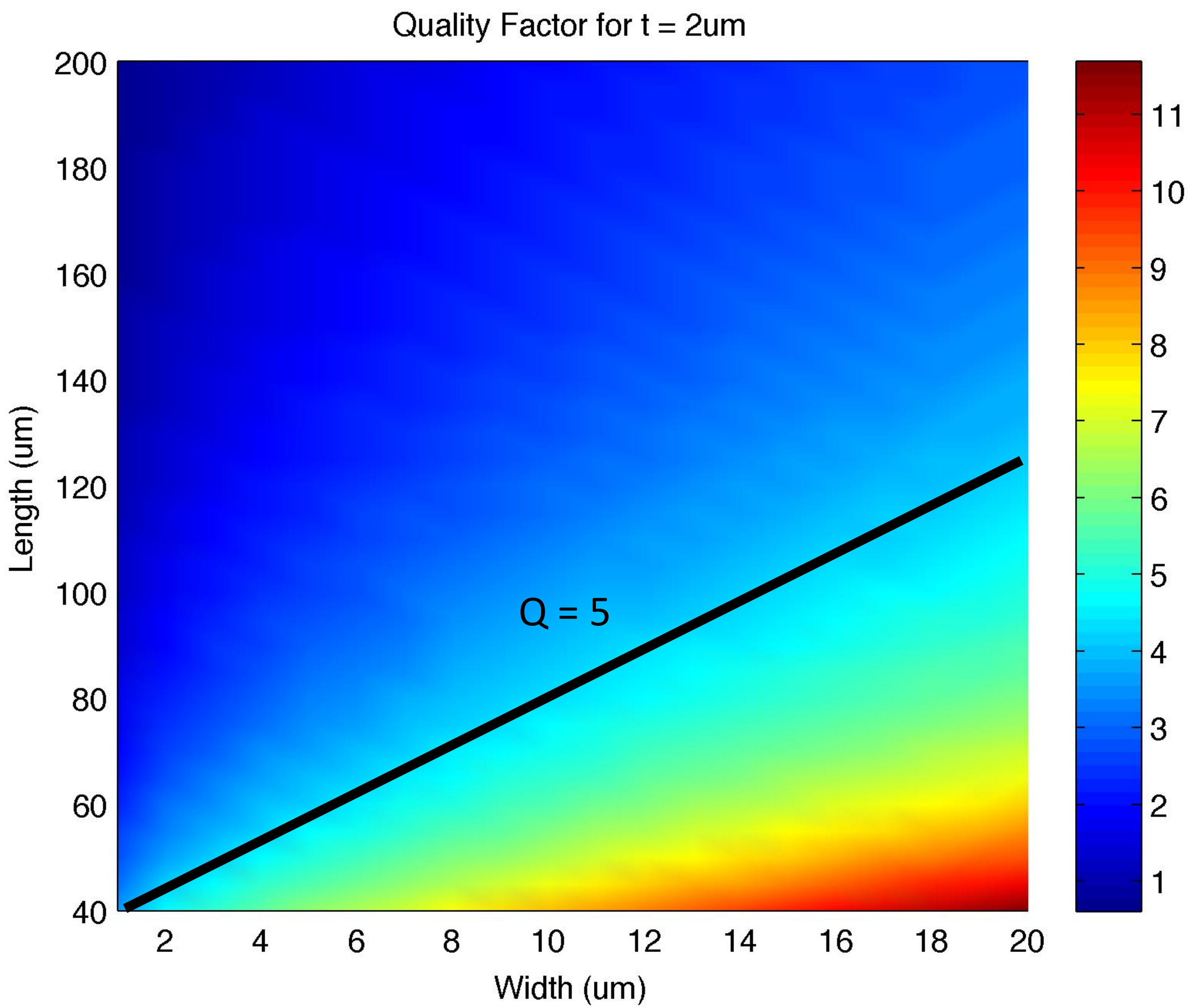

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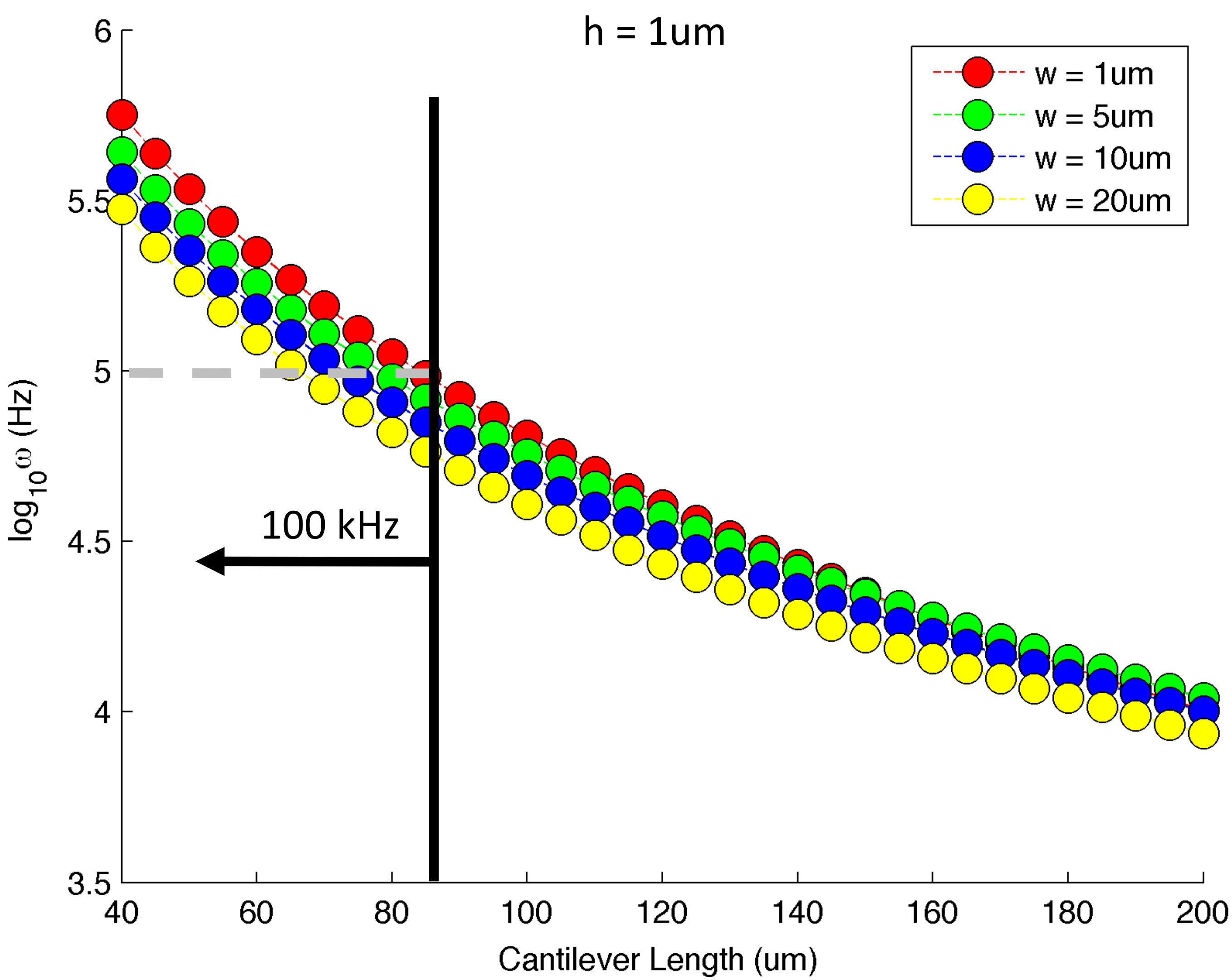

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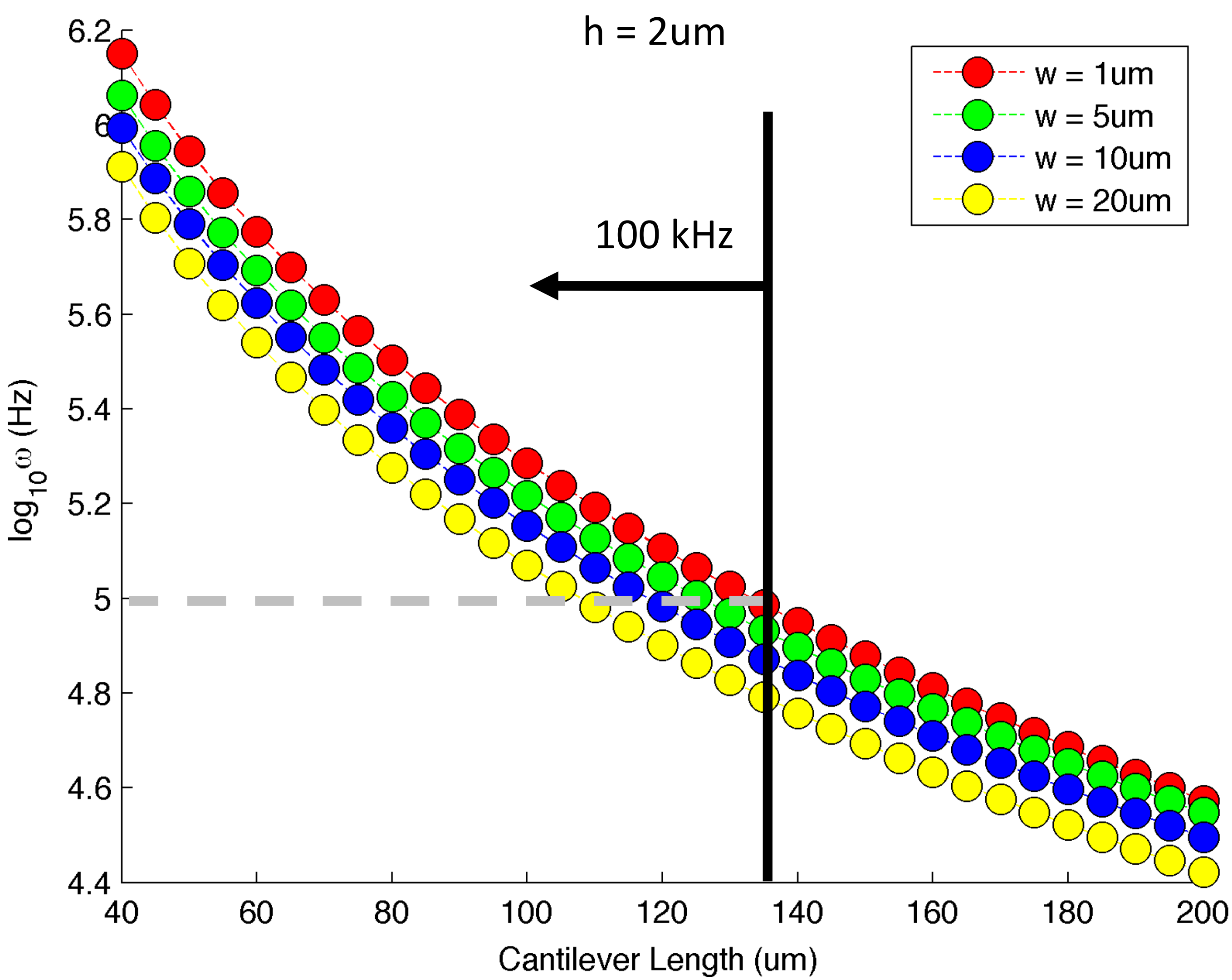

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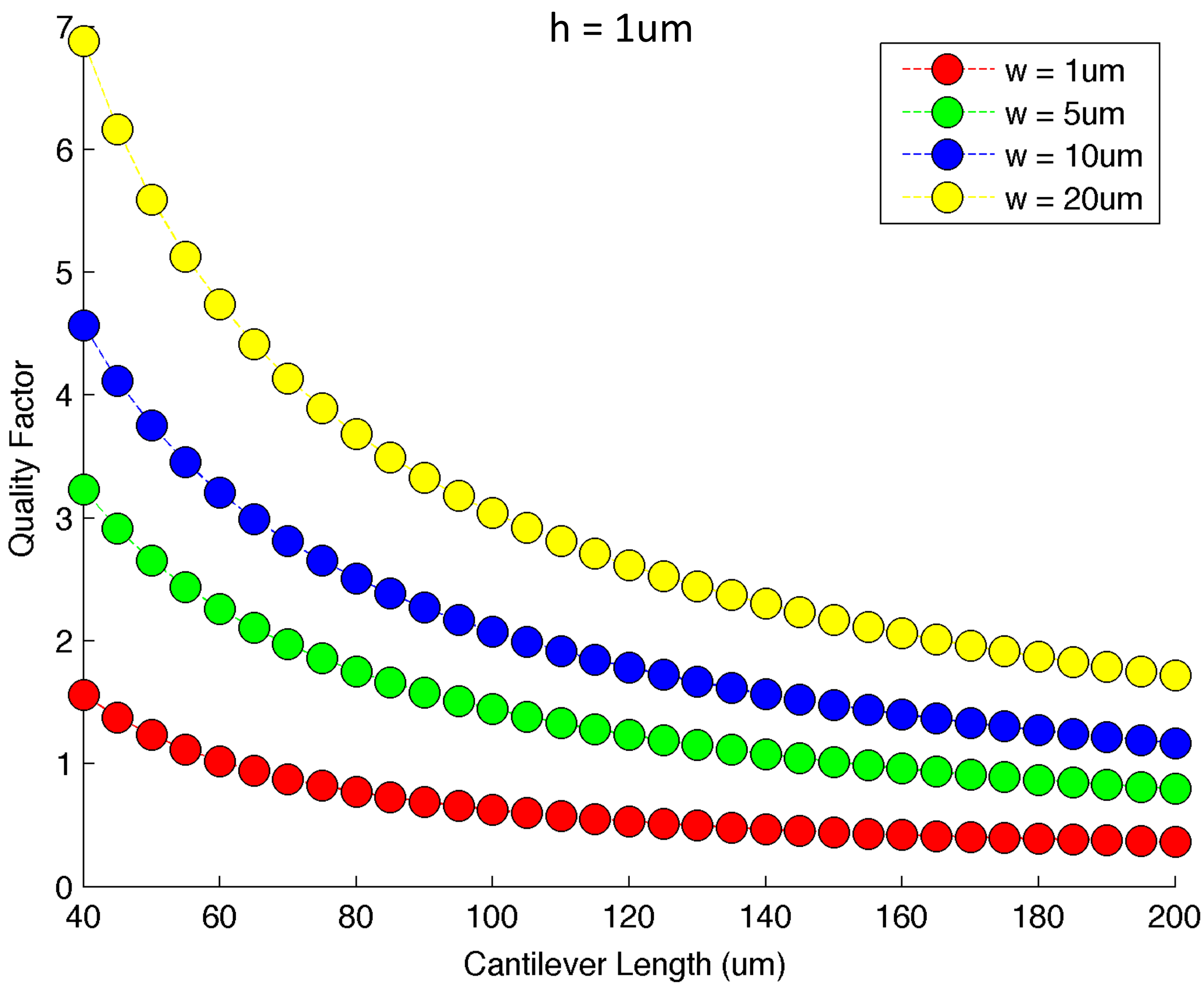

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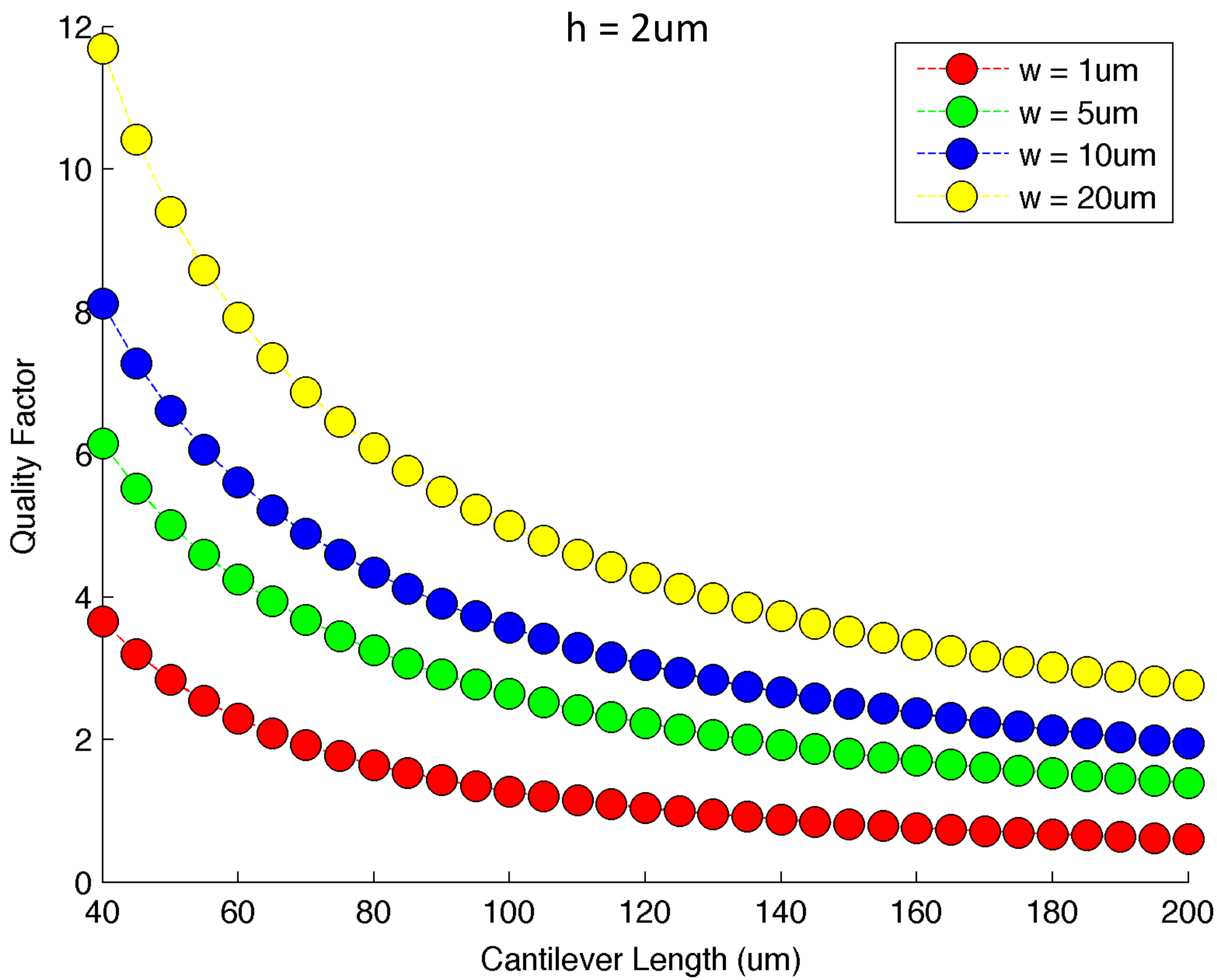
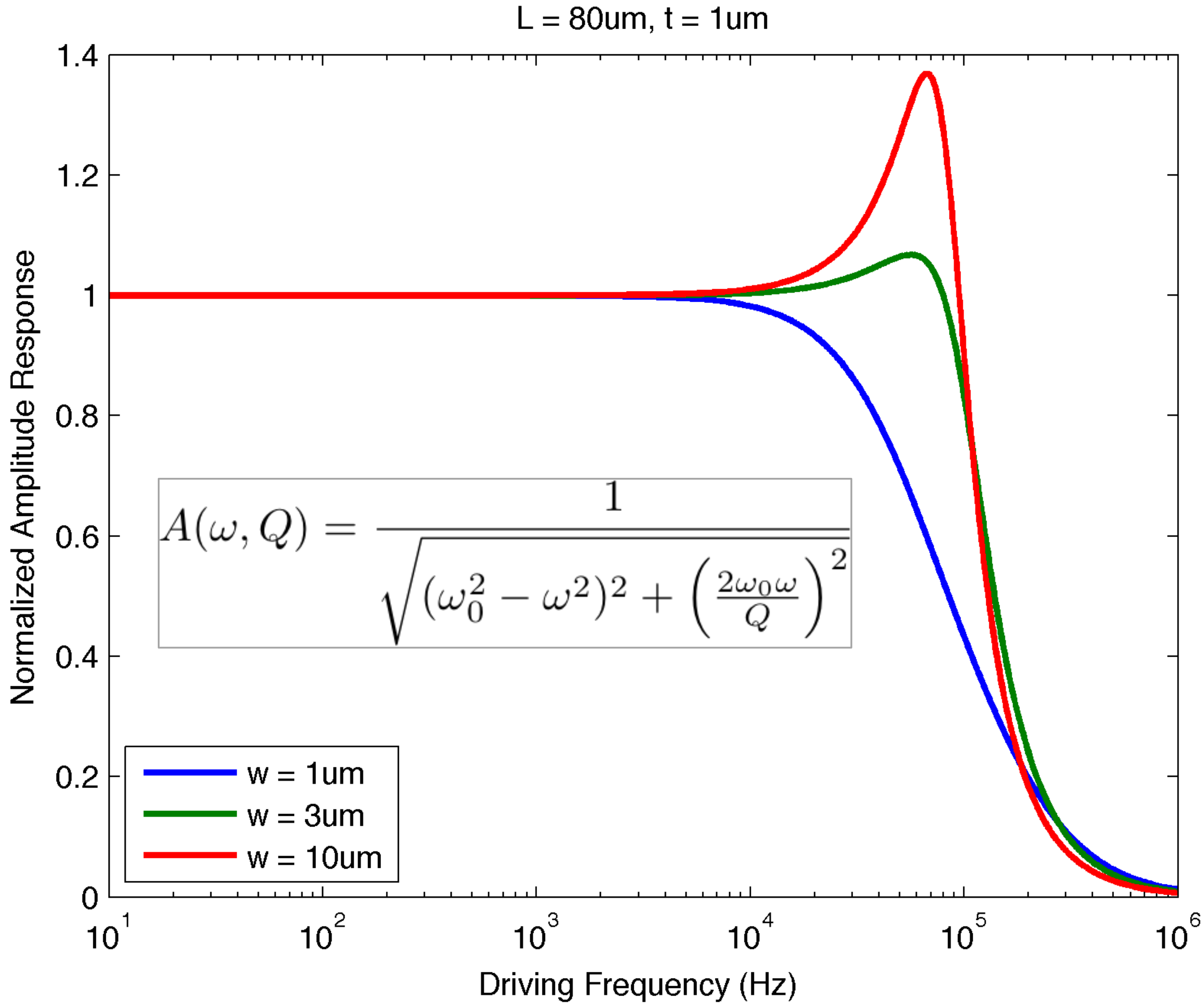


Frequency Response (SHO)



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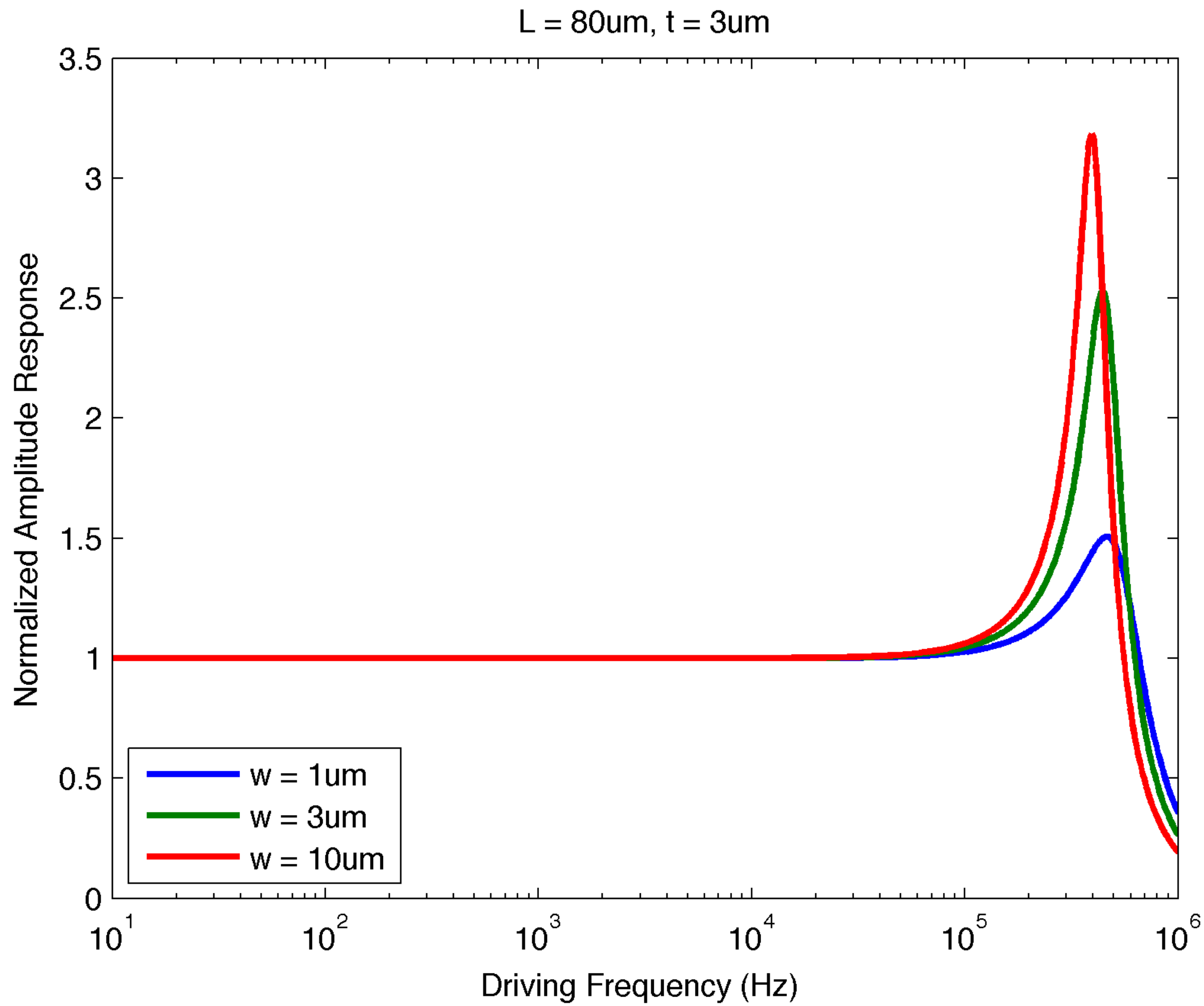
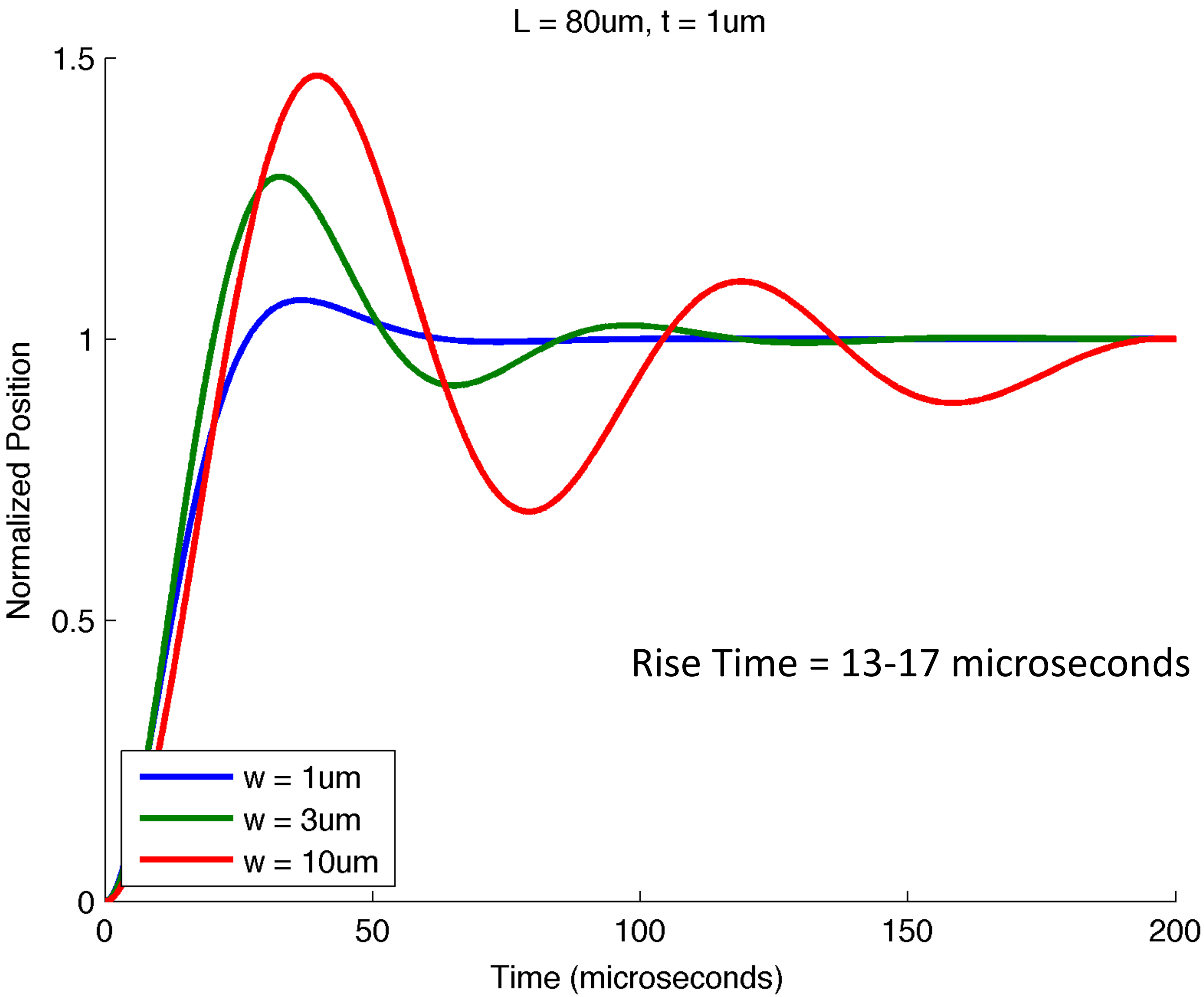


Open-Loop Step Response



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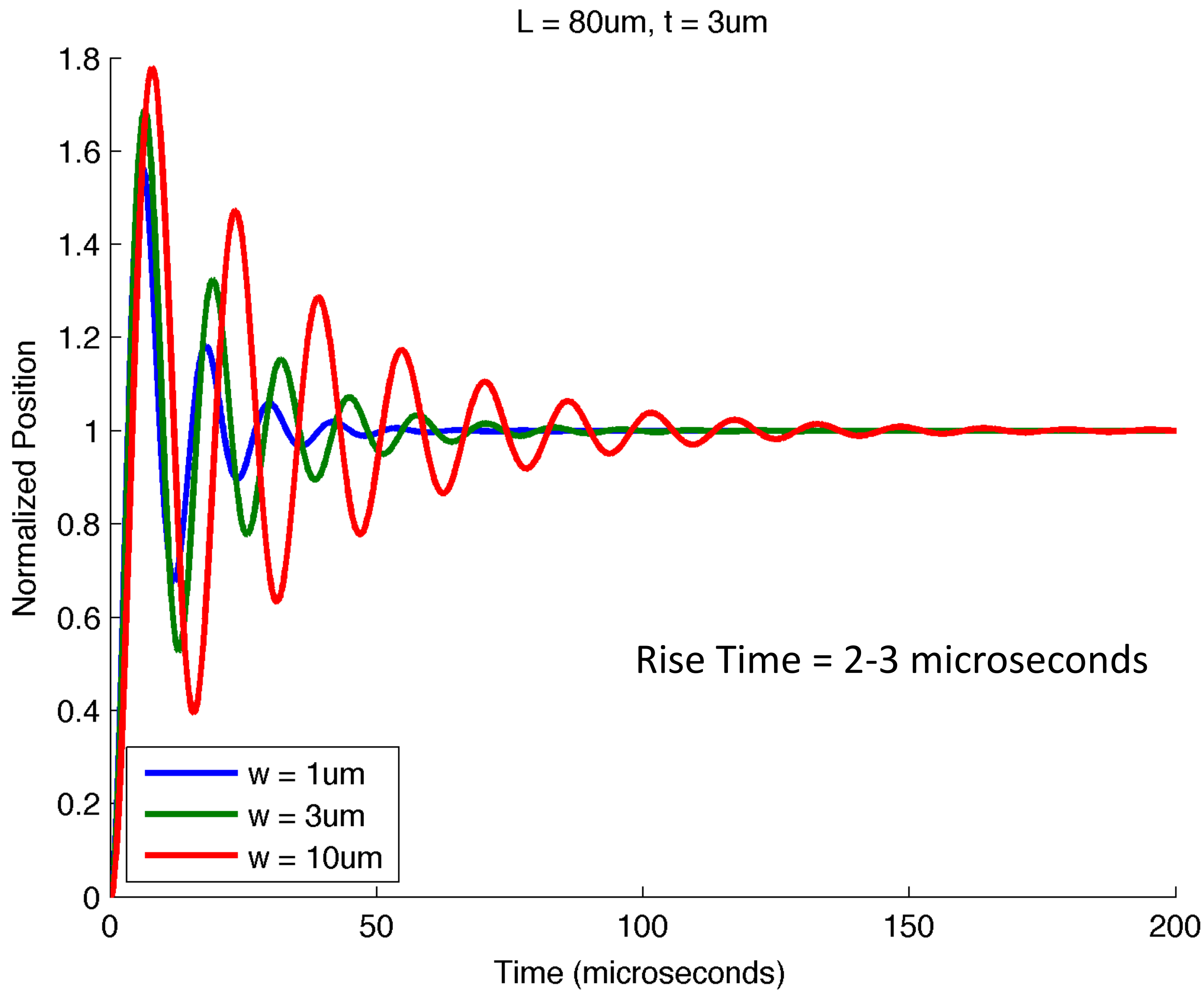

Fluid Modeling Conclusions

- Flat frequency response to 100 kHz requires damped natural frequency ~500 kHz
- Width matters in fluid. Reducing width:
  - Increases first resonant mode frequency
  - Reduces quality factor
- But won't want to reduce w/t too much
- Microsecond rise time is feasible, independent of Q
- Cantilever near a surface
  - Surface doesn't matter if gap > cantilever width
  - If gap < cantilever width, dissipation increases dramatically

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Comparison with Other Approaches

- Normal process
  - Pick a thickness
  - Choose length and width based upon natural frequency constraints
  - Choose piezoresistor dimensions from Harley analysis of 1/f noise considerations or Sung-Jin's work for ion implantation
  - Choose doping & maximize bias voltage

Comparison with Other Approaches

- Can we write the problem more generally?
- Problem statement: Minimize force resolution given
  - Frequency span of signal to be measured
  - Fabrication constraints
  - Power dissipation (quasi-constraint)
- Other optimizations
  - Minimize rise time
  - Maximize effective bandwidth (e.g. $< 5\%$ frequency response deviation)
  - Minimize noise at a particular frequency

Model and Goal

- Optimize cantilever inputs to maximize performance
  - Cantilever geometry
  - Piezoresistor Geometry
  - Piezoresistor doping
  - Bias voltage
- Constants
  - Fluid media
  - Cantilever mechanical properties
- Constraints
  - Resonant frequency
  - Power dissipation
- Goals
  - Force resolution

Electrical Modelling

- Piezoresistor
  - Epitaxial only (for now, see conclusions)
  - Concencentration dependent mobility
  - Piezoresistive coefficient from Harley data
  - Voltage drop completely across the piezoresistor (reasonable for metal lines)
- Noise
  - 1/f, Johnson, amplifier (no thermomechanical, fluid yet)
  - $\alpha = 10^{-5}$ (approximated from Harley data)

How Well does the Model Fit?

- Compare model to epi cantilever experimental data
  - Harley’s 89nm thick cantilever

Cantilever

Thickness	89 nm
Width	44 um
Length	300 um

Piezoresistor

Thickness	30 nm
Width	44 um
Length	45 um
Gap	3 um

Other

Freq Min	10 Hz
Freq Max	1 kHz
Bias	5 V
Doping	4e19/cm^3
Alpha	1e-5

How Well does the Model Fit?

	Calculated	**Measured**
Force Resolution (pN)	0.35	0.5
Resistance (Ohms)	2003	-
Integrated Noise (V)	5.2e-7	1.14e-6
Stiffness (N/m)	4.8e-5	3e-5
Knee Frequency (Hz)	1534	1000
Piezo Factor (m^2/N)	3.7e-10	4e-10
Johnson Noise Density (V)	5.7e-9	1.5e-8
Power Dissipation (mW)	12.5	-
Natural Freq, Vacuum (Hz)	1359	-
Natural Freq, Water (Hz)	**34**	-
Quality Factor	0.5	

Pretty good

The Optimization Problem

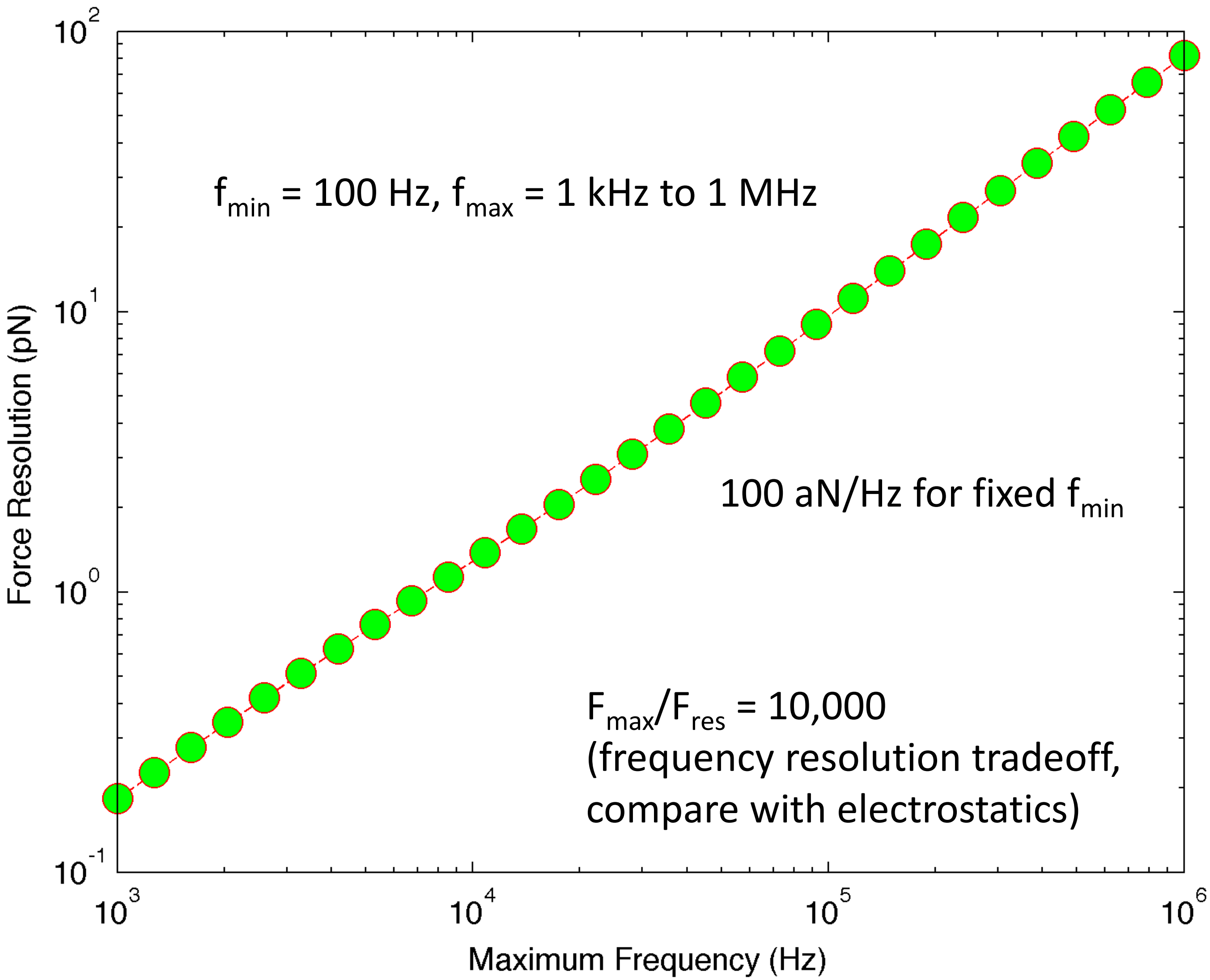
- Optimization characteristics
  - Smooth functions
  - Suggest single global optimum (proof?)
- Constraints
  - Simple boundaries on geometry, doping dictated by fabrication capabilities
  - Nonlinear constraints (e.g. frequency, power, other)
- Options
  - Brute force global (10^n = infeasible)
  - Guess-and-check (heuristics)
  - Constrained, nonlinear optimization

Piezoresistive Microphone Design Pareto Optimization: Tradeoff Between Sensitivity and Noise Floor, Papila et al, JMEMS (2006)

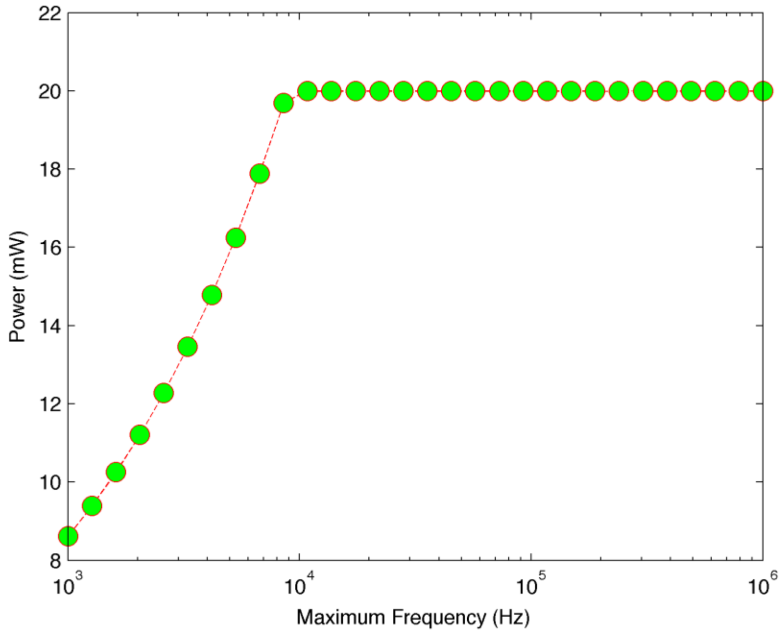
Optimization Problems

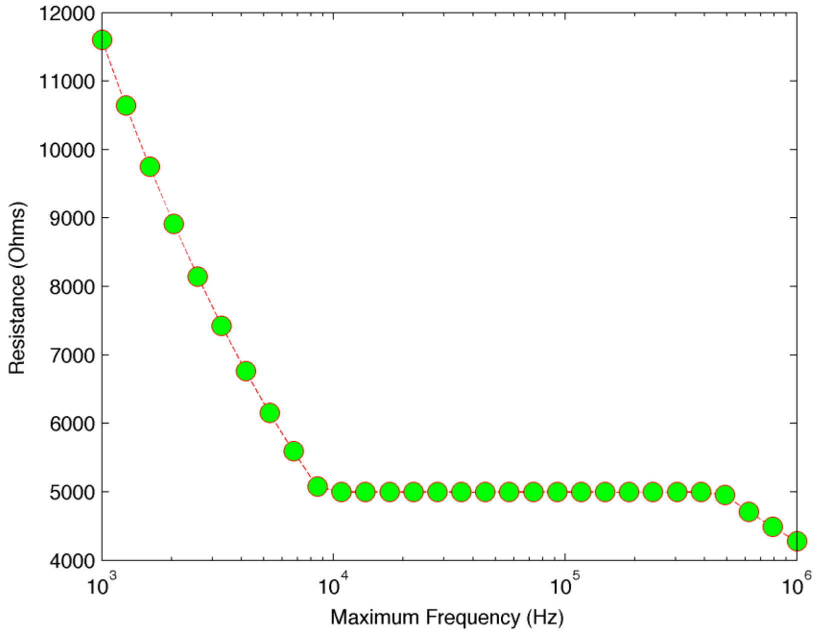
- Fixed f_{min}, varying f_{max} (resonance and noise integration)
  - f_{min} = 100 Hz
  - t_{min} = 1um
  - w_{min} = 1um
  - N_{max} = 1e20/cc
  - V_{max} = 5V
- Fixed f_{max}, varying f_{min}
  - f_{max} = 100 kHz
  - Rest same as above
- Both optimizations performed for vacuum
- ~100 iterations per data point => 30 minutes
- Very early results, from the last few days

Force Resolution

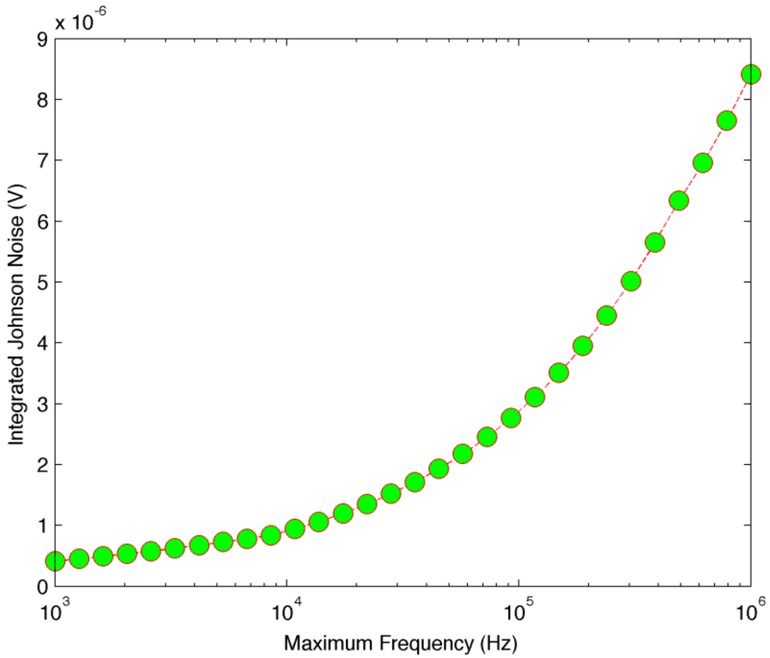


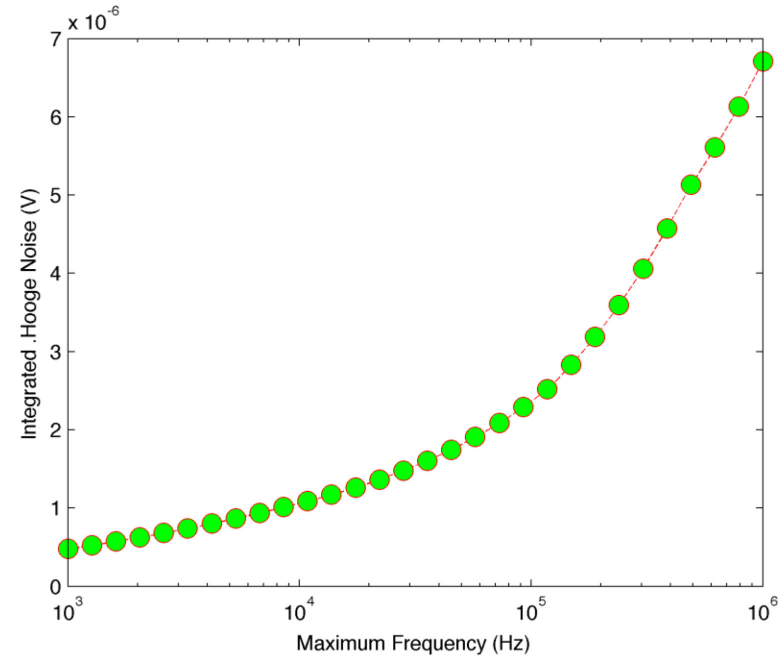
Power and Resistance





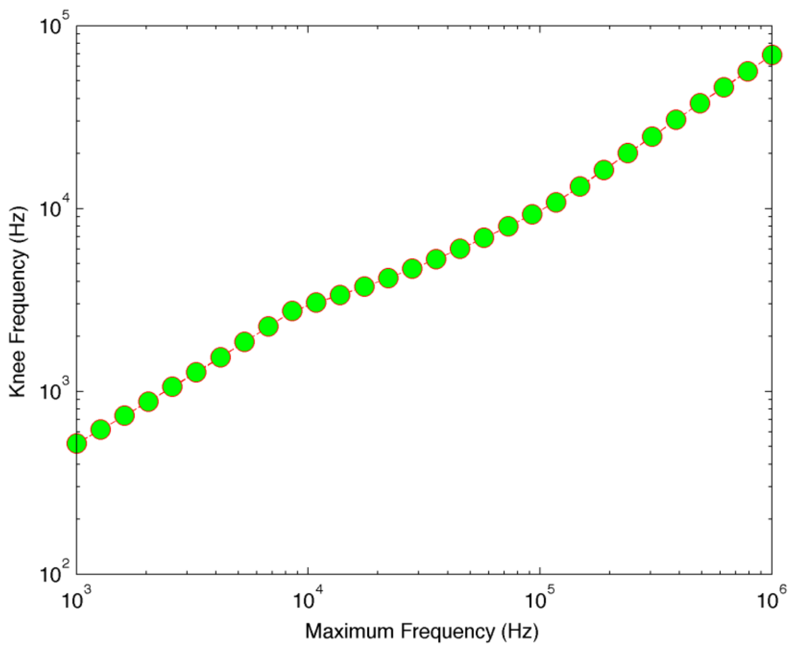
Johnson and Hooge Noise

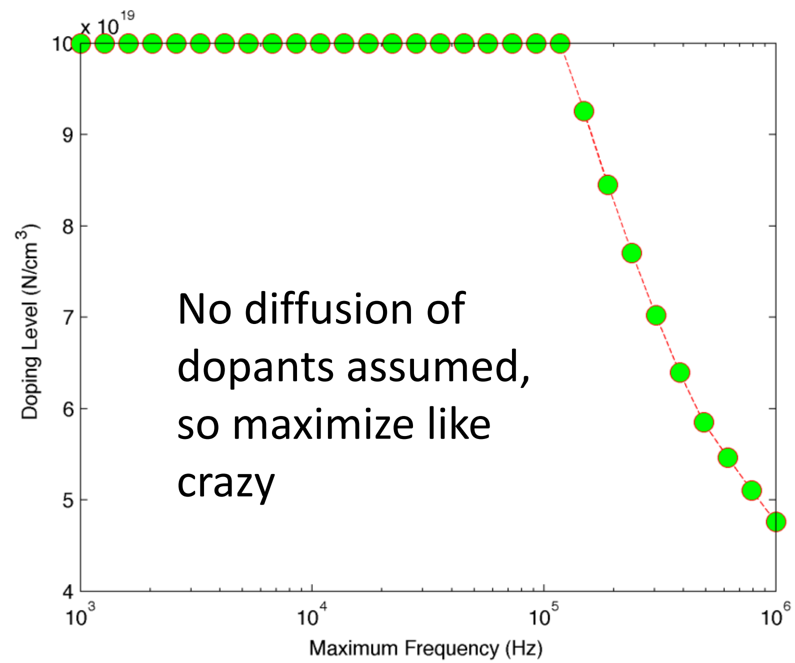




Roughly comparable Johnson and 1/f noise (need to prove that it's the global minimum and not just the local minimum)

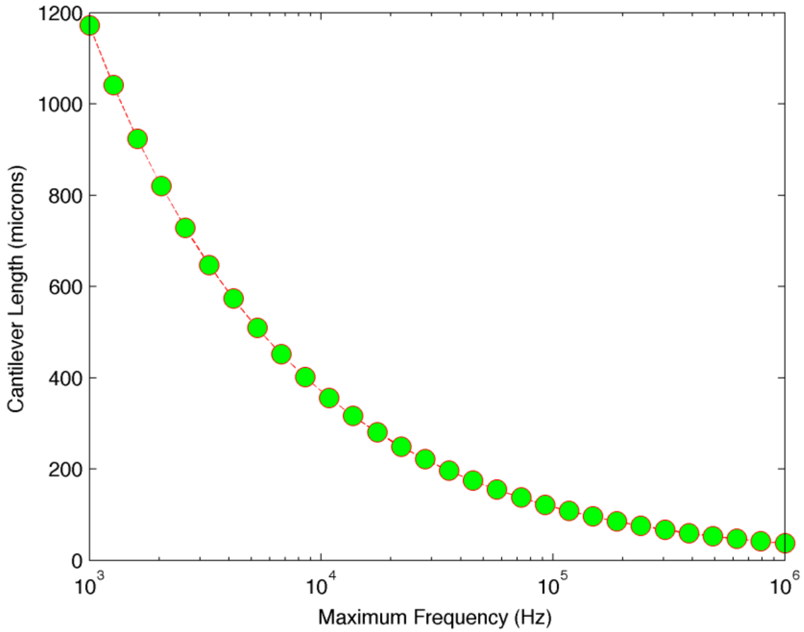
Knee Frequency and Doping

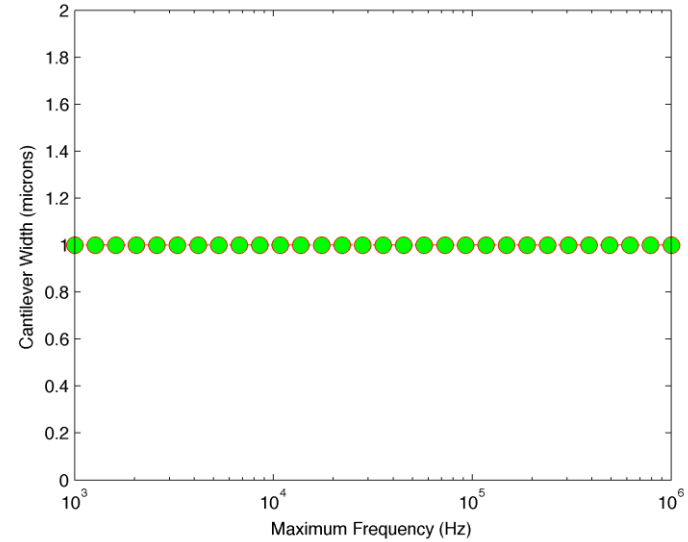


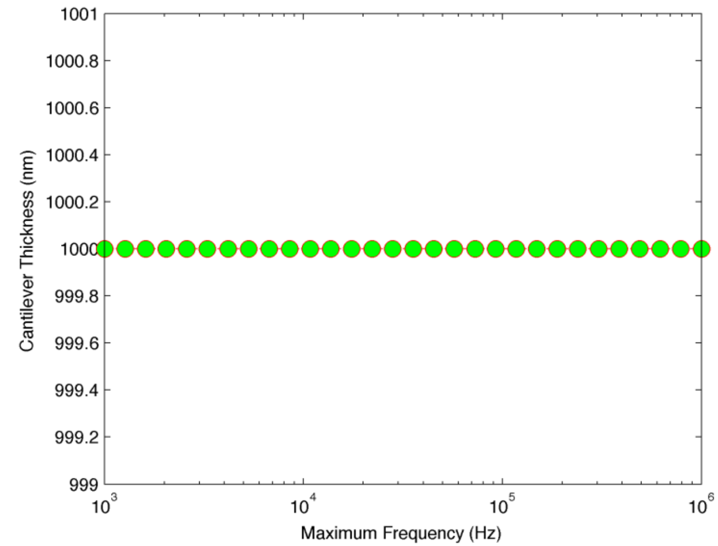


Compare knee frequency and f_{max}. High doping levels.

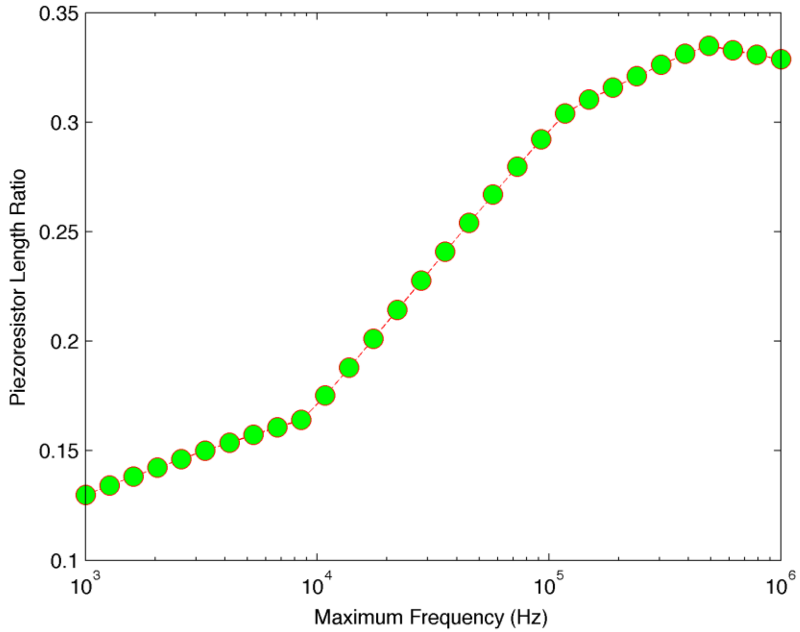
Cantilever Geometry

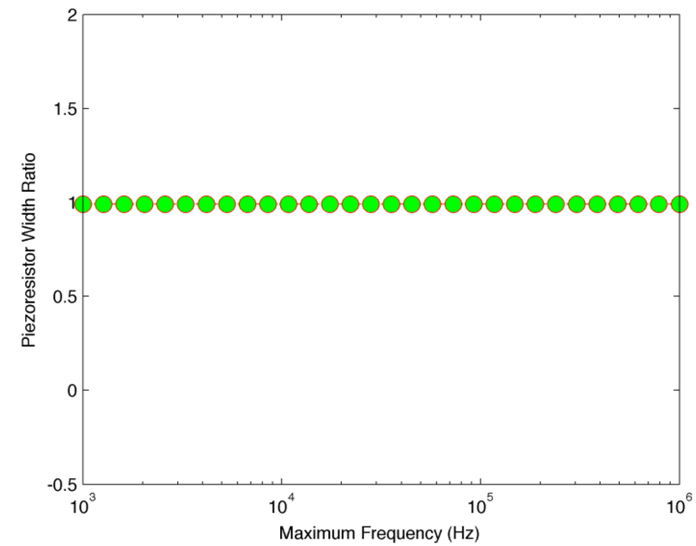


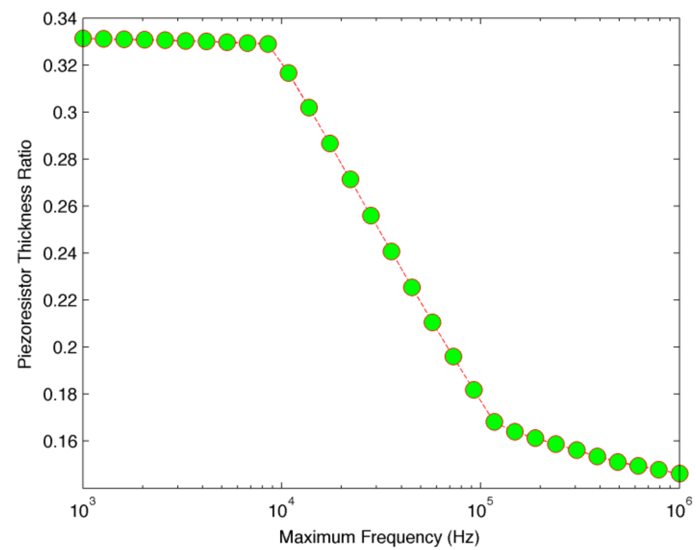




Piezoresistor Geometry

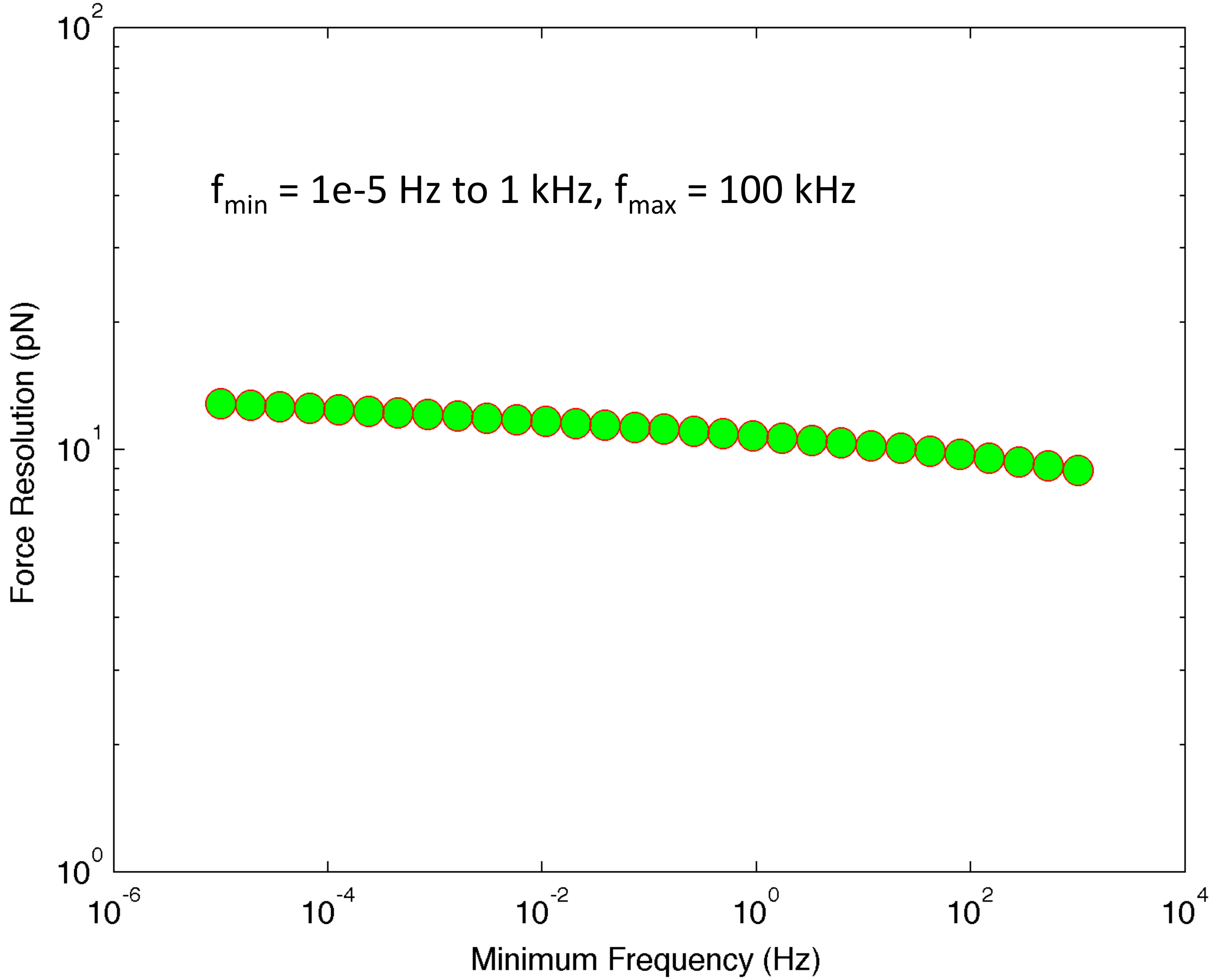




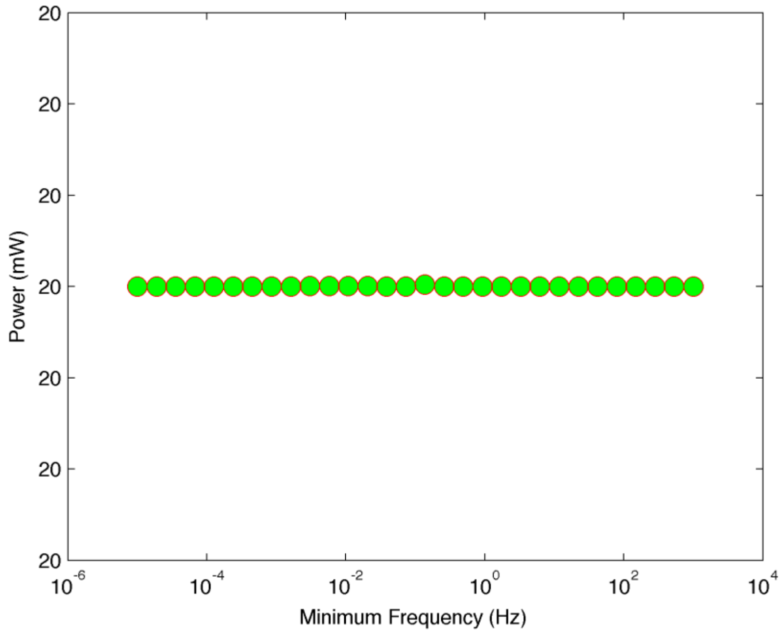


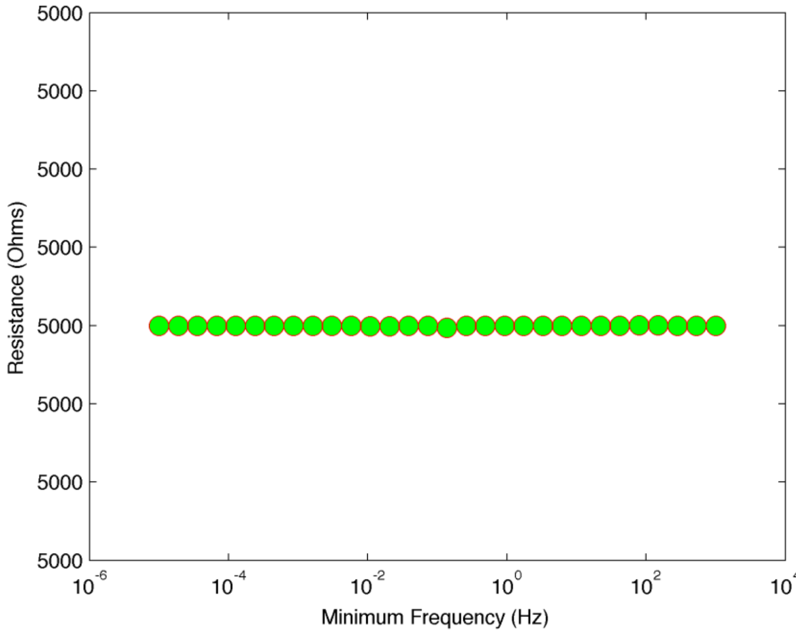
Not the design parameters described by Harley

Force Resolution

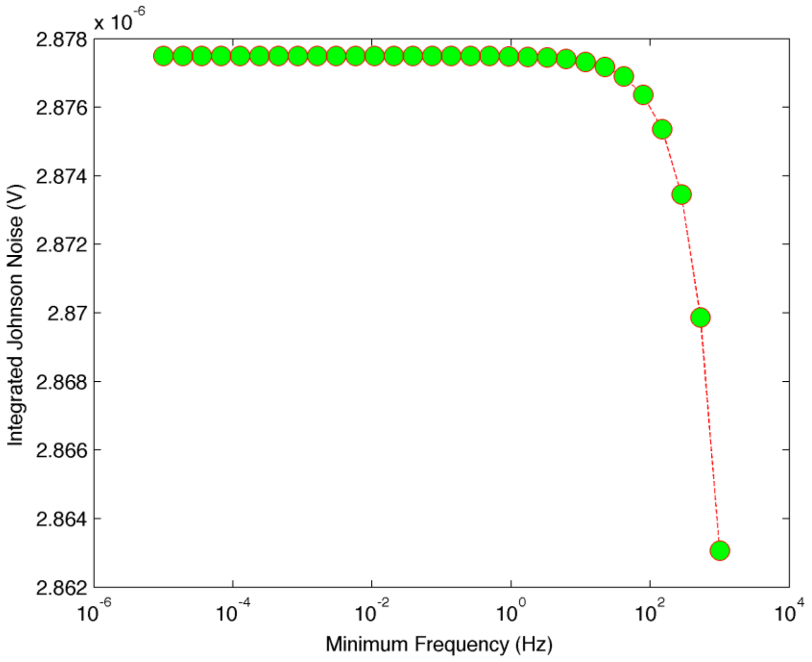


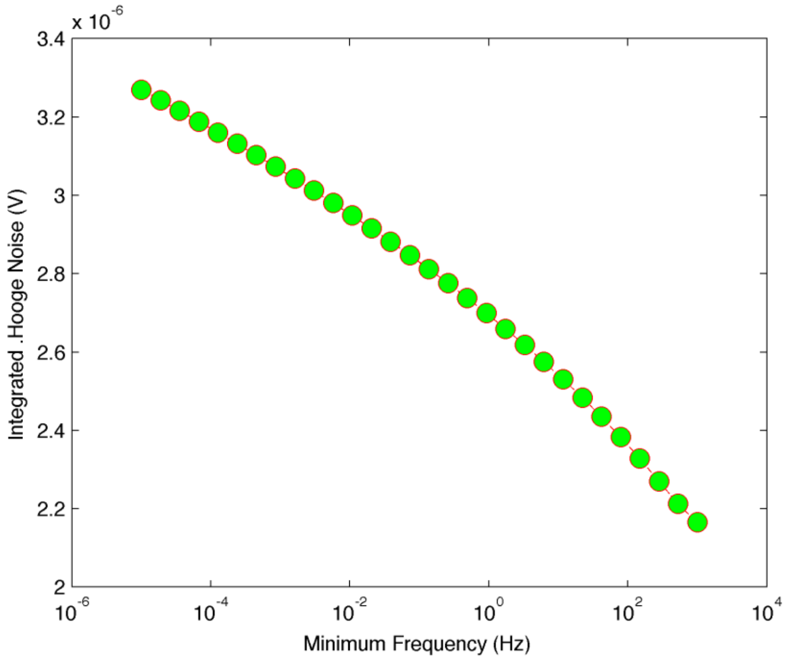
Power and Resistance





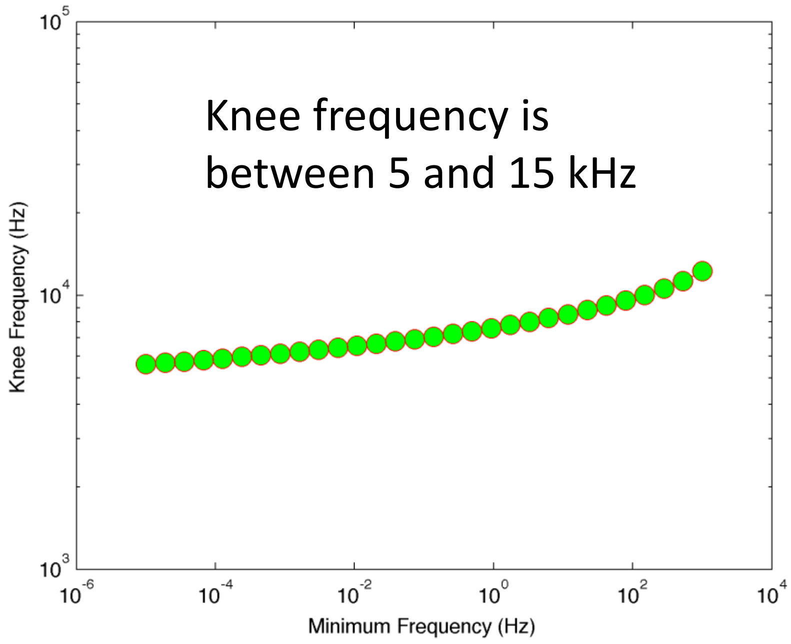
Johnson and Hooge Noise

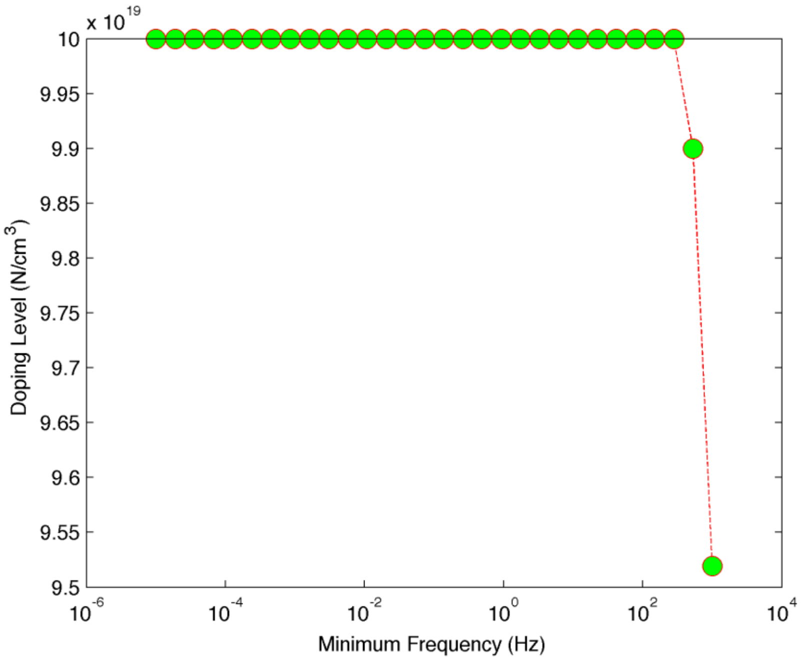




Little change in integrated 1/f noise by changing piezoresistor dimensions.

Knee Frequency and Doping





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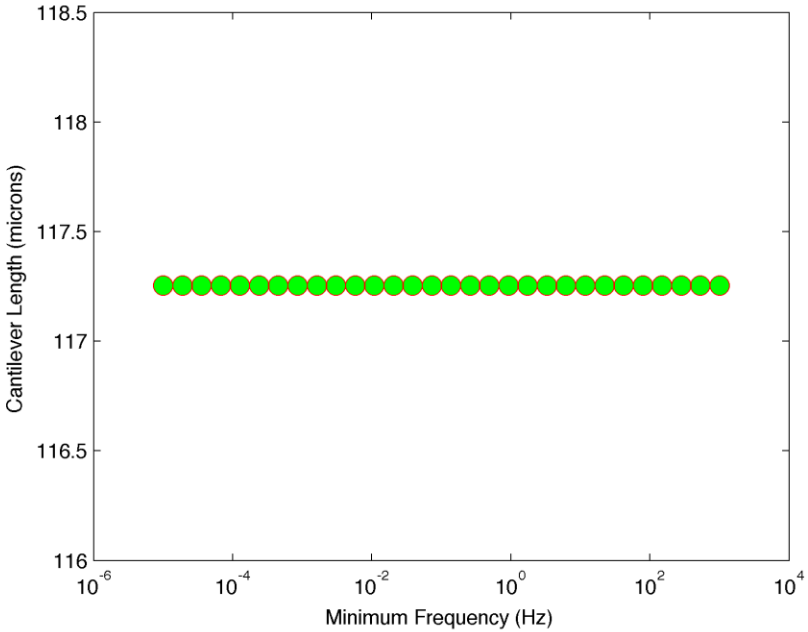

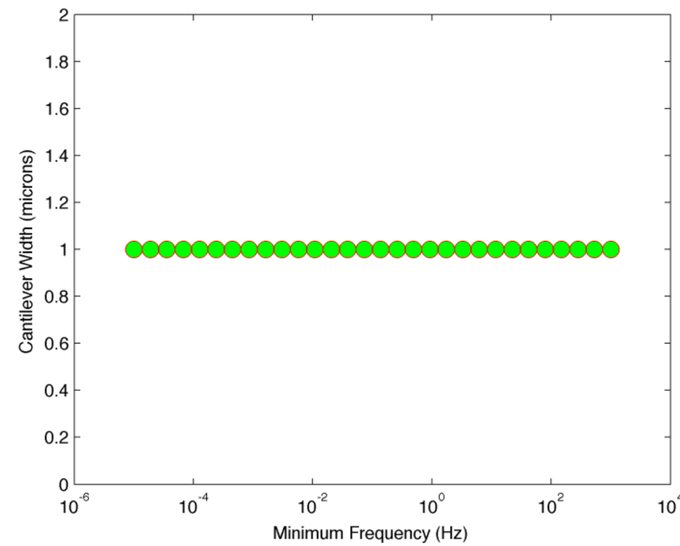

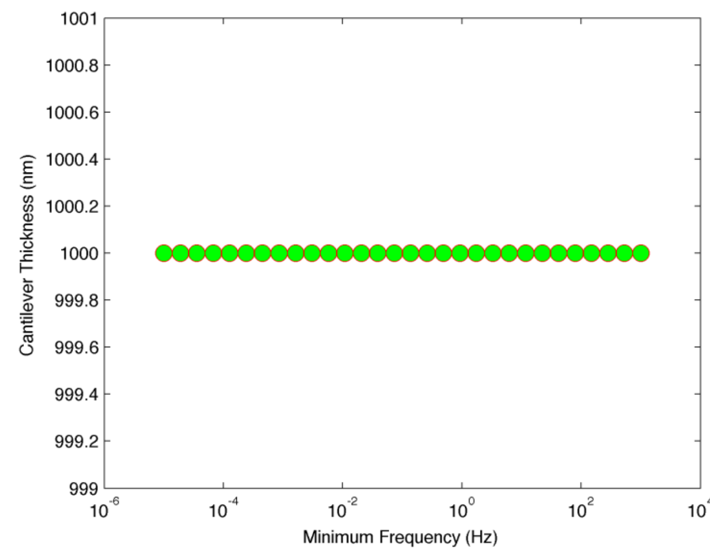

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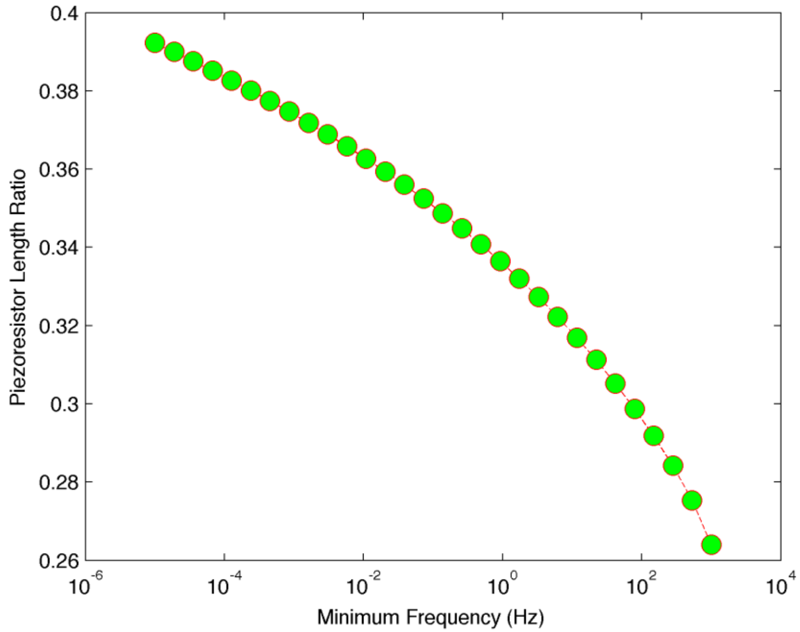

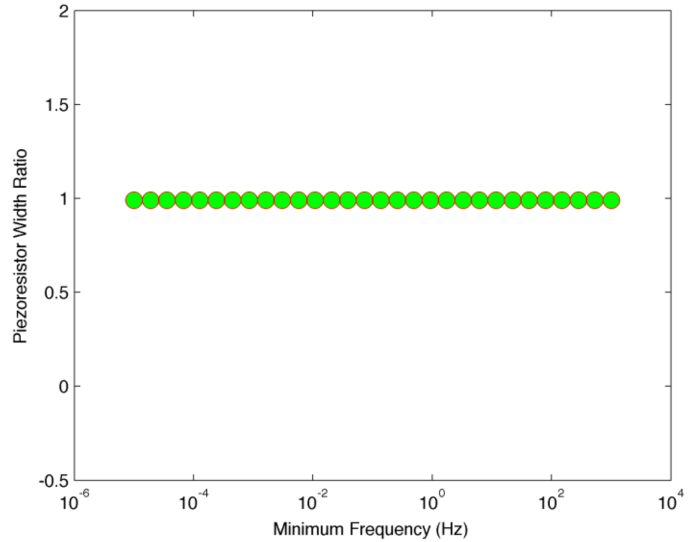

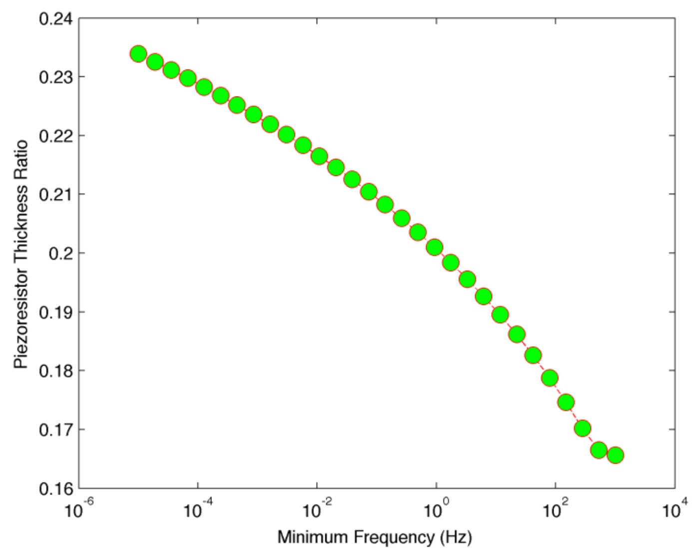

Again, not the design parameters described by Harley

Optimization Conclusions

- High doping is preferred
  - Even without taking TCF into account
  - Based upon Harley fit to experimental data
- Maximize piezoresistor width
- Piezoresistor thickness and length ratios don't agree with prior optimizations
  - Still need to definitively prove that these global optima (in progress)
- Model agrees with ultra thin epitaxial cantilevers
- Numerical optimization is more flexible and simple than heuristic design
- More on extending the optimization at the end

Future Design Work

- Optimization
  - Thermal model rather than power dissipation
  - Integration with TSUPREM for ion implantation, won't need lookup tables
  - Integration with Comsol for complete model
  - Optimize rise time, useful frequency range
- Modeling
  - Complete electromechanical model (e.g. piezoelectric charging, power electronics)

Optimization Code and Model

- Originally written in Python using SciPy (March)
  - Optimizers did not reliably converge, lots of headaches
- Switched to Matlab using object oriented features introduced in R2008a (May)
- Uses local, nonlinear constrainted optimization
  - L-BFGS-B (fmincon)
- Code is online
  - http://microsystems.stanford.edu/git/cantilever_optimization.git
    - http://microsystems.stanford.edu/wiki/Version_Control_with_Git
  - Reasonably clean code, will have README soon

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Piezoelectric Actuation Model

	Stiffness (10^{10} N / m^2)	Strain Coefficient (10^{-12} C / N)	Relative Permittivity	Coupling Coefficient K^2 (%)	Velocity (m / s)	Density (kg / m_3)
Aluminum Nitride (AlN)	33.0	5.6 (d_{33})	8.6	6.0	11,300	3.26
Barium Titanate ($BaTiO_3$) *	11.0 - 27.5	82-145 (d_{33})	625-1350	39 – 46	4460	5.85
Lithium Niobate ($LiNbO_3$)	24.5	19.2 (d_{33})	44	17.2 †	4379 †	4.64
Lithium Tantalate ($LiTaO_3$)	23.3	8.0 (d_{33})	41	4.7 †	4112 †	7.64
P(VDF–TrFE)	0.3	-12.0 (d_{31})	13	0.18	2400	1.88
Quartz (SiO_2)	10.7	2.3 (d_{11})	4.5	0.11 †	3948 †	2.65
PZT (PbZrTiO3)*	4.8 – 13.5	240-550 (d_{33})	1100-3200	66 - 73	4600	7.55
Zinc Oxide (ZnO)	21.0	10-12 (d_{33})	8.5	7.5	6,080	5.60

SAW Substrates

Thickness mode, thin film

Ferroelectric ceramic, bulk material

Ferroelectric polymer

$$k^2 = \sqrt{\frac{mechanical\ \ energy\ \ stored}{electrical\ \ energy\ \ applied}}$$

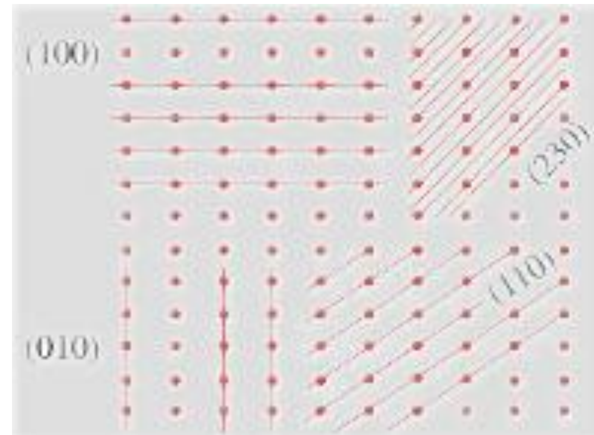
Borrowed from Justin Black, UC Berkeley

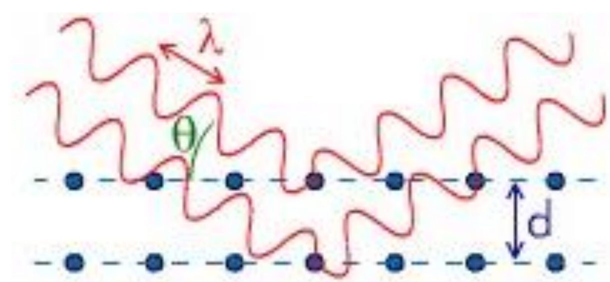
X-Ray Diffraction

- Diffraction occurs only when the distance travelled by the rays reflected from successive planes differs by a complete number n of wavelengths:

  $n\lambda = 2d \sin\theta$

- By varying the angle θ, the Bragg's Law conditions are satisfied by different d-spacings in polycrystalline materials.
- A perfect crystal would give peaks that were delta functions.





λ is the x-ray wavelength

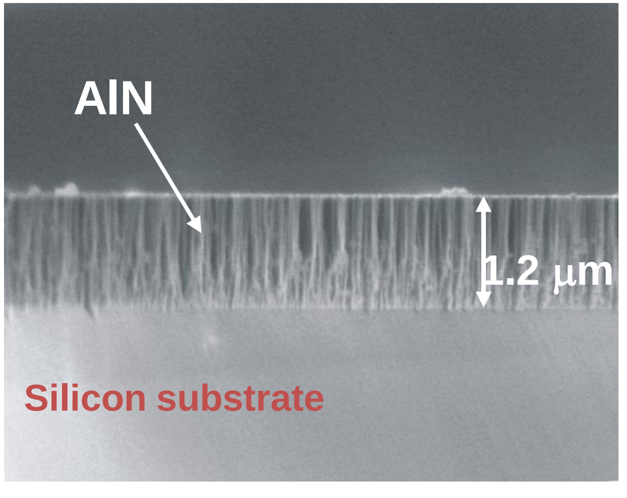
θ is the angle between the incident ray and crystal surface

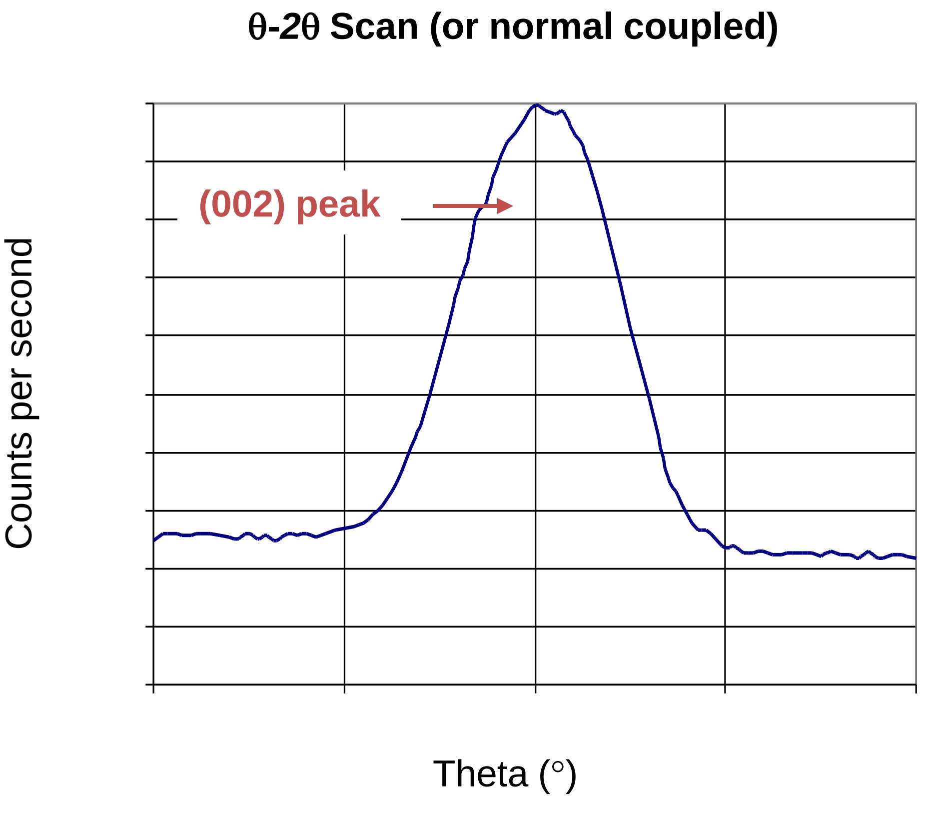
d is the spacing between the layers of atoms

Borrowed from Justin Black, UC Berkeley

Aluminum Nitride

- A *normal coupled scan* gives the stochiometry (relative composition) of different crystal orientations (e.g. (002), (110))
- For AlN, the piezoelectric (002) crystal peak orientation occurs at 36.1°
- A *rocking curve* measures the alignments of the (002) crystallites

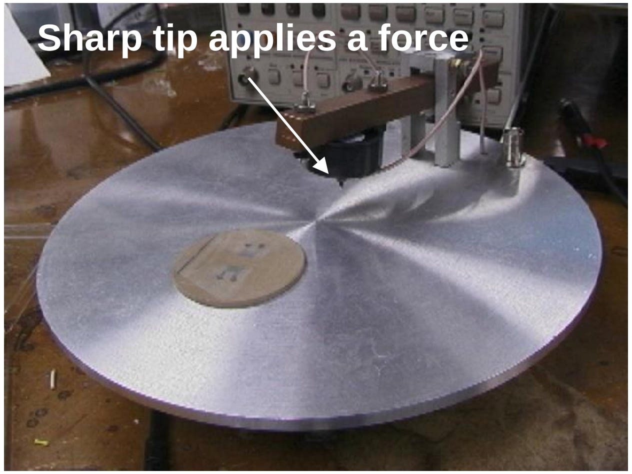


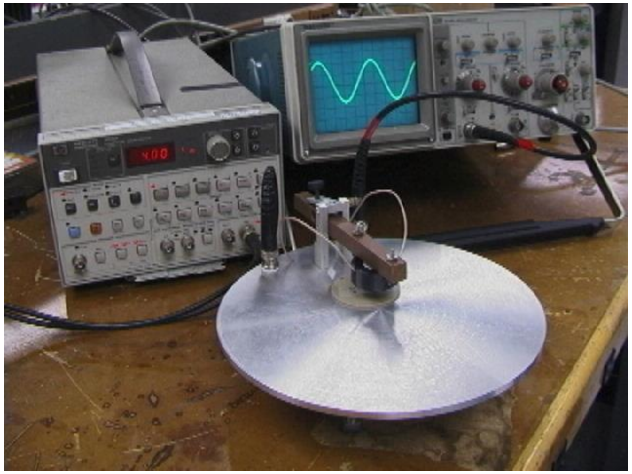


Borrowed from Justin Black, UC Berkeley

d_{31} and d_{33} Measurement

Commercial versions cost $3500 +





Stress induced charge collected from the sample surface

This charge is capacitively divided between piezoelectric sample and C_{in} of the oscillopscope

Current plan is to actuate cantilevers and measure tip displacement with LDV (indirect), but other methods include applying a force with a conducting AFM tip and collecting the charge

Borrowed from Justin Black, UC Berkeley

Piezoelectric Actuation Model

117 nm (want 500 nm) static tip deflection for:

- d_{31} = 3 pC/N
- $w_{cantilever} = w_{piezoelectric}$ = 10um
- $t_{cantilever}$ = 1um, $t_{piezoelectric}$ = 500nm
- $l_{cantilever}$ = 150um, $l_{piezoelectric}$ = 30um
- V_{bias} = 5V

$$\delta(x) = \frac{x^2 d_{31} \boldsymbol{E}_p (t_e + t_p) A_e E_e A_p E_p}{(t_e + t_p)^2 A_e E_e A_p E_p + 4(A_e E_e + A_p E_p)(E_e I_e + E_p I_p)}$$

More complicated for multimorphs, electrode and insulating layers can drastically change things (also in their paper)

Modeling and Optimal Design of Piezoelectric Cantilever Microactuators, DeVoe and Pisano, JMEMS (1997)

Overview

- Cantilevers in Fluid
  - Analytical modeling
  - Implications for design
- Numerical optimization of epitaxial cantilevers
  - Comparison with Previous Approaches
  - Numerical model
  - Comparison with experimental data (Harley)
  - Implementation
  - Results
- Piezoelectric Actuation Model
- **Summer and Future Work**

Plan for the Summer

- XRD on aluminum nitride for process optimization
- ASML mask design
- Fabrication of actuating cantilevers to characterize mechanical resonance, d_{31} (July/August)
- Mask design again
- Fabrication of actuating, sensing cantilevers (August/September)
- Arsenic piezoresistors (July?)

Arsenic Piezoresistors

- Arsenic Piezoresistors
  - Lower modulus in <100> versus <110>
  - Higher mobility for N-type dopants (lower R for fixed N)
  - Higher piezoresistive coefficient (from Kanda, limited experimental data)
  - Lower diffusivity in silicon (300nm junctions achievable via ion implantation)
  - Would like to test with the class cantilever process to get P(N) and alpha(sqrt(Dt)), expected results…