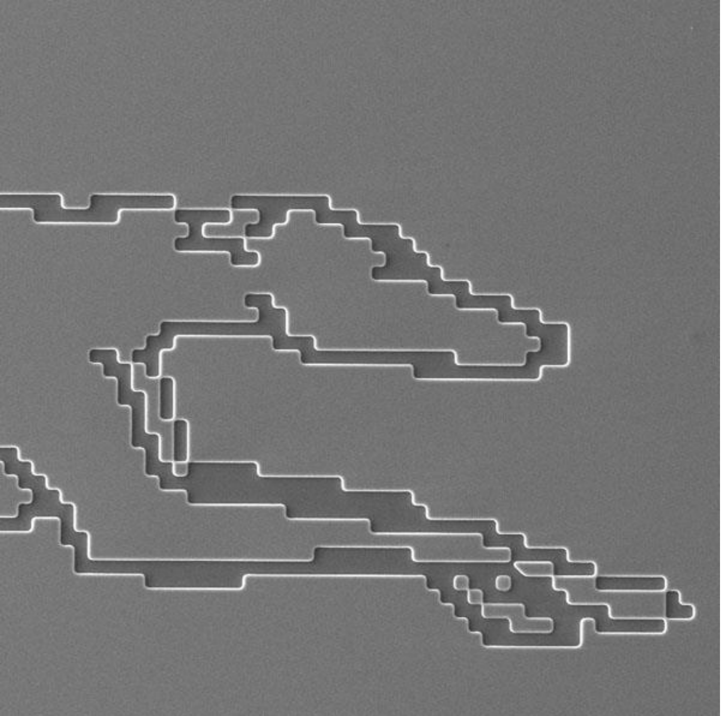
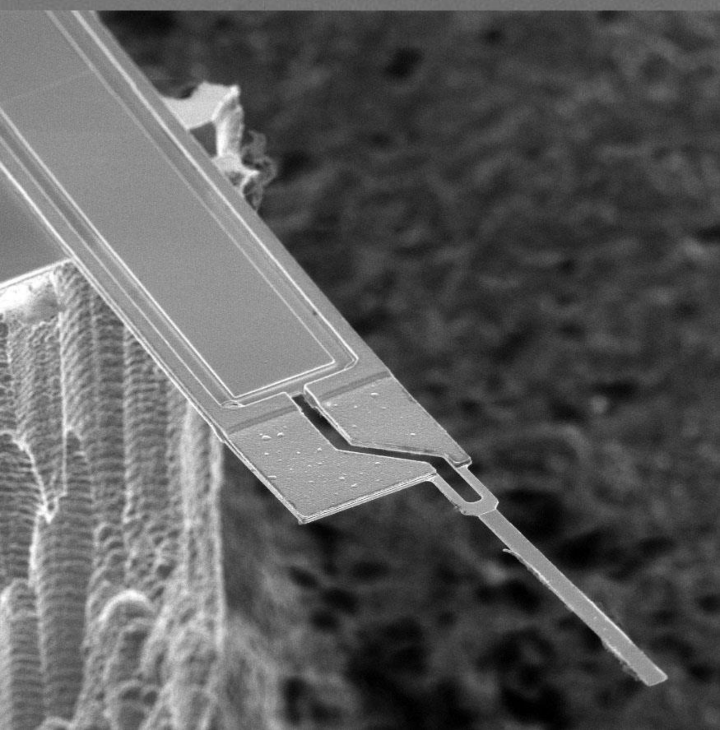




MEMS Force Probes for Mechanobiology at the Microsecond Scale

Joey Doll

PhD Dissertation Defense

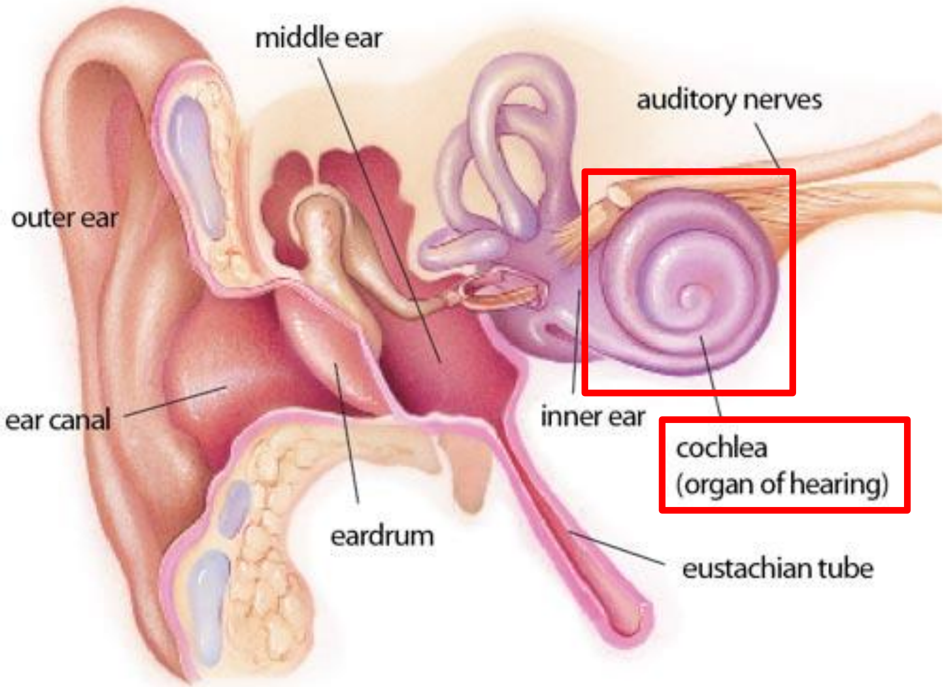
March 7, 2012

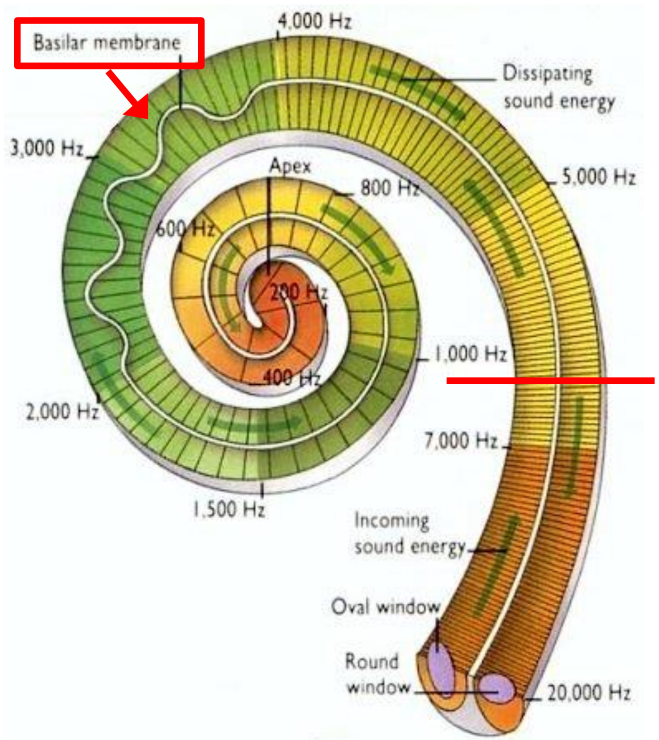
Outline

1) How hearing works and why we need a fast force probe

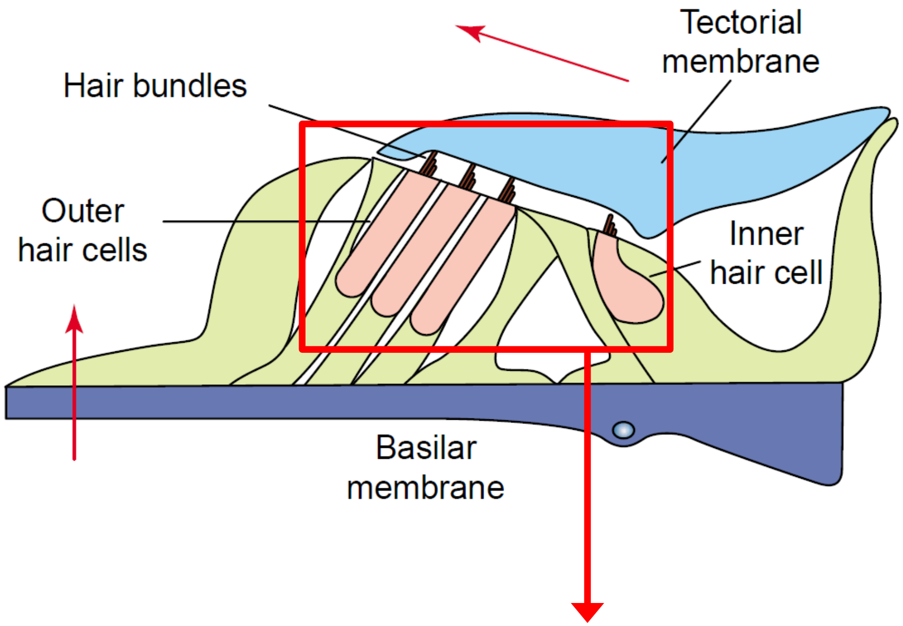
2) Probe design, fabrication and characterization

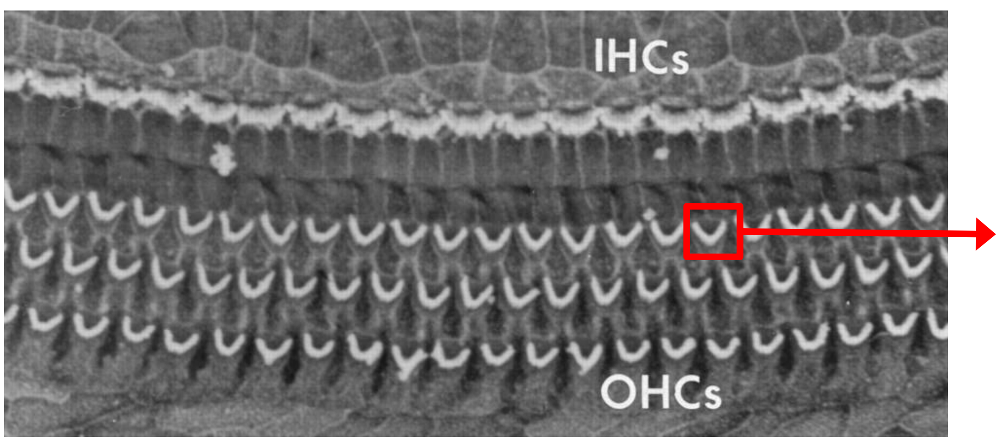
3) System integration and hair cell measurements





Images courtesy of NIH Medicine Plus



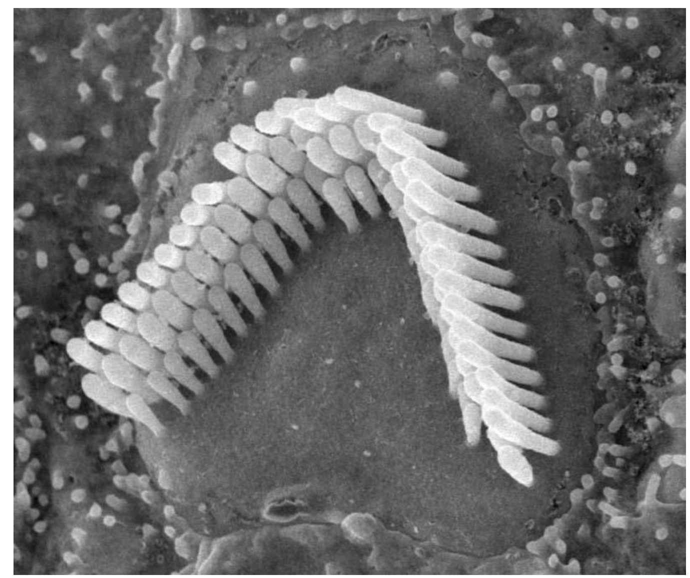


<u>Inner hair cells (IHCs)</u>

Convert sound into electrical signals

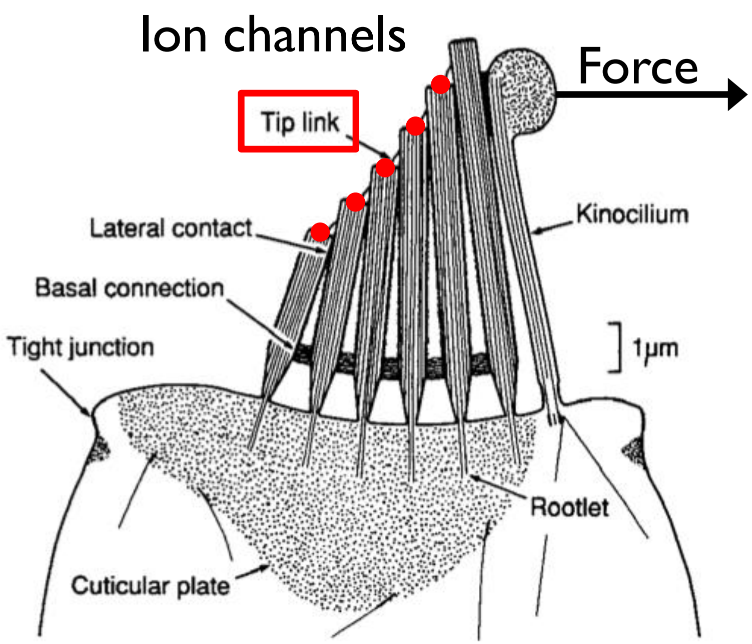
<u>Outer hair cells (OHCs)</u>

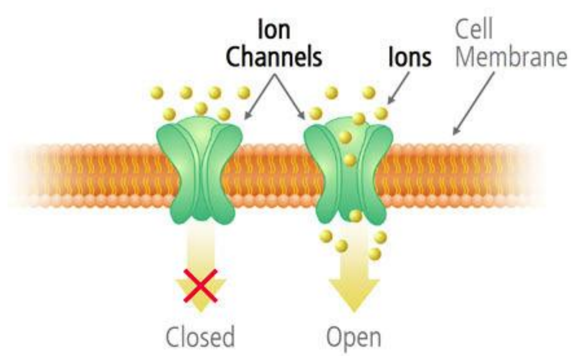
Mechanical amplifiers and filters

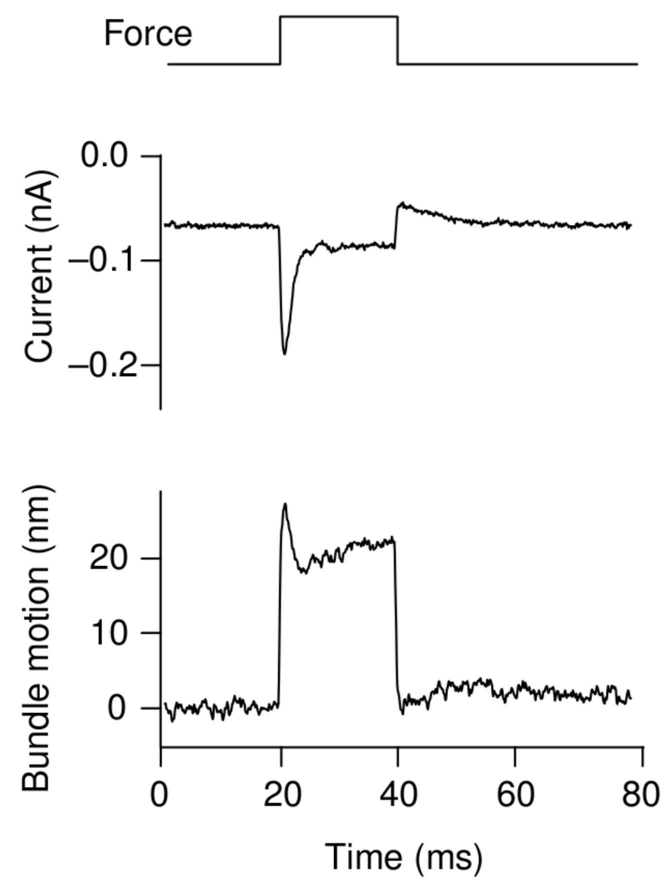


Images from Ryan (2000) and Fettiplace (2001)

Hair cell bundles transduce force into an electrical signal

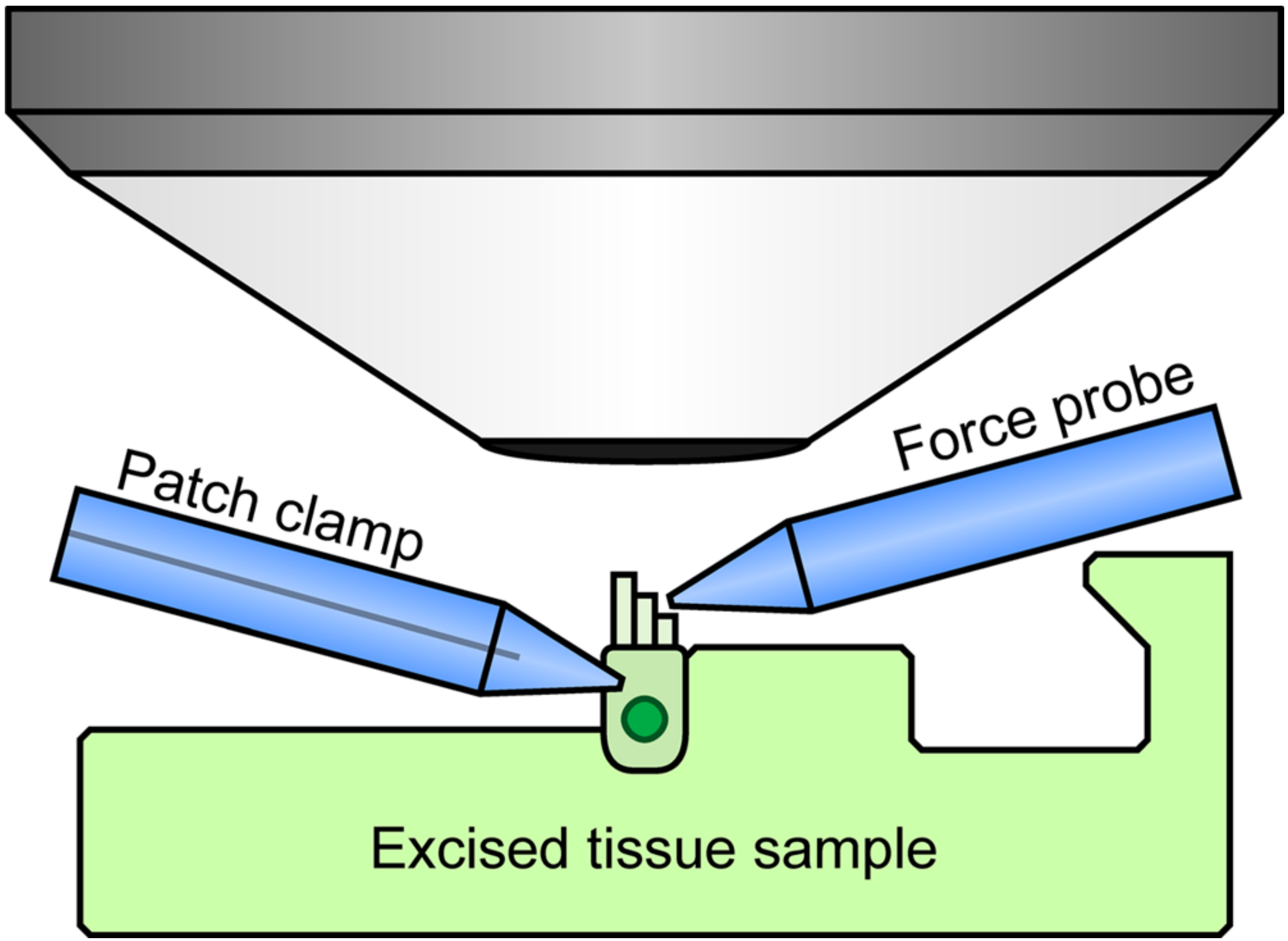




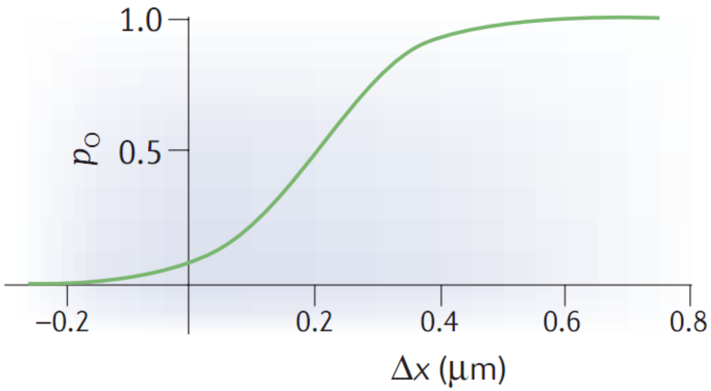


Images from Fettiplace (2001) and Icagen

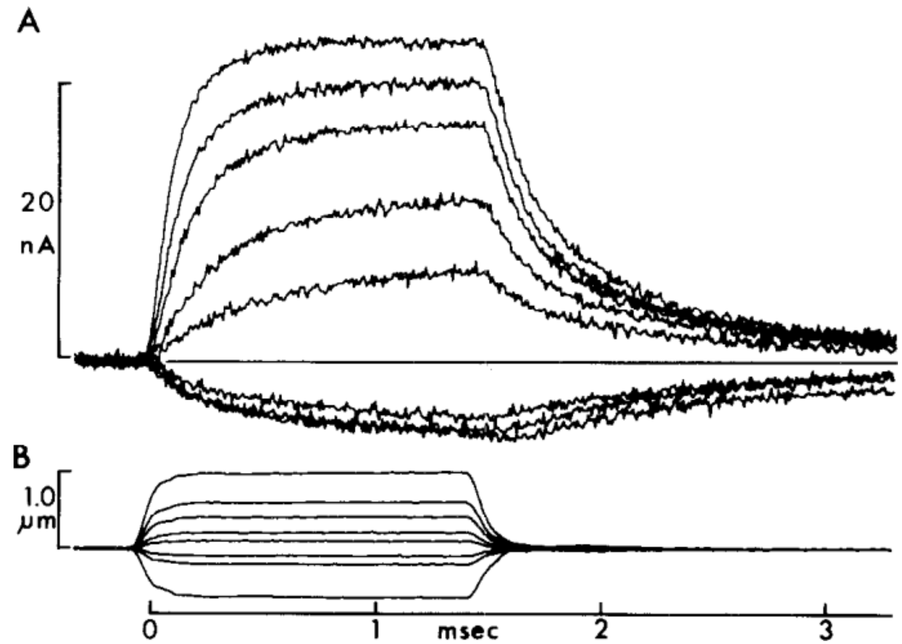
Hair cell experimental setup



Bundle mechanics
(soft probes, 1 mN/m)



Channel kinetics
(stiff probes)



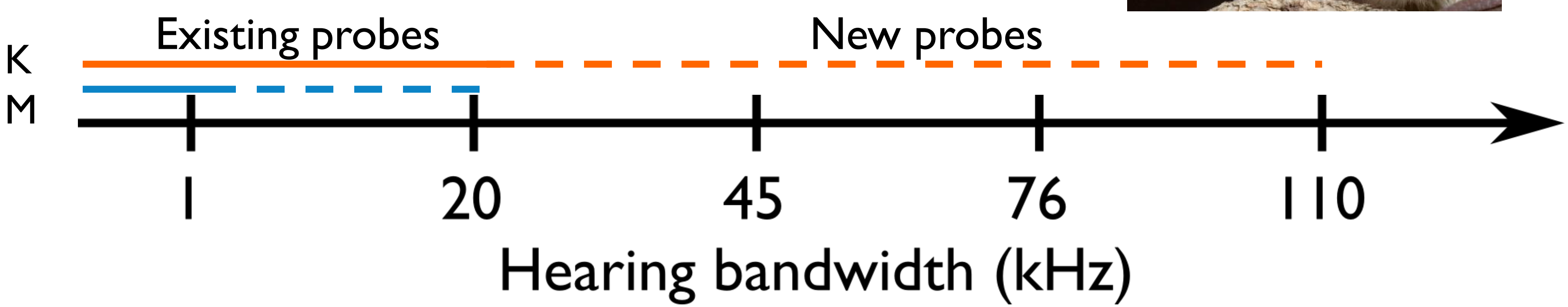
Limited by probe size

Limited by actuator speed

The force probe needs to be faster than the hair cell

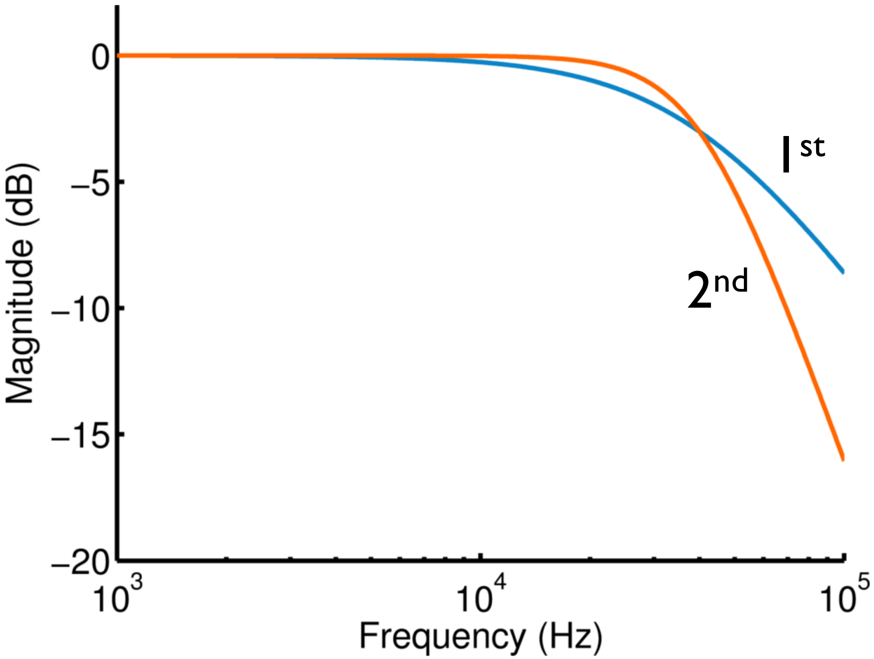
Images from Fettiplace (2006) and Corey (1983)

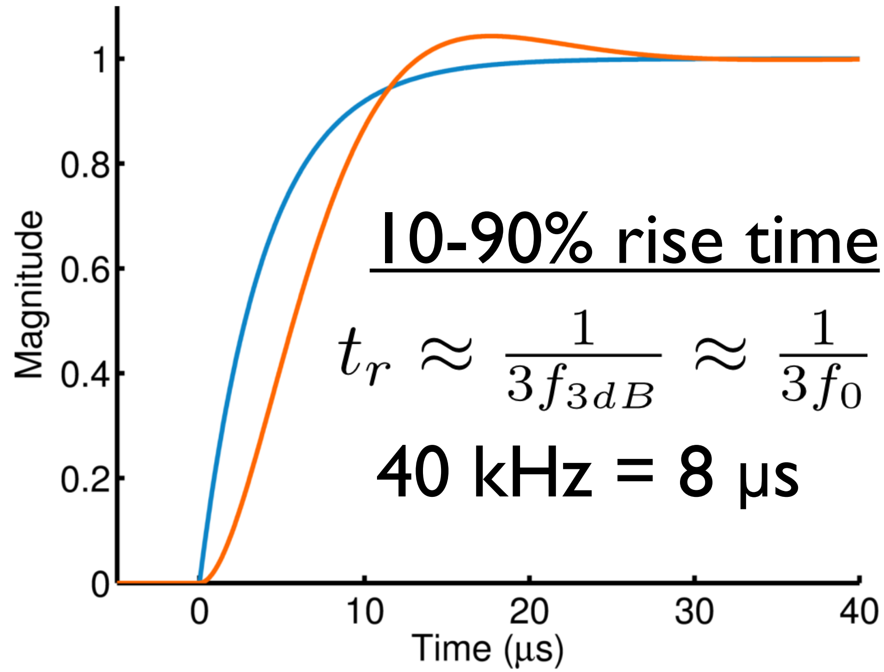
How fast do the probes need to be?



Images from iStock Images, Ryan Photography, Wonder Costumes and Wikimedia Commons

Bandwidth vs. rise time





10-90% rise time

$$t_r \approx \frac{1}{3 f_{3dB}} \approx \frac{1}{3 f_0}$$

40 kHz = 8 μs

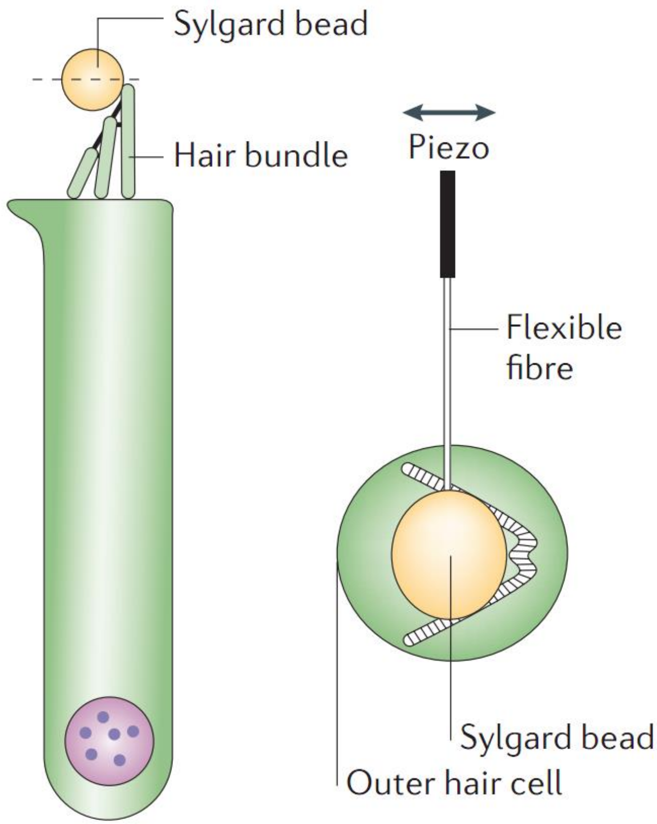
1st order system: f_{3dB} = 40 kHz

2nd order system: f_0 = 40 kHz, Q = .707

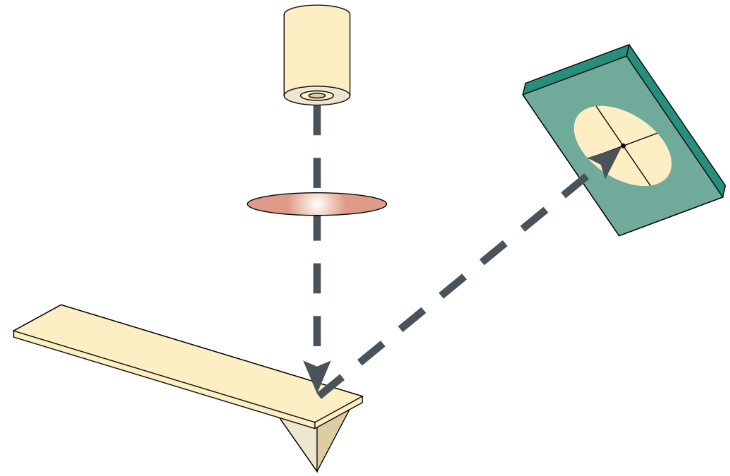
Target force probe performance

- Mechanics
  - 1 mN/m spring constant
  - 5-20 kHz bandwidth (20-60 μs rise time)
- Kinetics
  - Any spring constant
  - 50-200 kHz bandwidth (2-7 μs rise time)
- Both
  - 500 nm tip deflection
  - Operate in grounded salt water

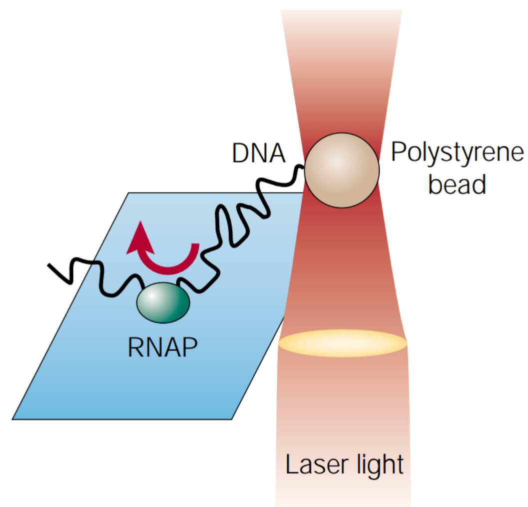
Macroscale



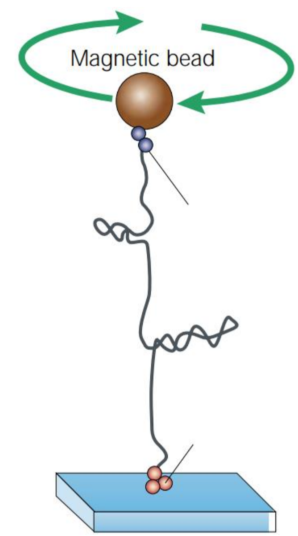
AFM



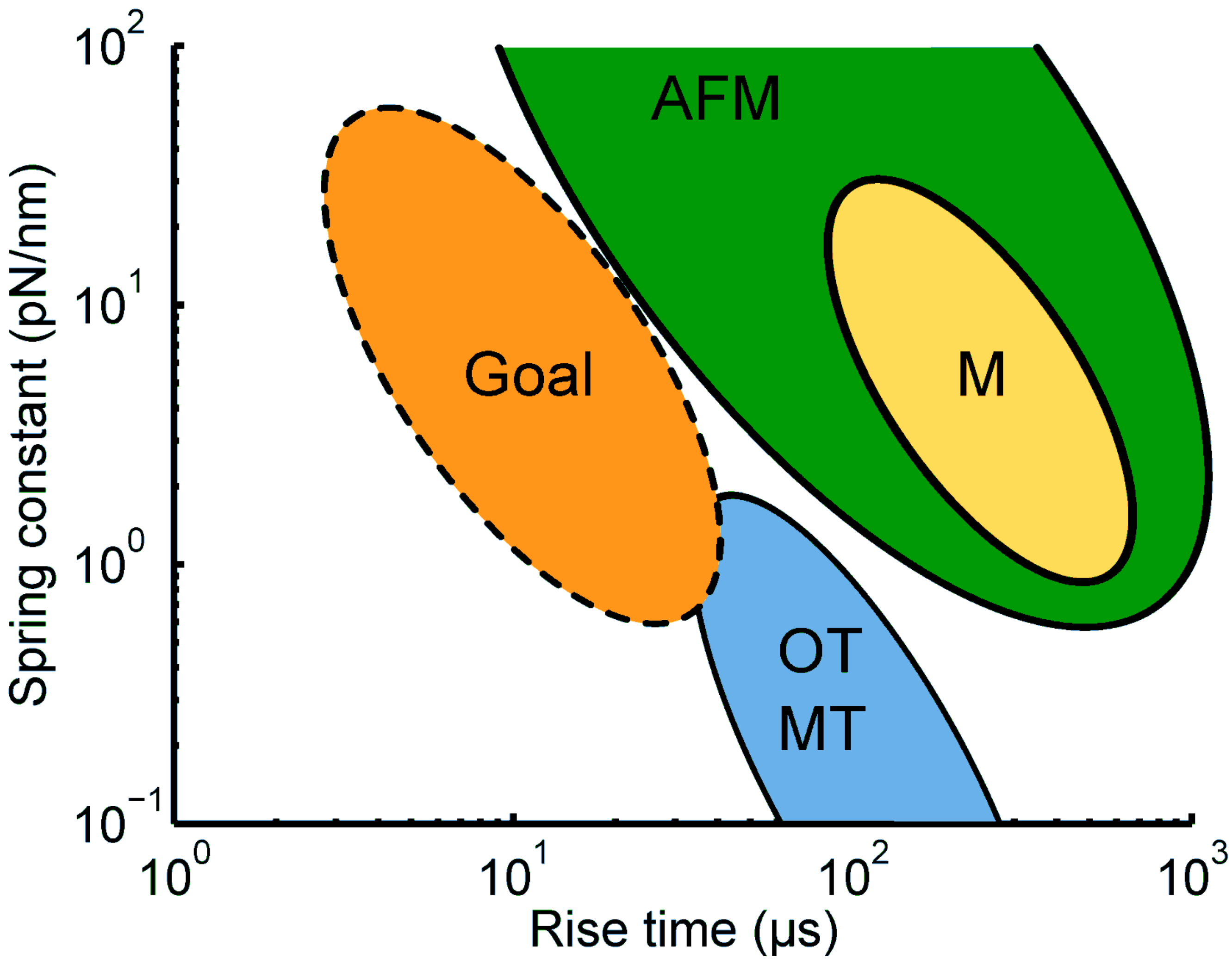
Optical tweezers



Magnetic tweezers



Images from Fettiplace (2006) and Bustamante (2000)



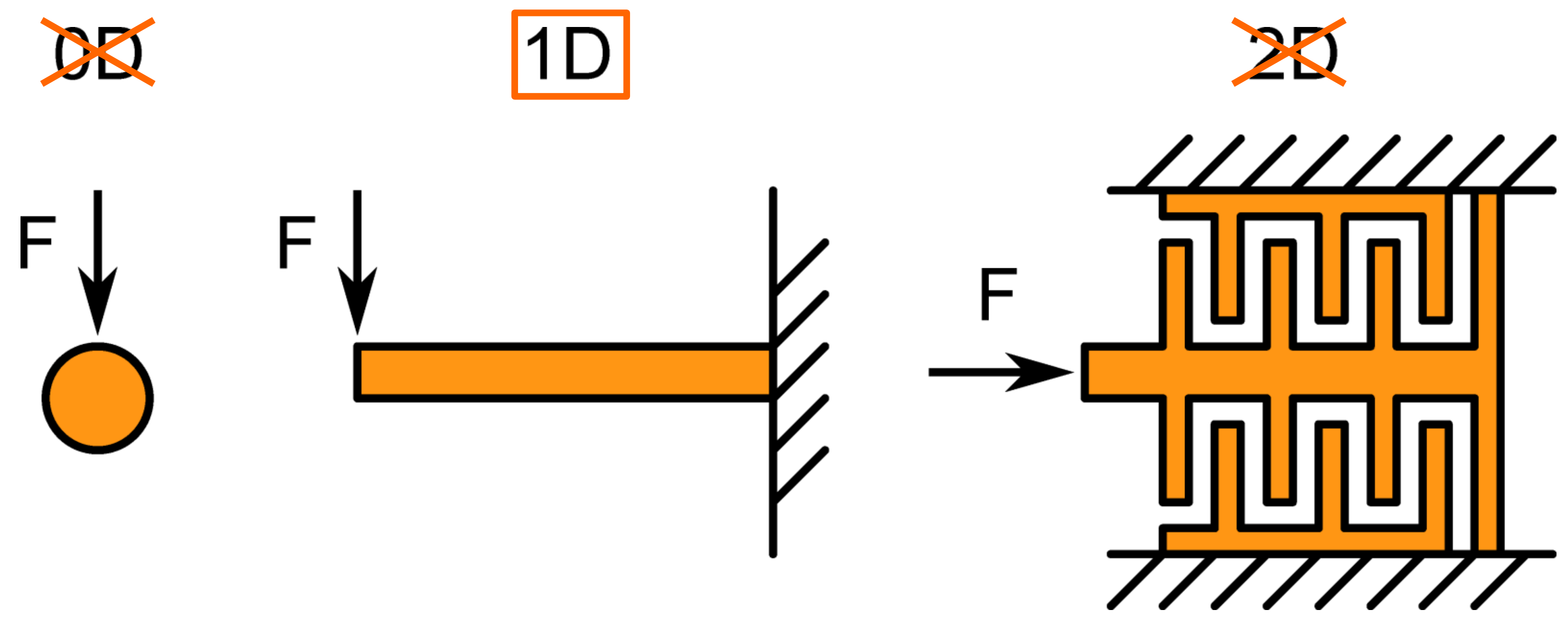
$$t_r \approx \frac{1}{3f_0} \propto \sqrt{\frac{\boxed{m_{eff}}}{k}}$$

$$(\text{for } Q = 1/\sqrt{2})$$

Based upon "Single-molecule force spectroscopy: optical tweezers, magnetic tweezers and atomic force microscopy", Neuman and Nagy (2008)

Design overview
(size/shape + sensor + actuator)

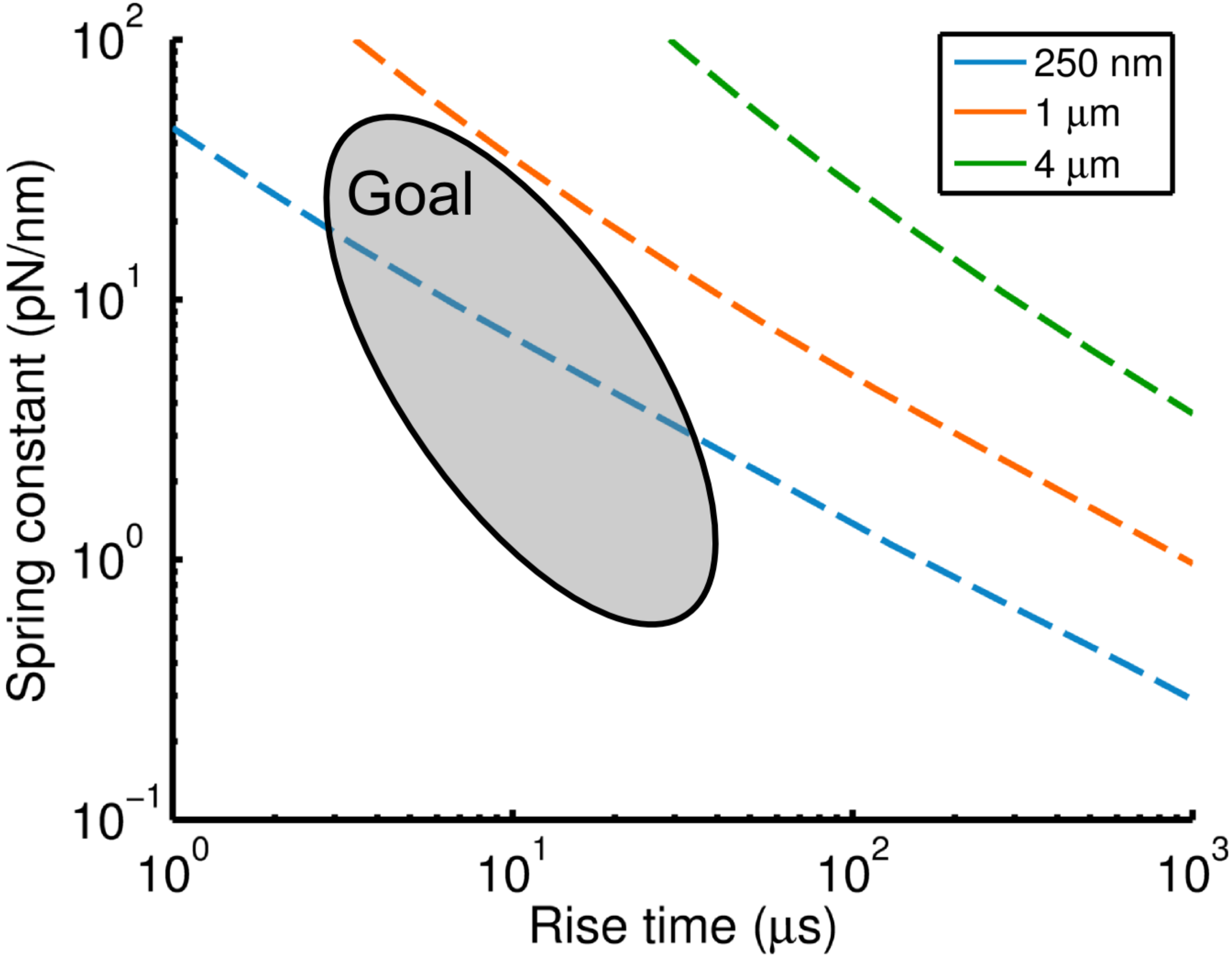
What should a force probe look like?



Goals:

1) Minimize probe mass
2) Allow stiffness tuning

The force probes need to be thin



Operation in

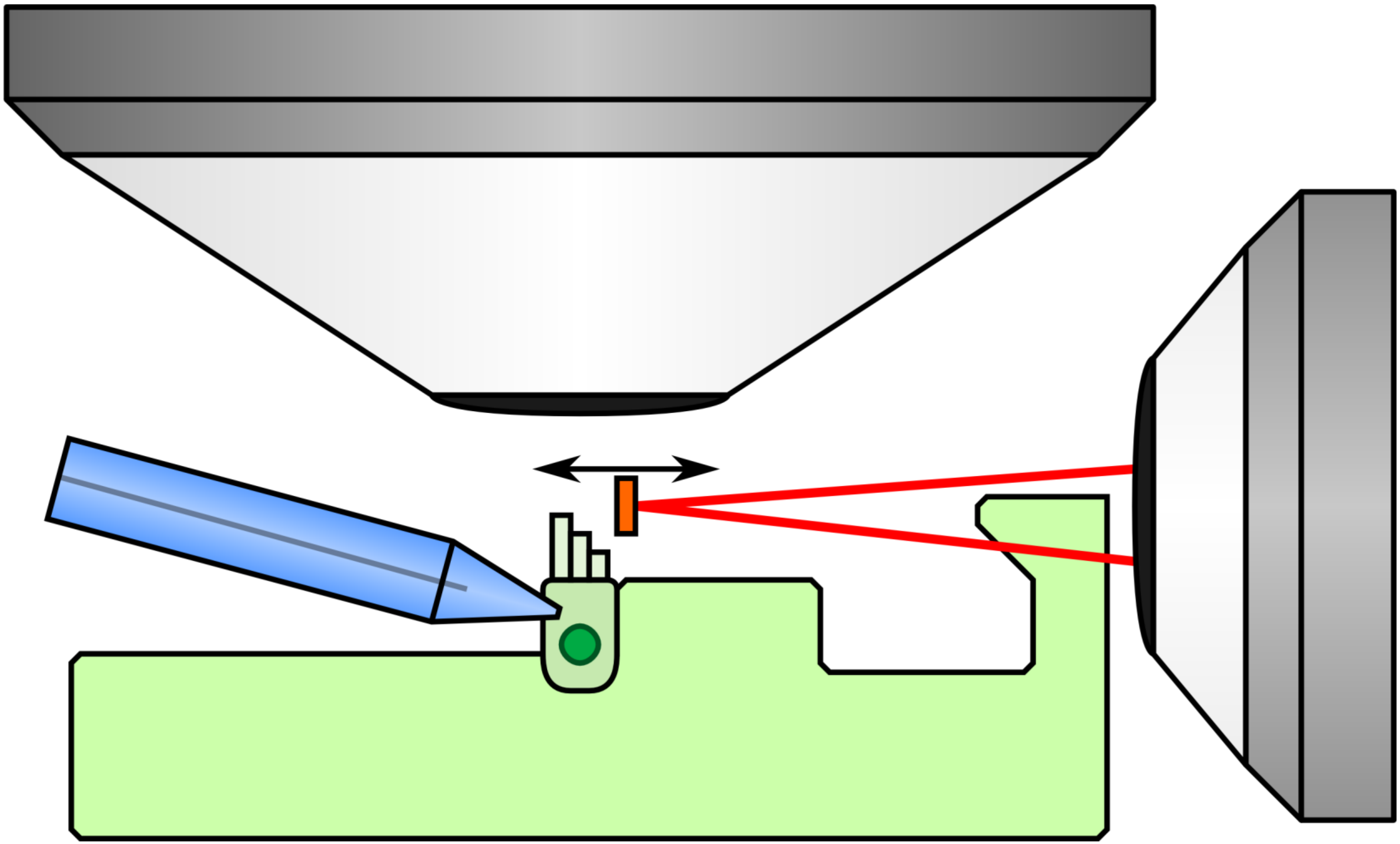
Water

Air

$$kt_r \propto \frac{\sqrt{E_c \rho_c} w_c t_c^2}{l_c}$$

$$(\text{for } Q = 1/\sqrt{2})$$

Optical deflection sensing is impractical



Force transduction options

Piezoresistive

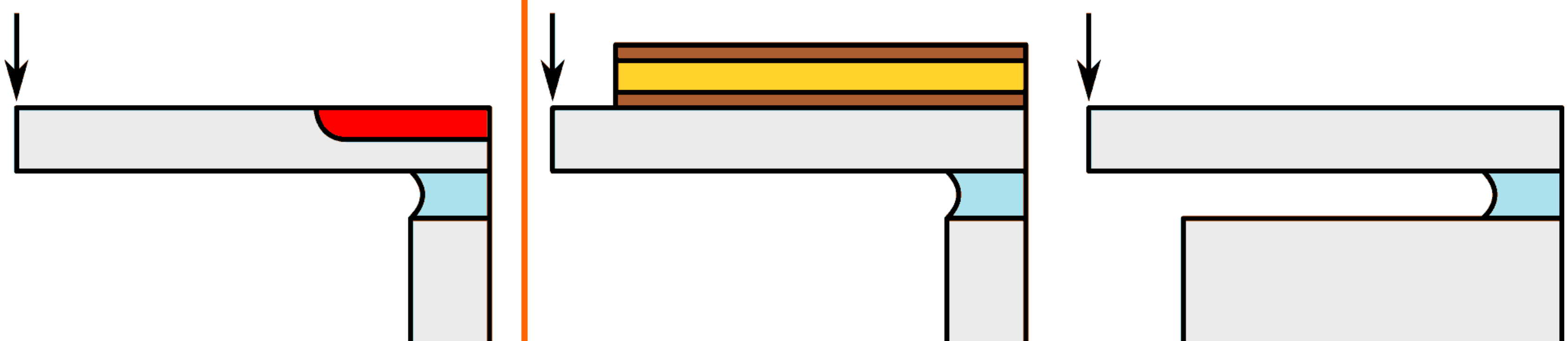
$$\Delta F \rightarrow \Delta R$$

~~Piezoelectric~~

$$\Delta F \rightarrow \Delta Q$$

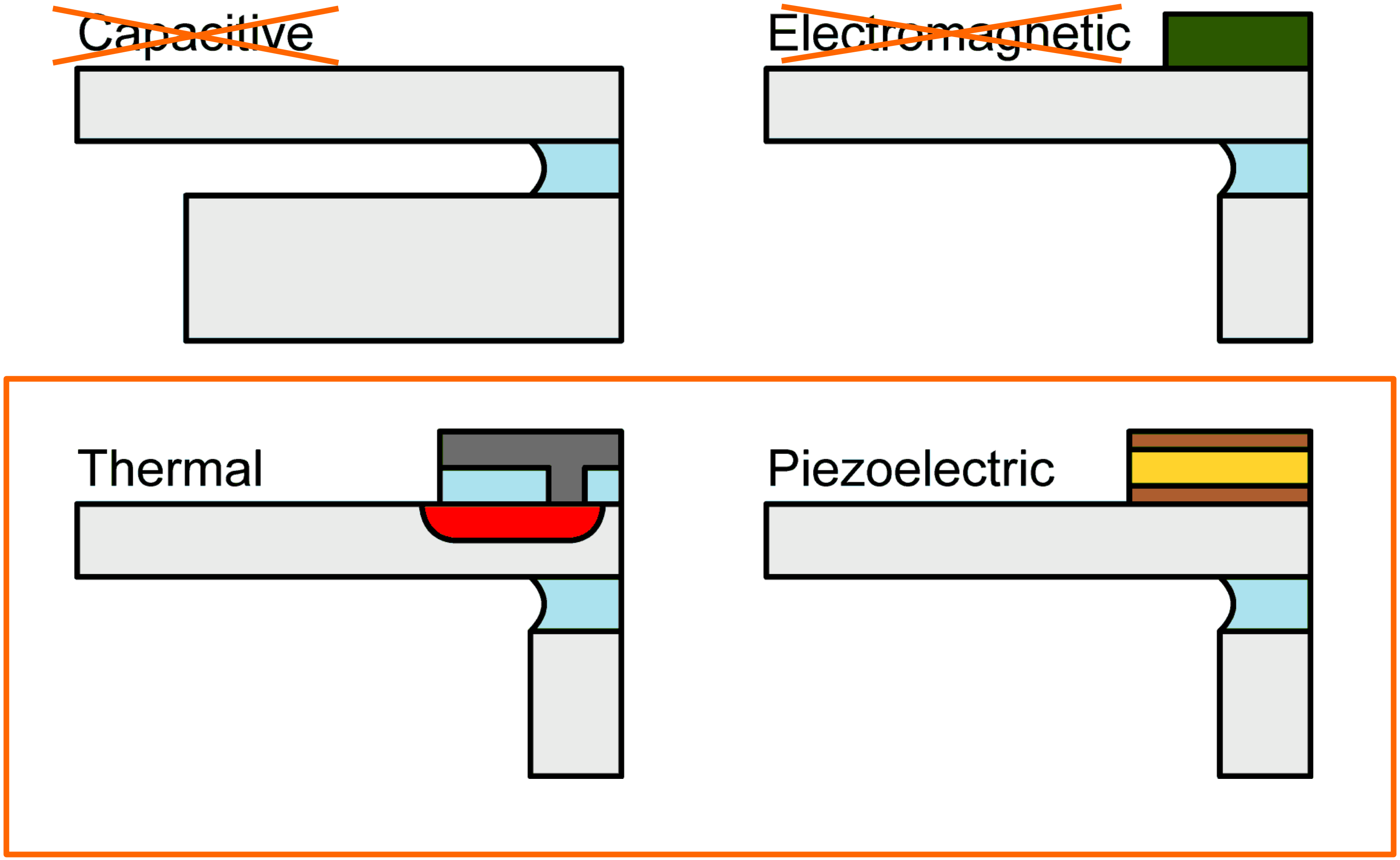
~~Capacitive~~

$$\Delta F \rightarrow \Delta C$$

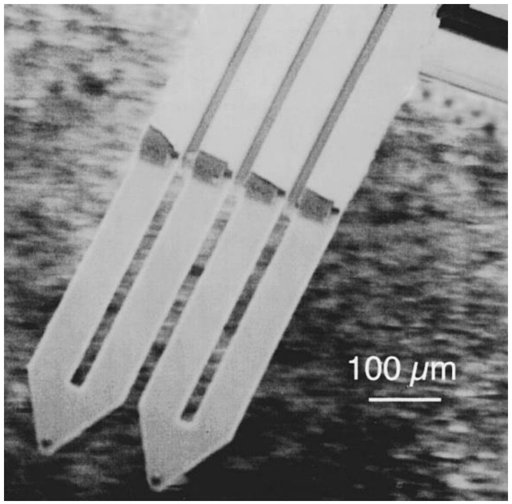


Design of Piezoresistive vs. Piezoelectric Contact Mode Scanning Probes
J.C. Doll and B.L. Pruitt
Journal of Micromechanics and Microengineering (2010)

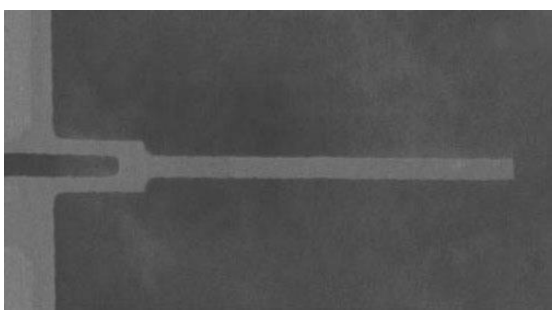
Actuator options



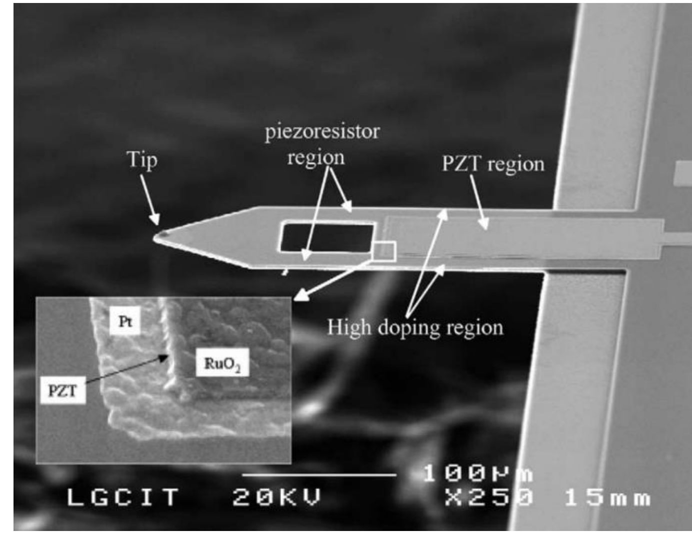
Previous devices have been too large



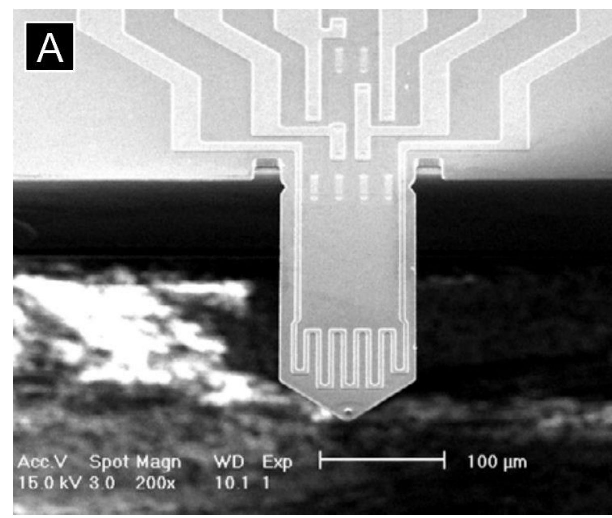
Minne et al. (1995)
3.5 μm x 85 μm x 420 μm



Harley and Kenny (1999)
90nm x 4 μm x 60 μm

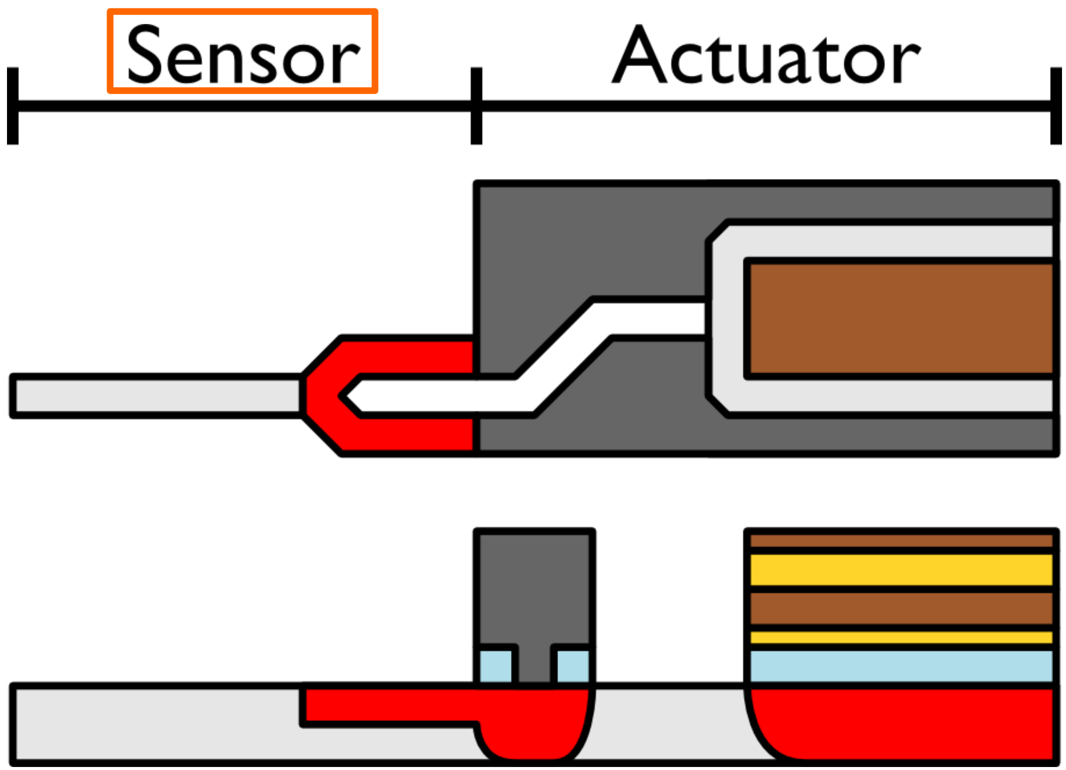


Kim et al. (2003)
3 μm x 70 μm x 200 μm

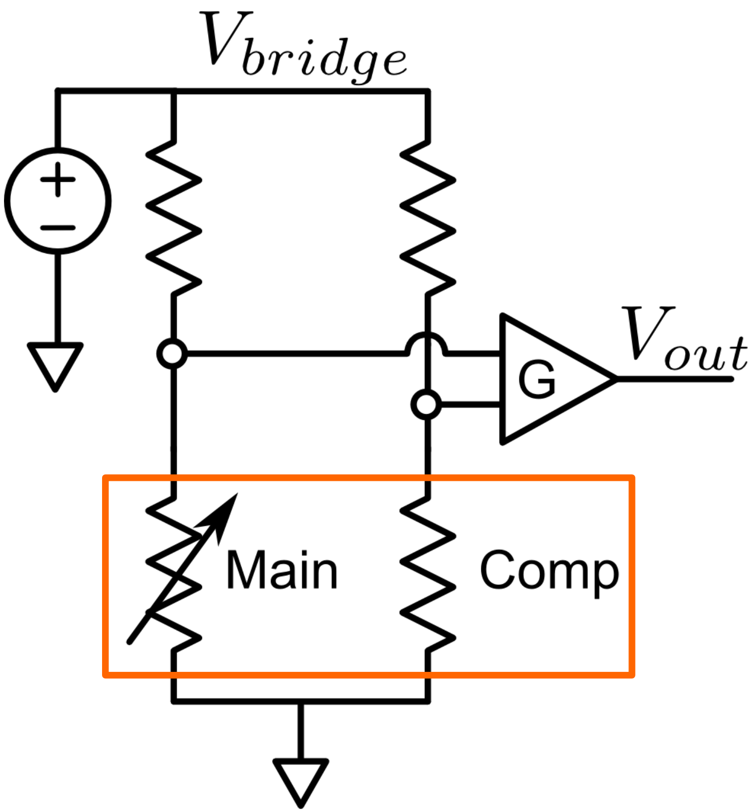


Fantner et al (2009)
5 μm x 110 μm x 320 μm

Design



Piezoresistor fundamentals

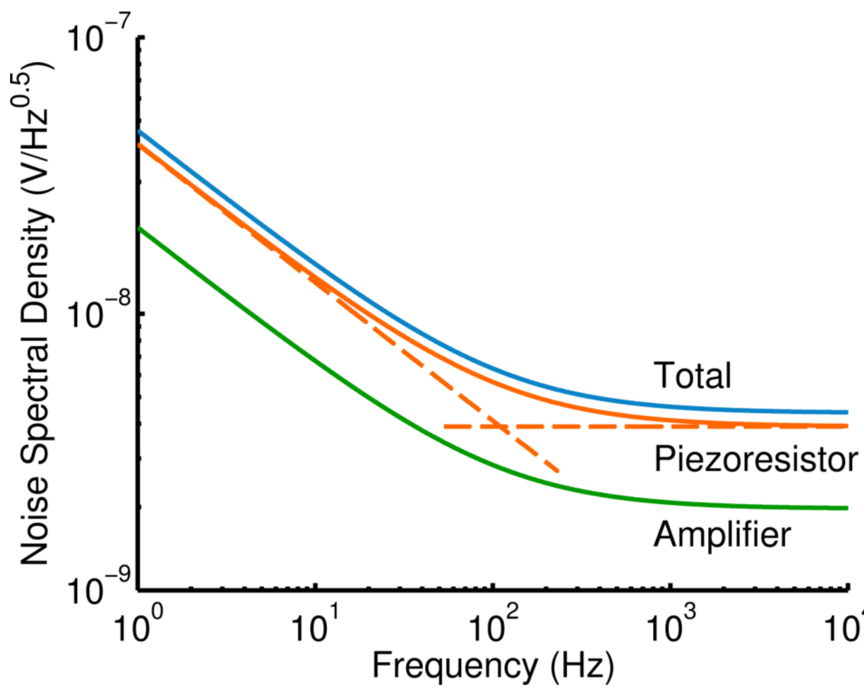


$$V_{out} \approx \frac{\Delta R}{4R} V_{bridge}$$

$$\frac{\Delta R}{R} \propto \pi\sigma$$

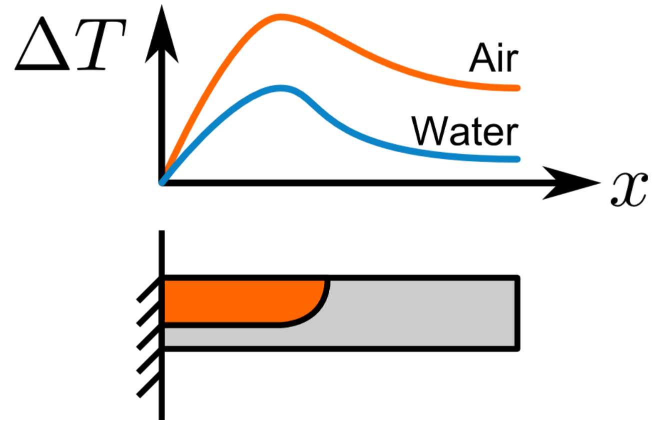
Piezoresistor design fundamentals

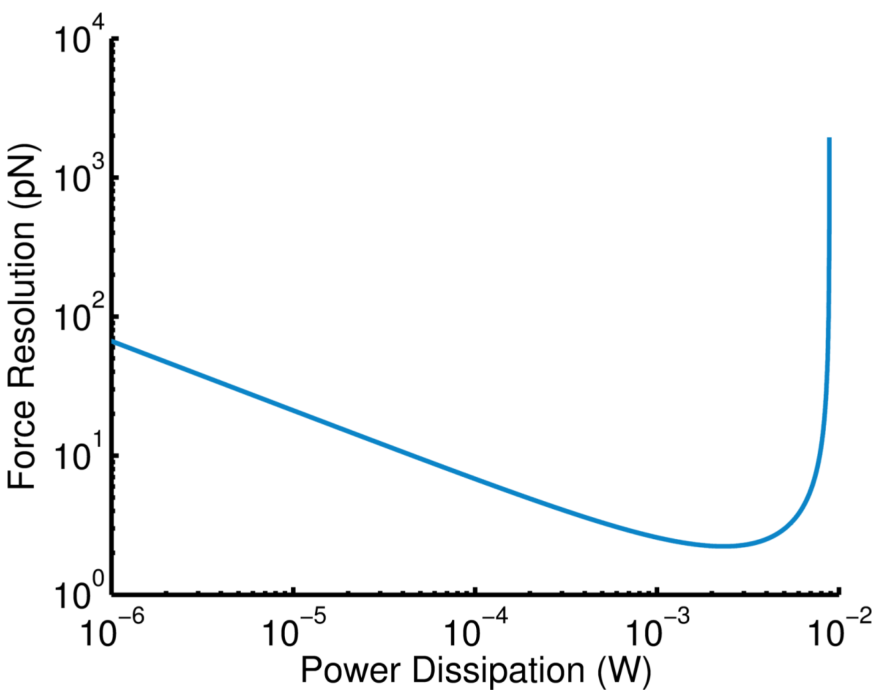
$$\text{Resolution} = \frac{\text{Noise}}{\text{Sensitivity}}$$

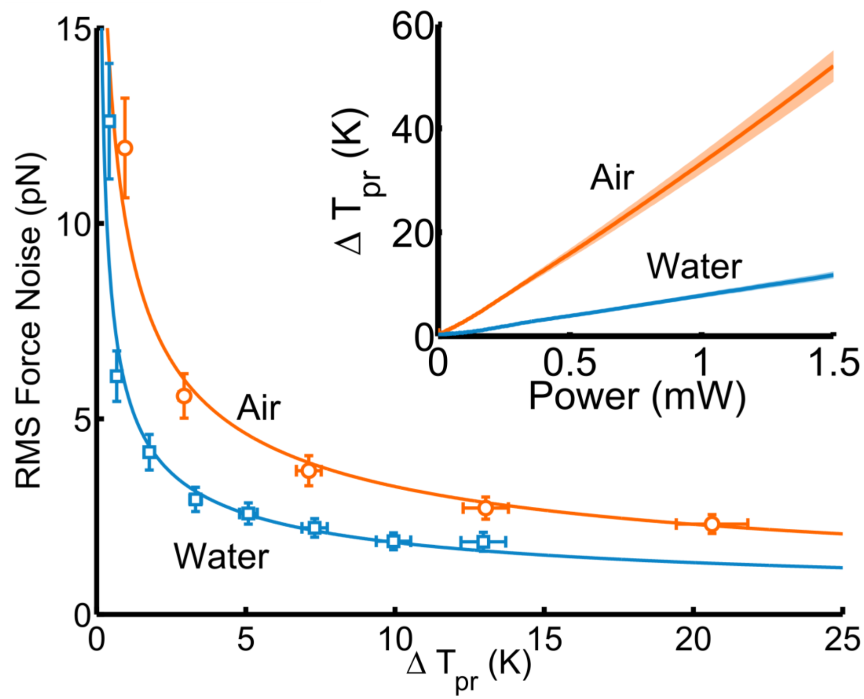


Goal: minimize the minimum detectable force (MDF) by adjusting the sensor dimensions, bridge bias and doping process

Piezoresistors love water





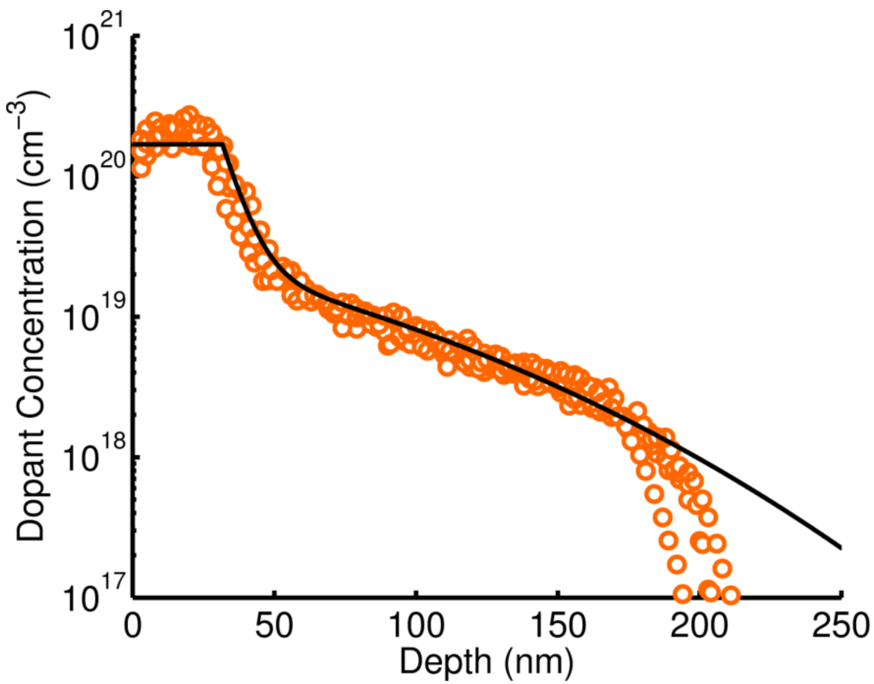


Self-heating in piezoresistive cantilevers
J.C. Doll, E.A. Corbin, W.P. King and B.L. Pruitt
Applied Physics Letters (2011)

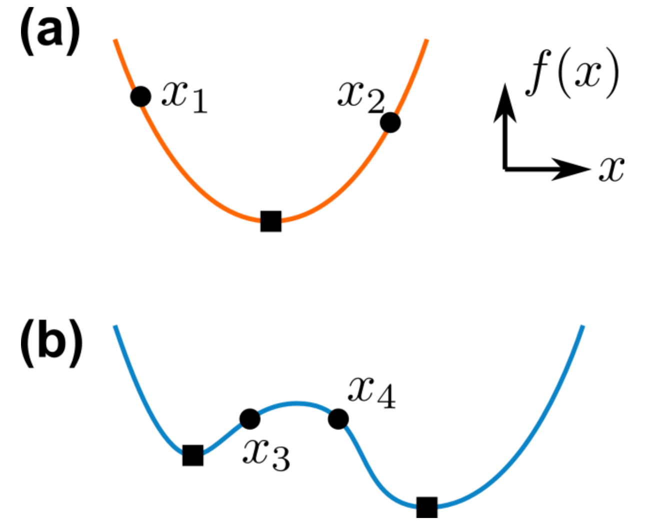
Piezoresistor design requires numerical modeling

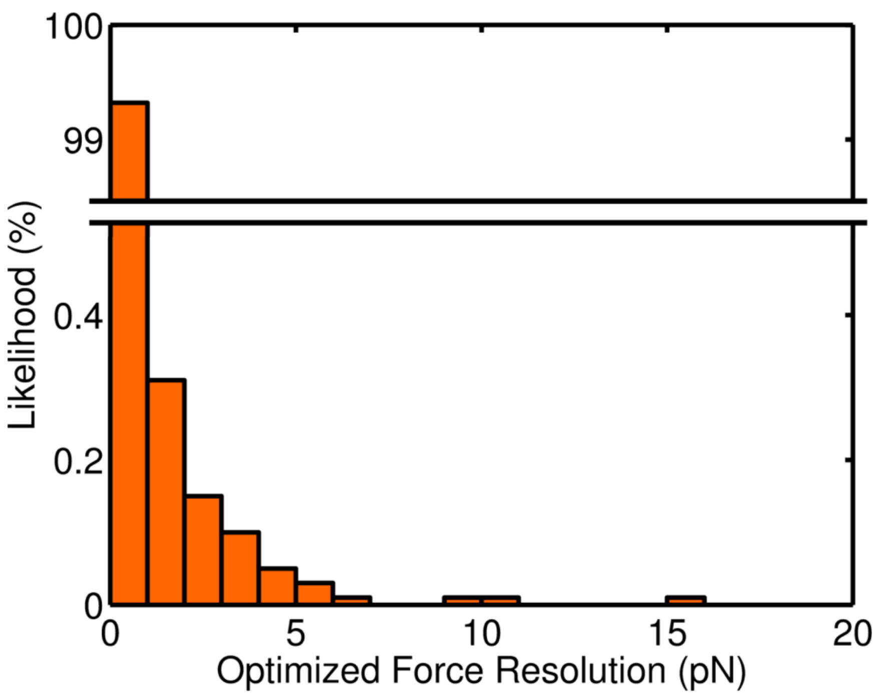
- Complex dopant profiles
- Self-heating
- Fluid damping

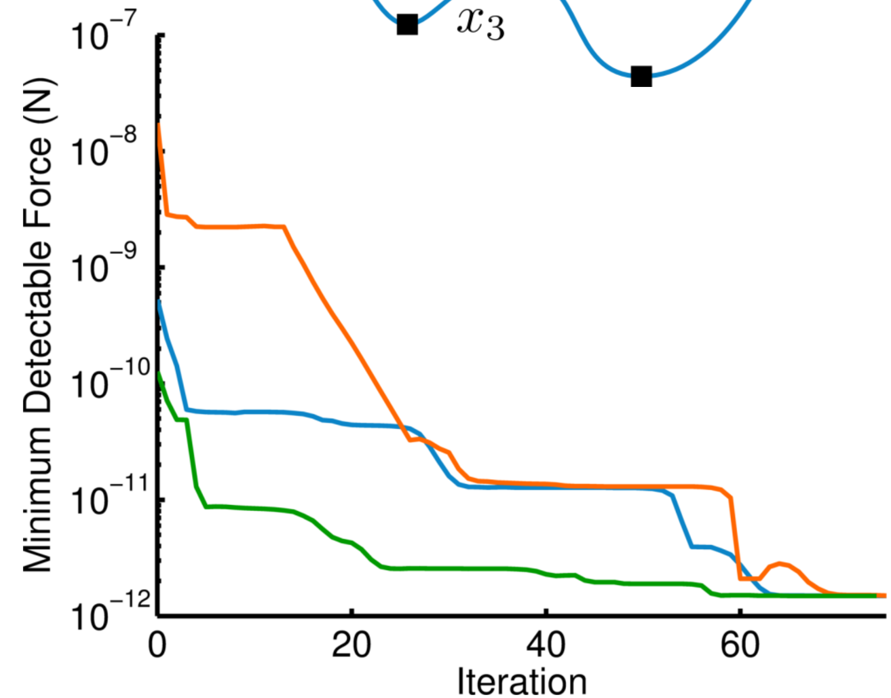
Example diffusion profile ($POCl_3$ @ 850C)



Numerical design optimization







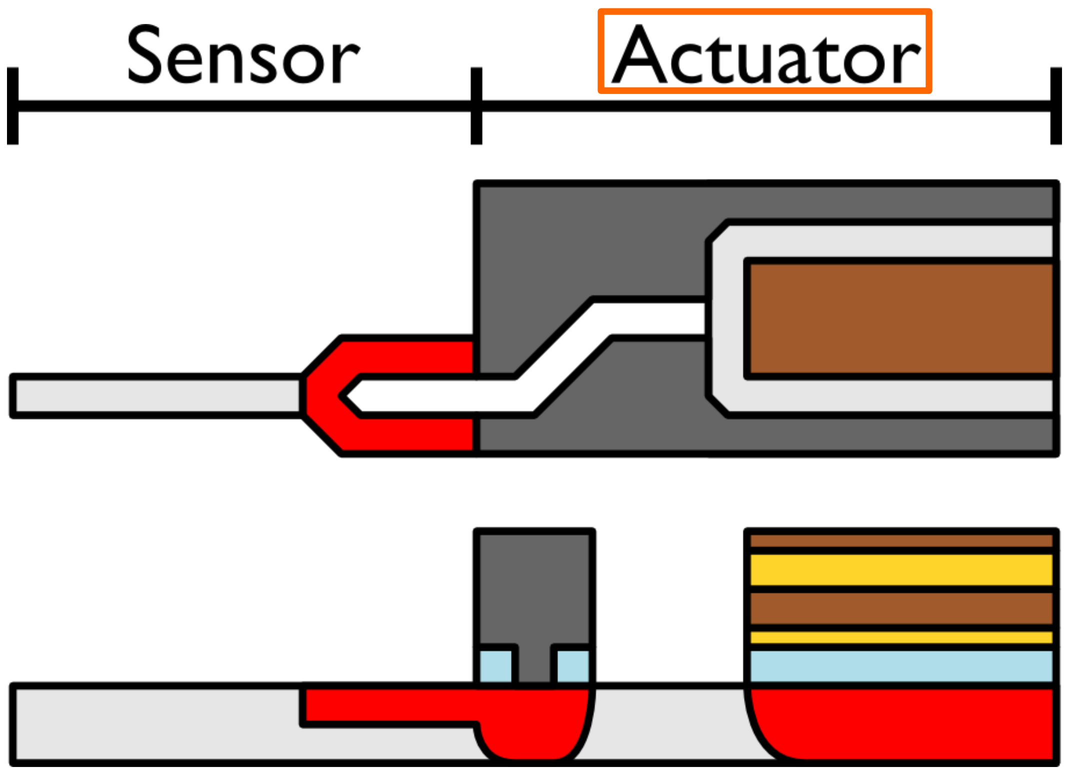
Design optimization of piezoresistive cantilevers for force sensing in air and water
J.C. Doll, S.-J. Park and B.L. Pruitt
Journal of Applied Physics (2008)

microsystems.stanford.edu/piezod

Design summary

Design #	l_c (μm)	k_c (mN/m)	f_0 (kHz)	f_d (kHz)	MDF (pN)
1	142	0.3	18	3.3	3.3
2	96	1.0	40	9.7	6.2
3	75	2.1	65	19	9.6
4	61	3.9	97	32	14
5	46	9.0	170	64	24
6	35	20	290	124	42
7	29	36	430	190	61

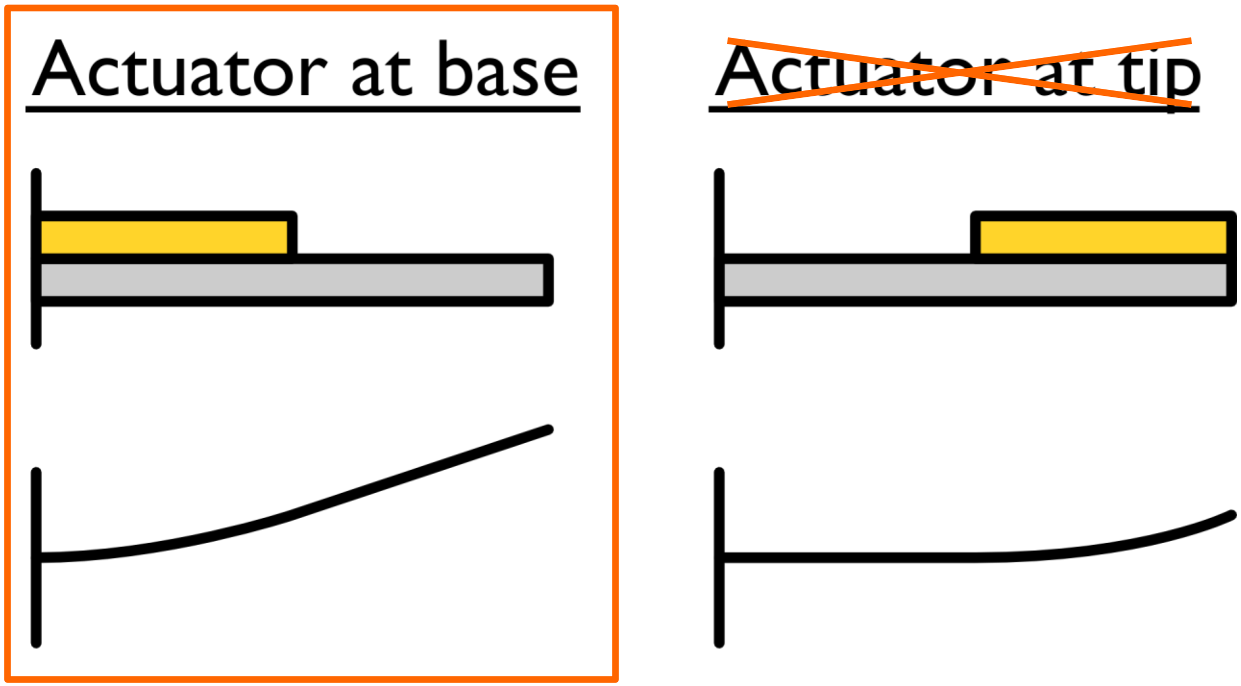
Design



Actuators transduce a voltage into a tip deflection

$$V \rightarrow \epsilon \rightarrow z_{tip}$$

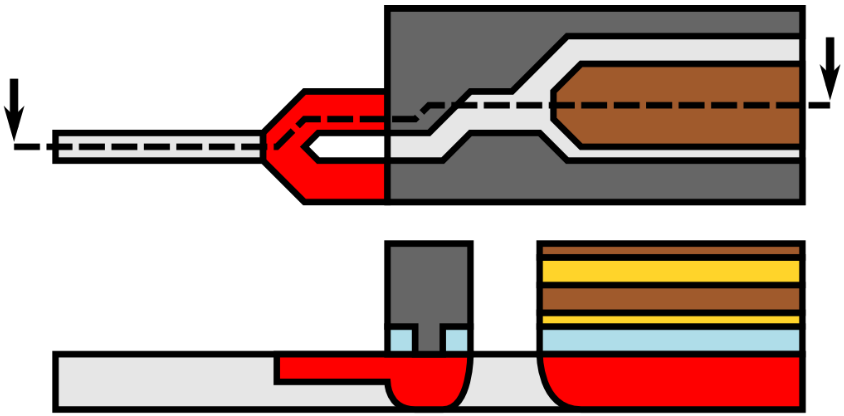
Actuator-sensor placement



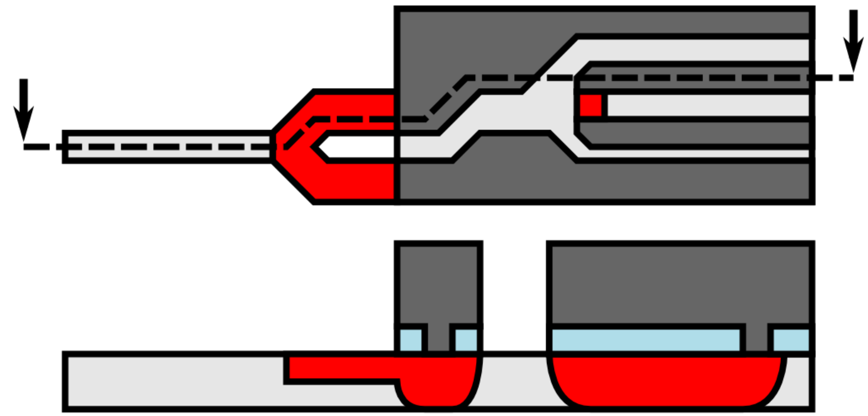
Actuator: thick and stiff
Sensor: thin and soft

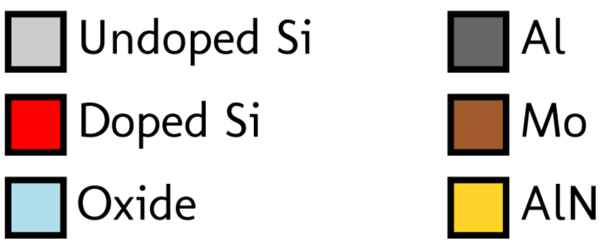
Force probe design summary

Piezoelectric actuation



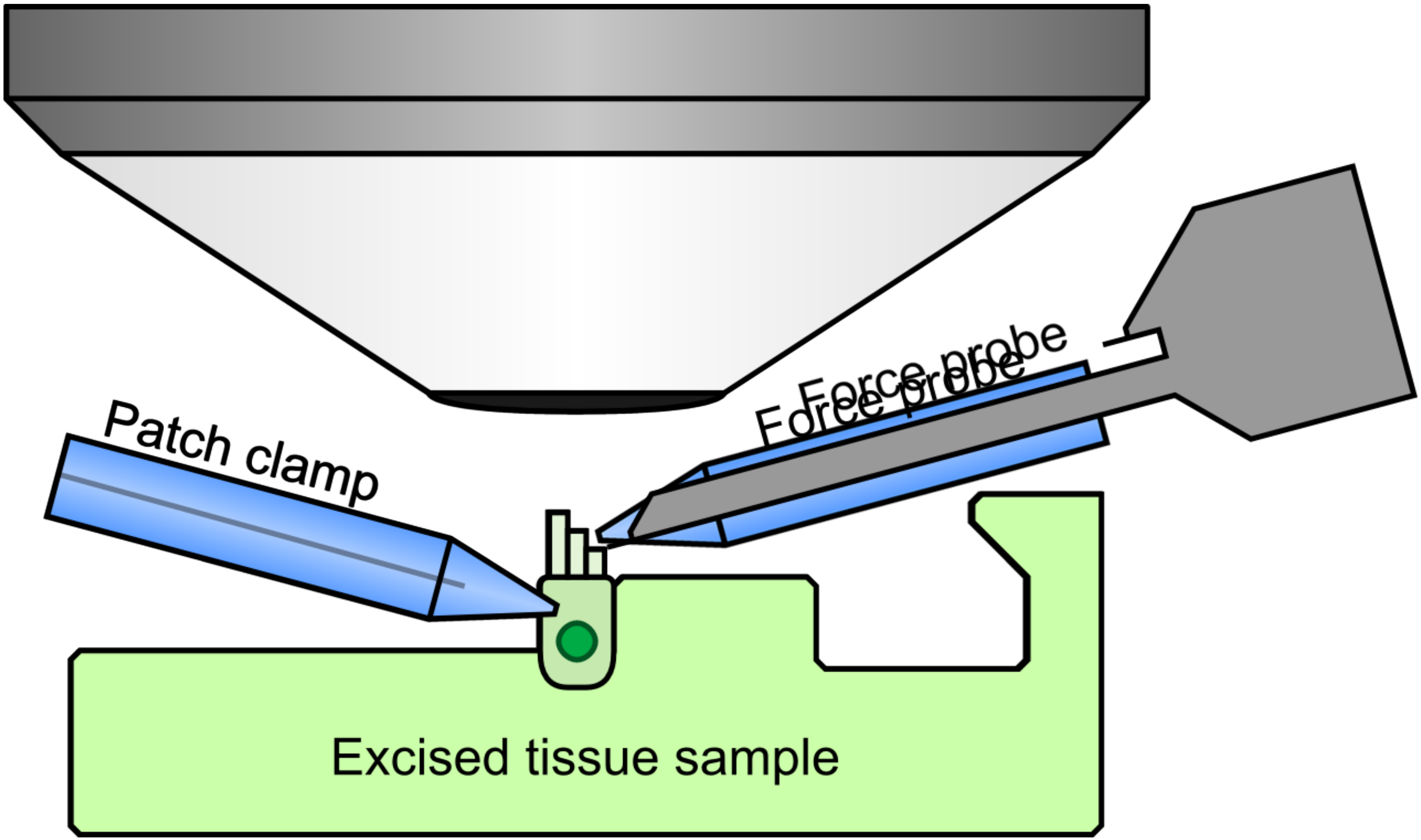
Thermal actuation





Actuator length varies depending on sensor resonant frequency

Designing for microscope compatibility



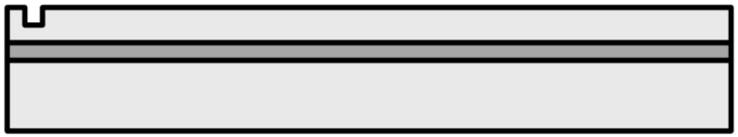
Fabrication

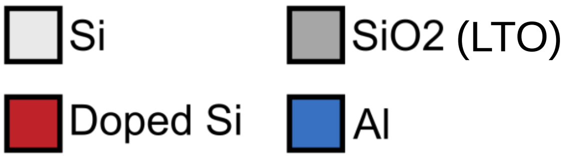
Fabrication overview

- Three processes
  - Piezoresistive sensor only
  - Thermal actuation
  - Piezoelectric actuation
- Process specs
  - 7 and 9 mask processes
  - 0.5 um CD and 0.25 um overlay tolerance
  - Start from 340nm device layer SOI wafers

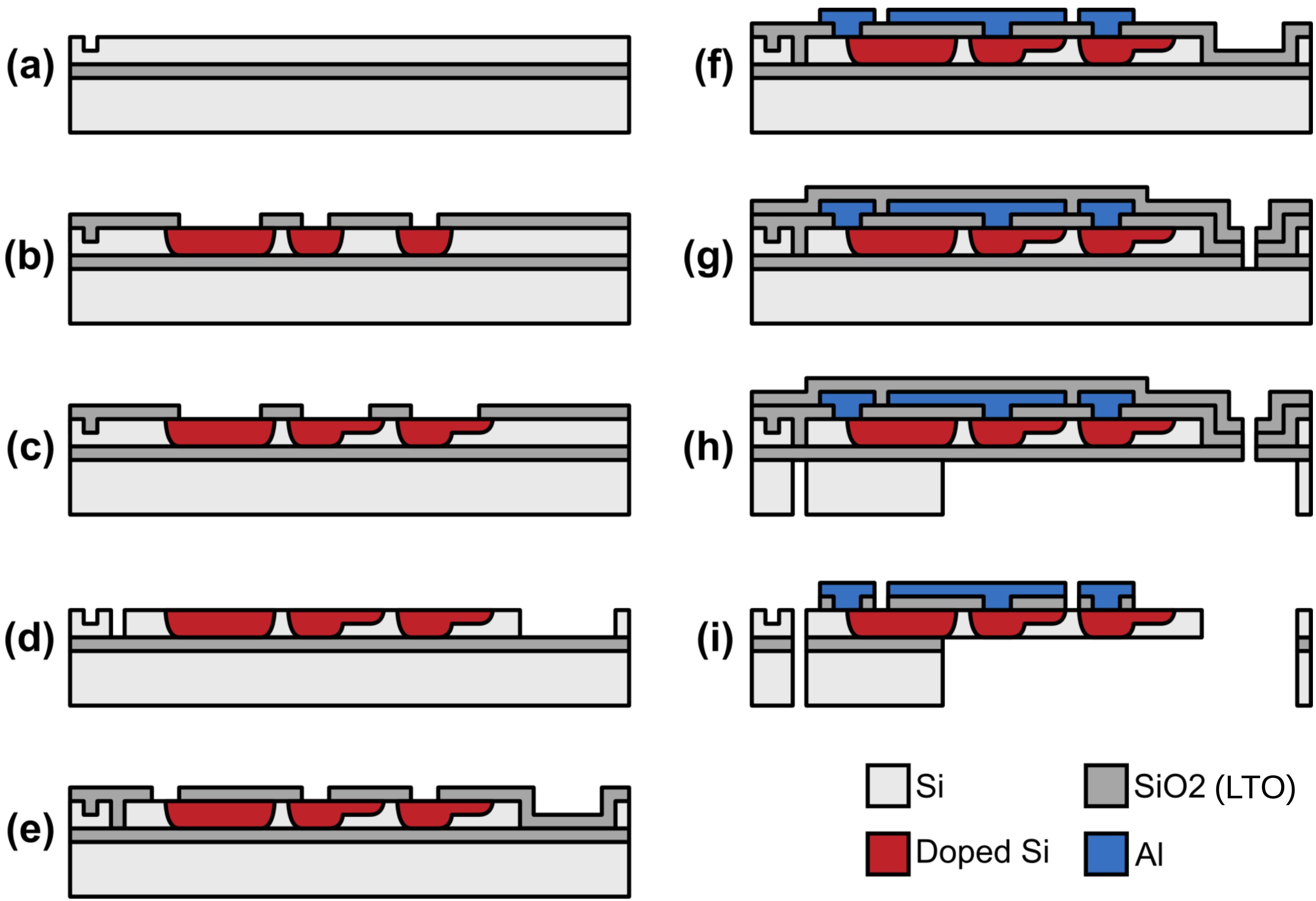
Piezoresistive sensor only

(a)

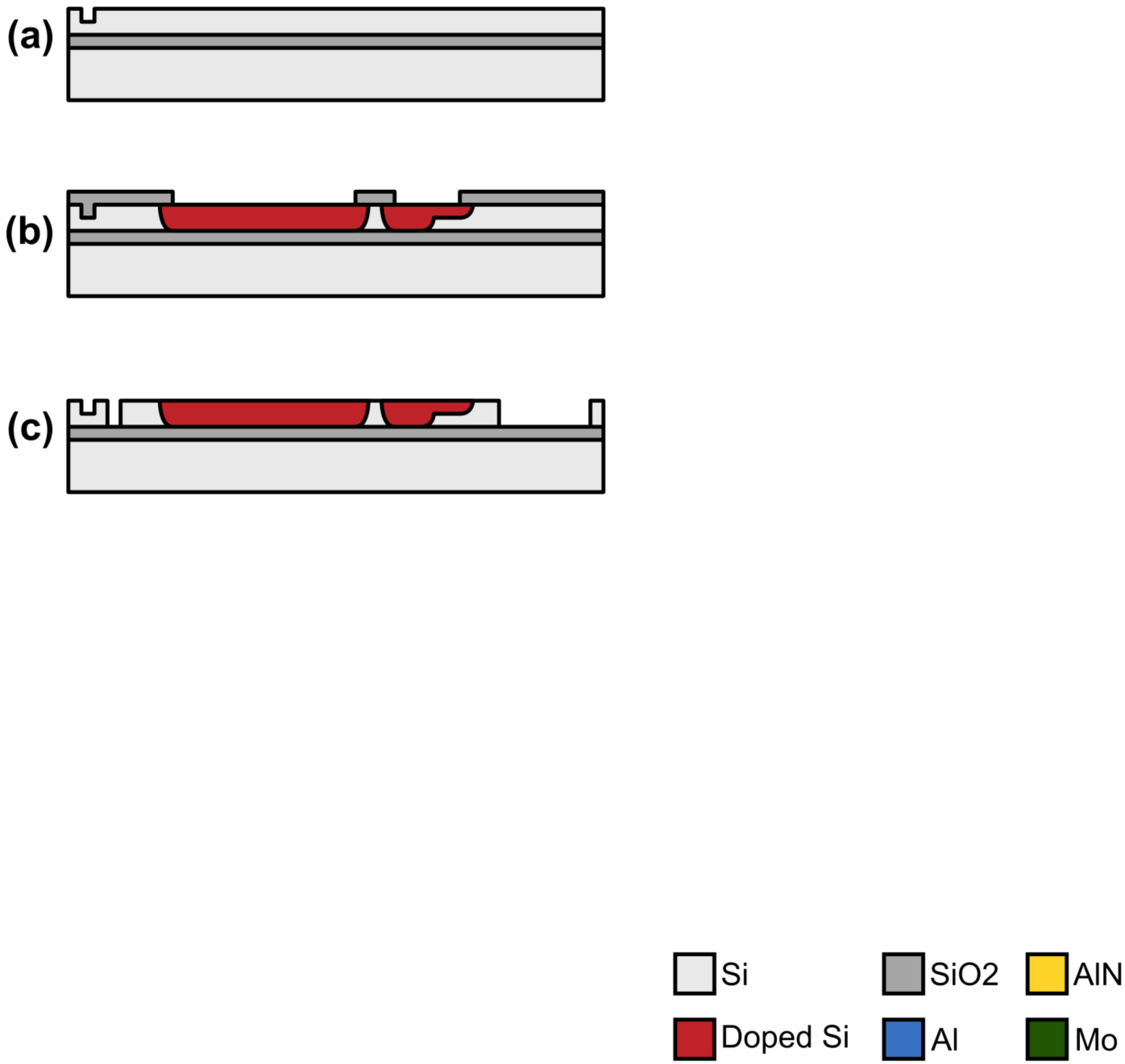


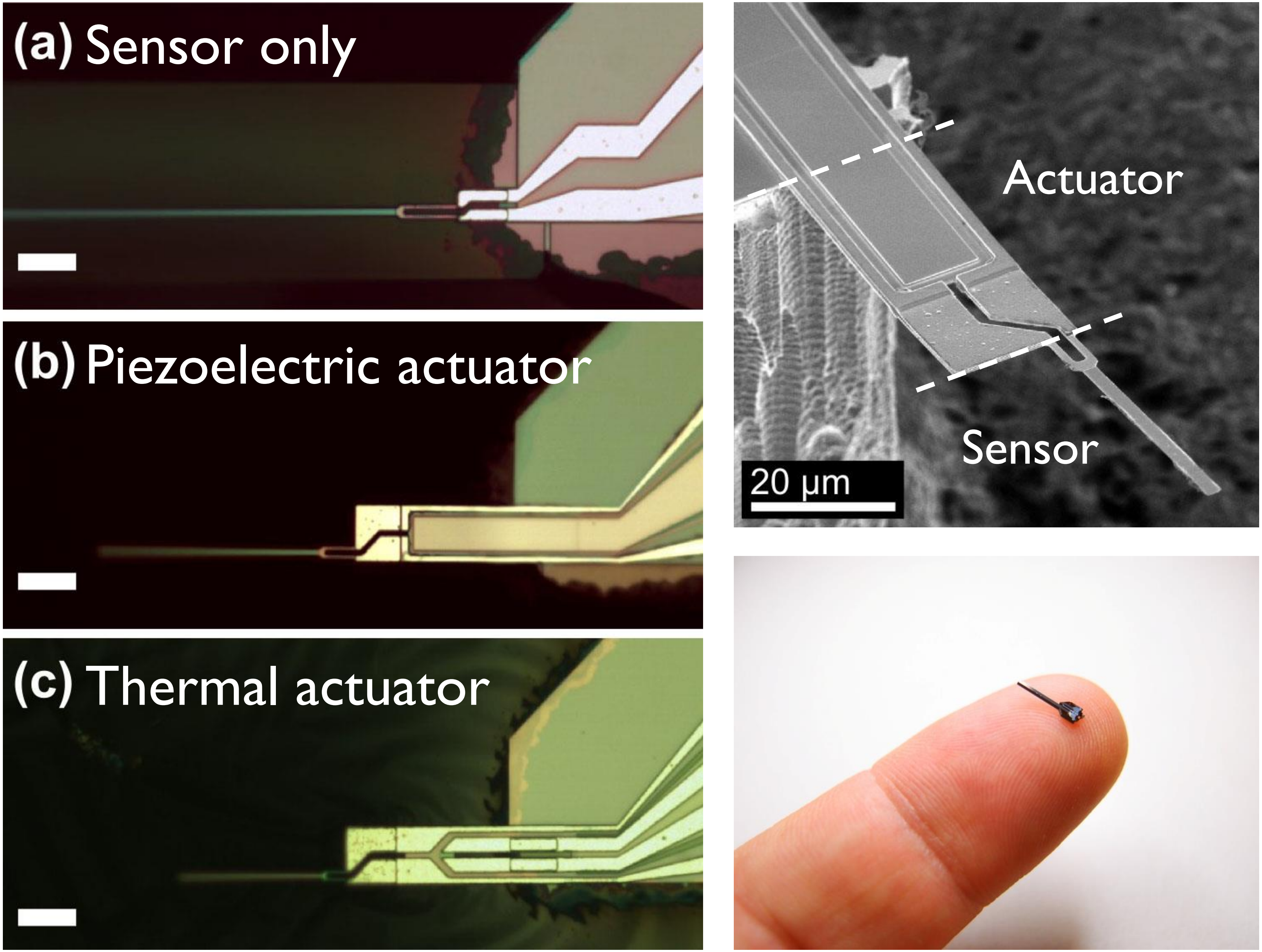


Thermal actuation

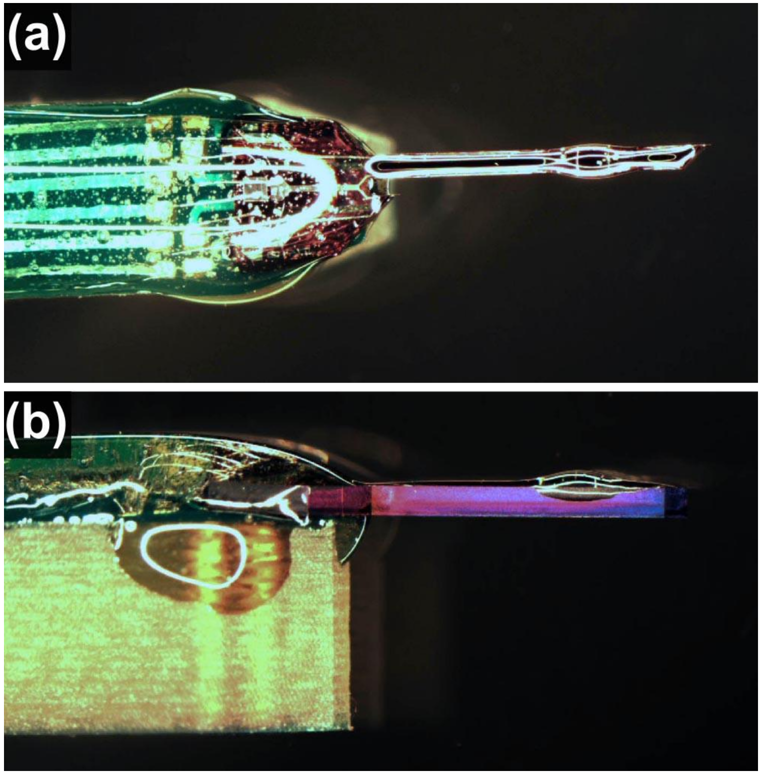


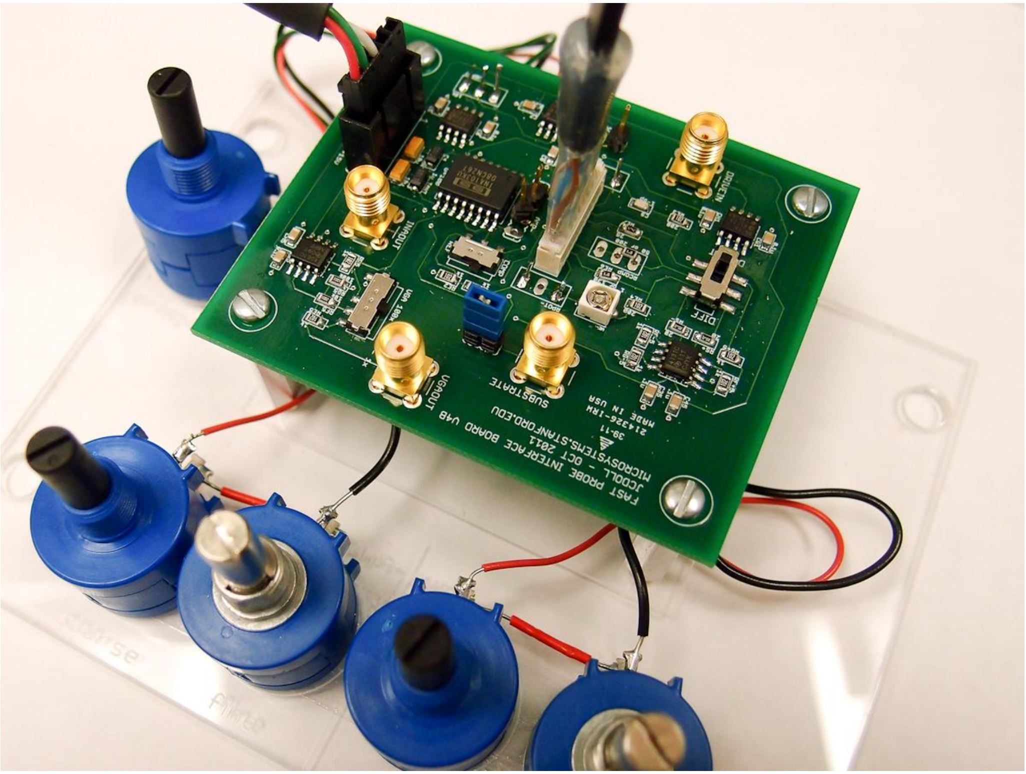
Piezoelectric actuation



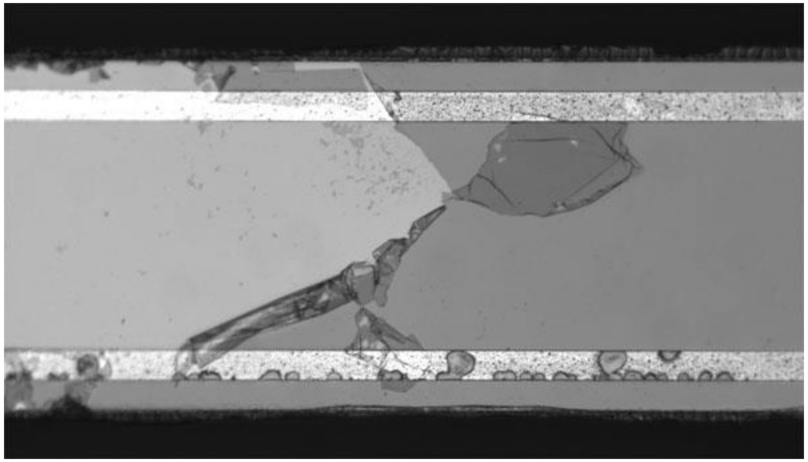

(a) Sensor only
(b) Piezoelectric actuator
(c) Thermal actuator
Actuator
Sensor
20 μm

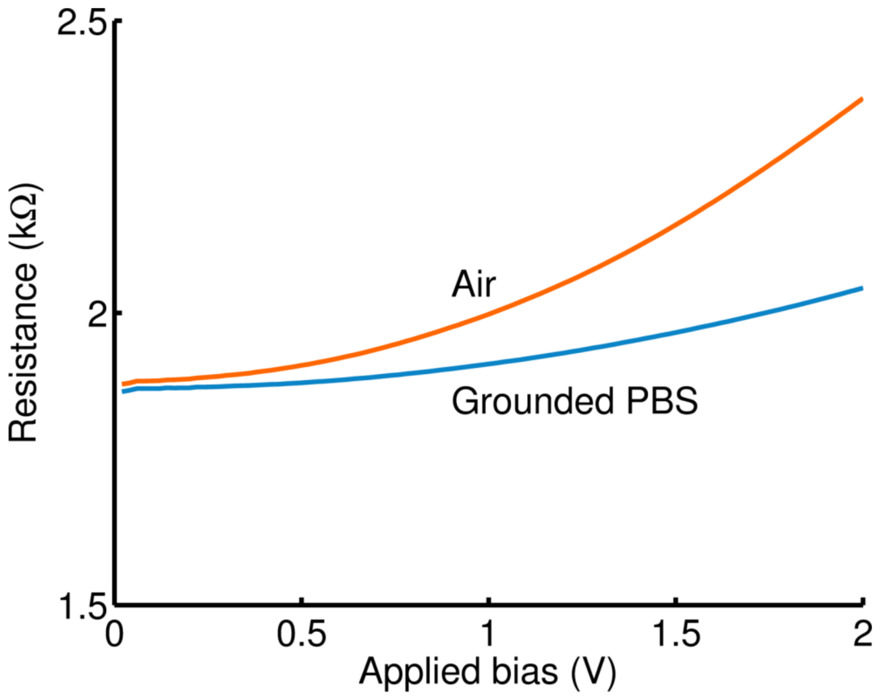
Assembly and Circuits

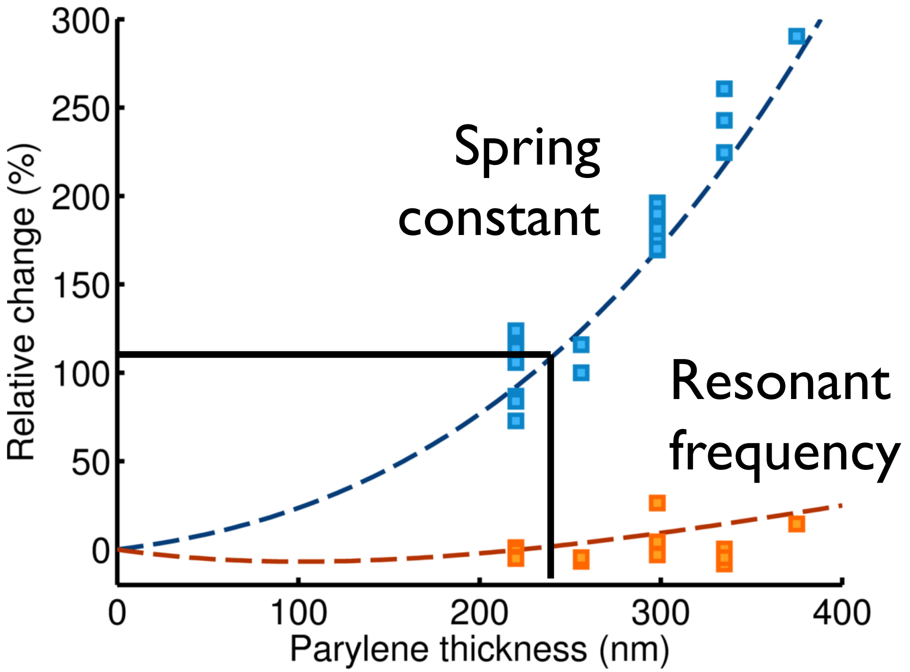




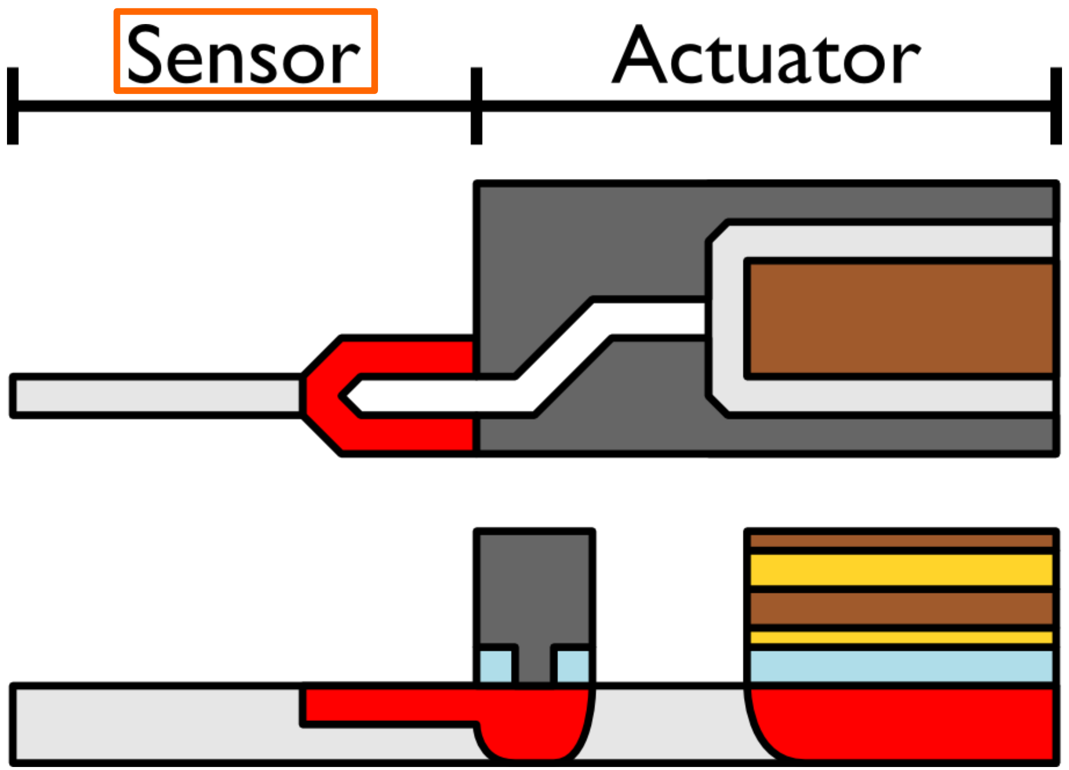
Parylene is required for operation in water



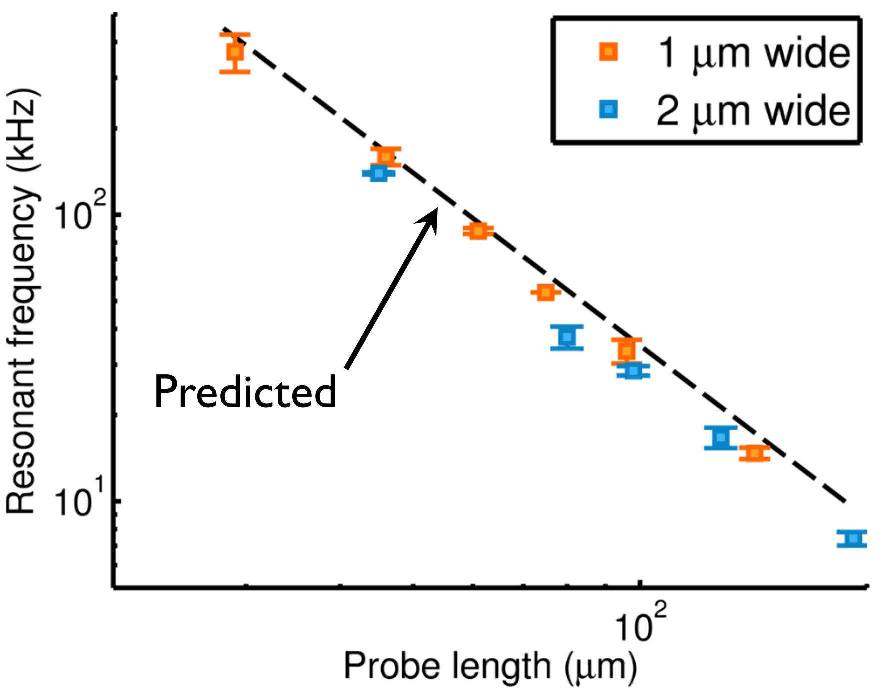


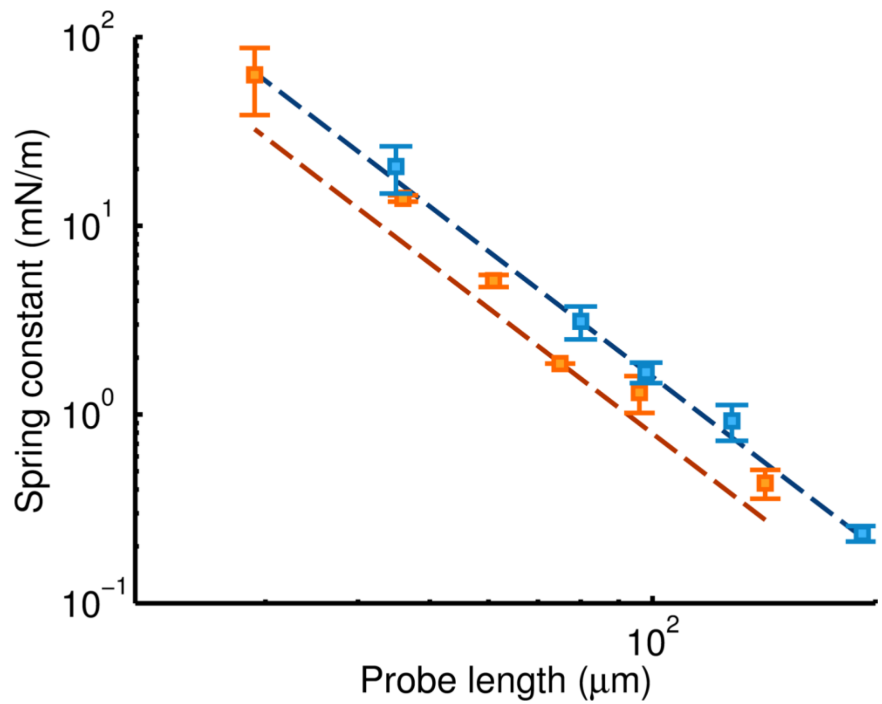


Characterization



Resonant frequencies and spring constants match model predictions

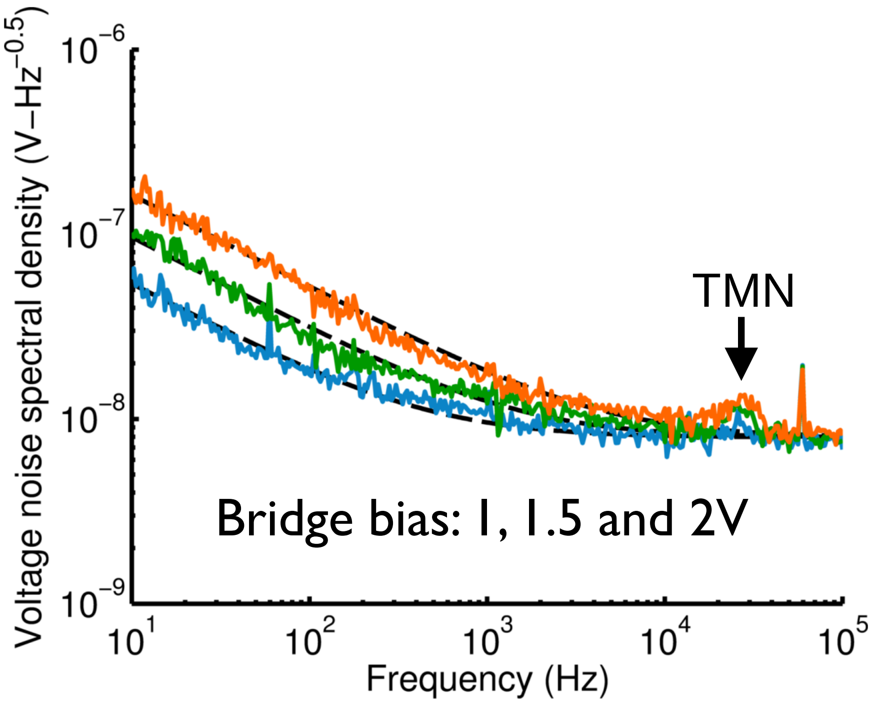




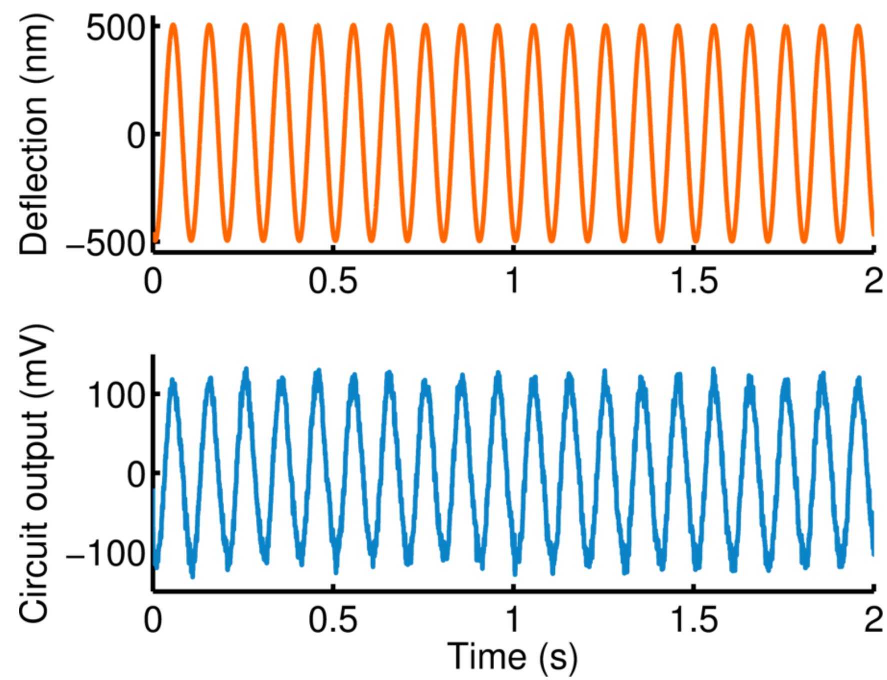
(from thermomechanical noise measured via laser doppler vibrometery)

Measuring sensor resolution

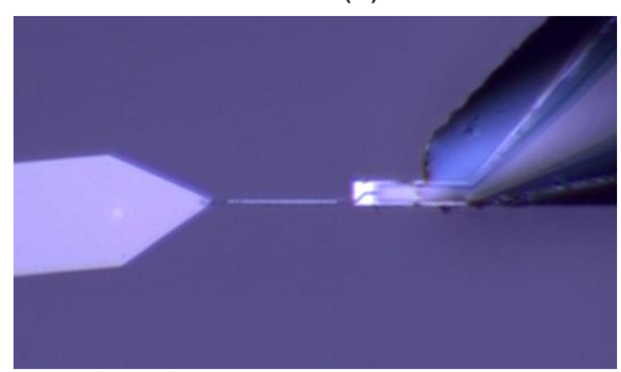
Sensor noise



Displacement sensitivity



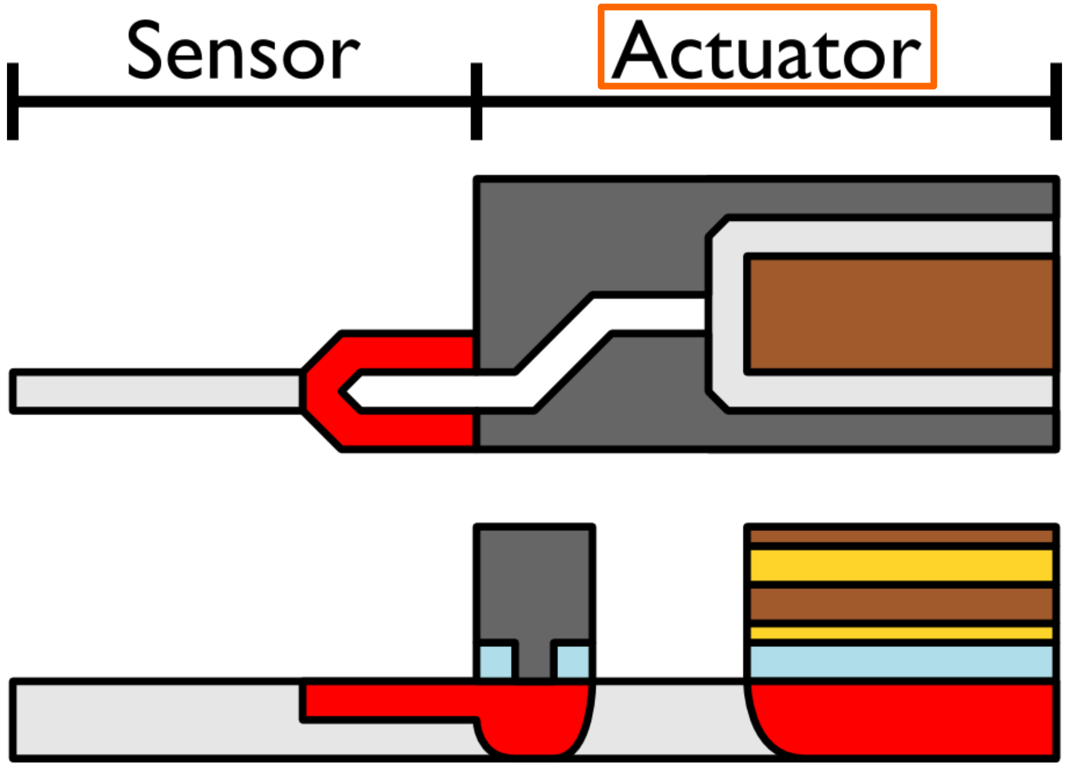
$$\text{Resolution} = \frac{\text{Noise}}{\text{Sensitivity}}$$



Example sensor performance

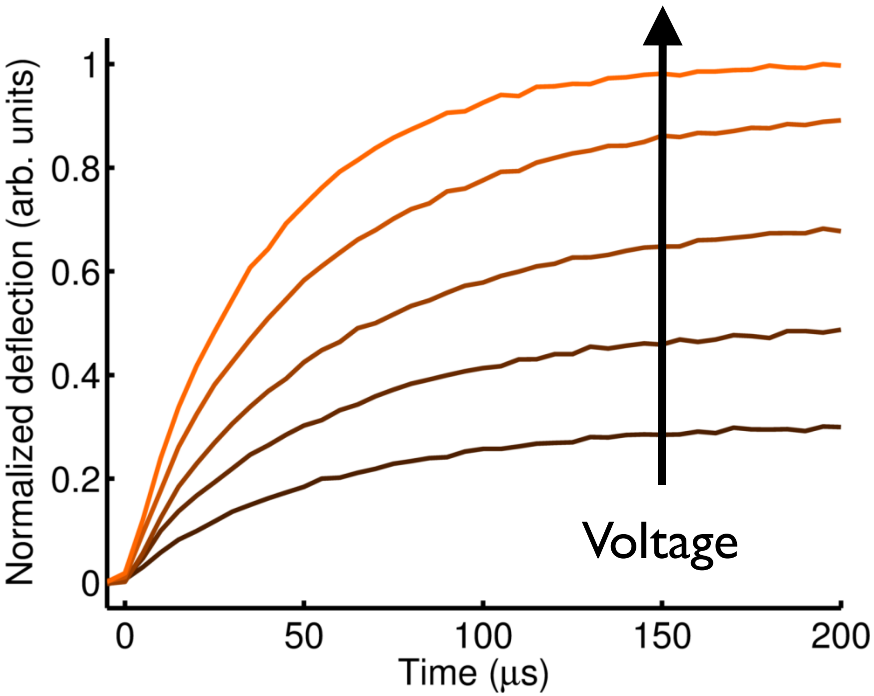
	Example devices	1		2	Model predictions
	l_c (μm)	98		192	
	l_{pr} (μm)	11.1		17.4	
	w_c (μm)	2		2	
	t_c (μm)	0.3		0.3	
Mechanics	f_0 (kHz)	27.8	**(36)**	7.1	**(9.5)**
	k_c (mN/m)	1.63 ± 0.13	**(1.68)**	0.26 ± 0.01	**(0.22)**
	Q (-)	3.8		1.5	
	V_{bridge} (V)	2		2	
	R (kΩ)	3.3		4.8	
	W (μW)	306		209	
	α (-)	$0.8 \pm 0.3 \times 10^{-5}$		$3.1 \pm 0.6 \times 10^{-5}$	
	S_{XV} (V/m-V)	225.2 ± 12.6		73.5 ± 10.3	
	S_{FV} (V/mN-V)	137.9 ± 13.5		282.7 ± 42.5	
	V_{noise} (μV)	0.60		0.74	
Resolution	MDD (nm)	2.7 ± 0.1	**(2.4)**	10.1 ± 1.4	**(9.4)**
	MDF (pN)	4.4 ± 0.4	**(4.0)**	2.6 ± 0.4	**(2.4)**
	TMN floor (pN)	1.0		0.6	

Characterization

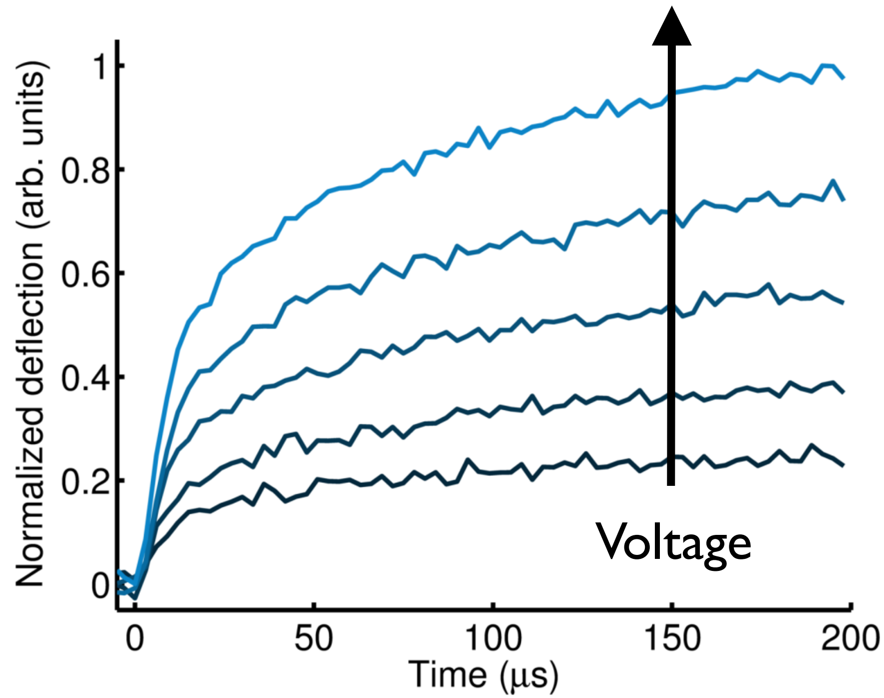


Thermal actuation – slower than expected

Air (90 µs rise time)

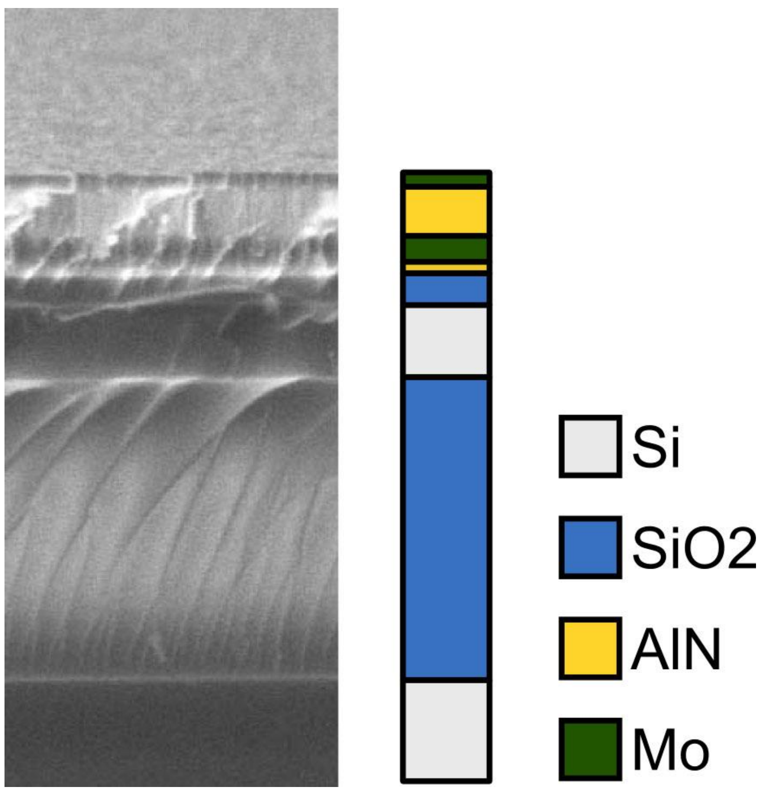


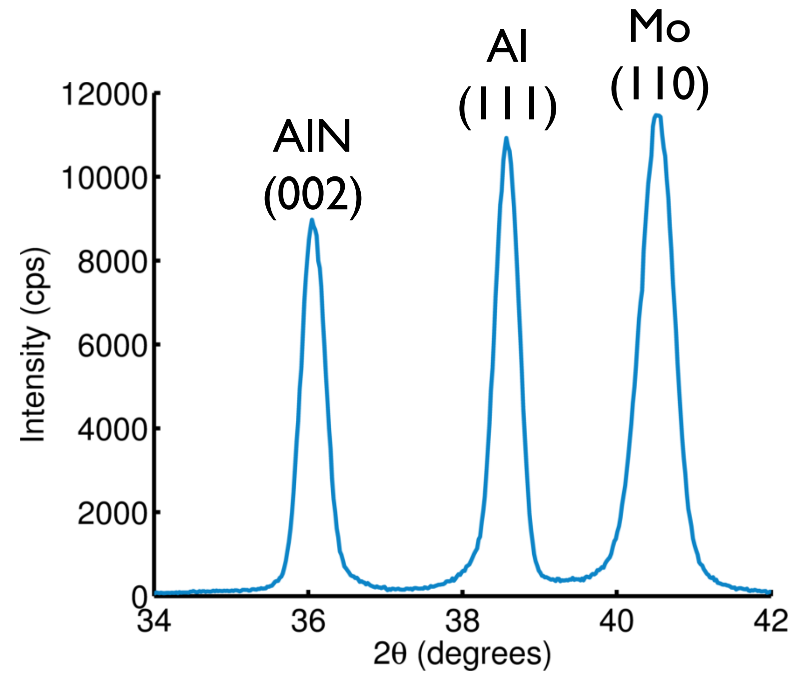
Water (80 µs rise time)

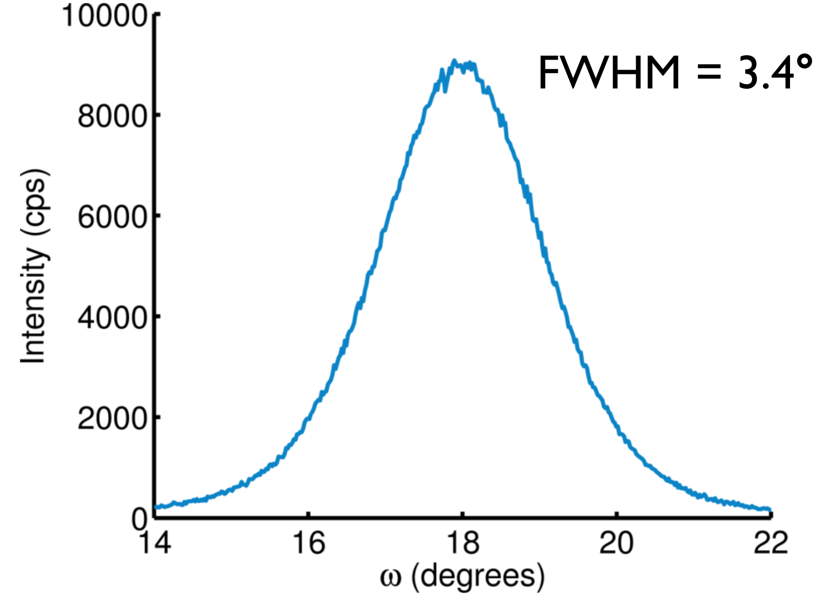


(measured with Anton Peng by projecting the probe shadow onto a photodiode pair)

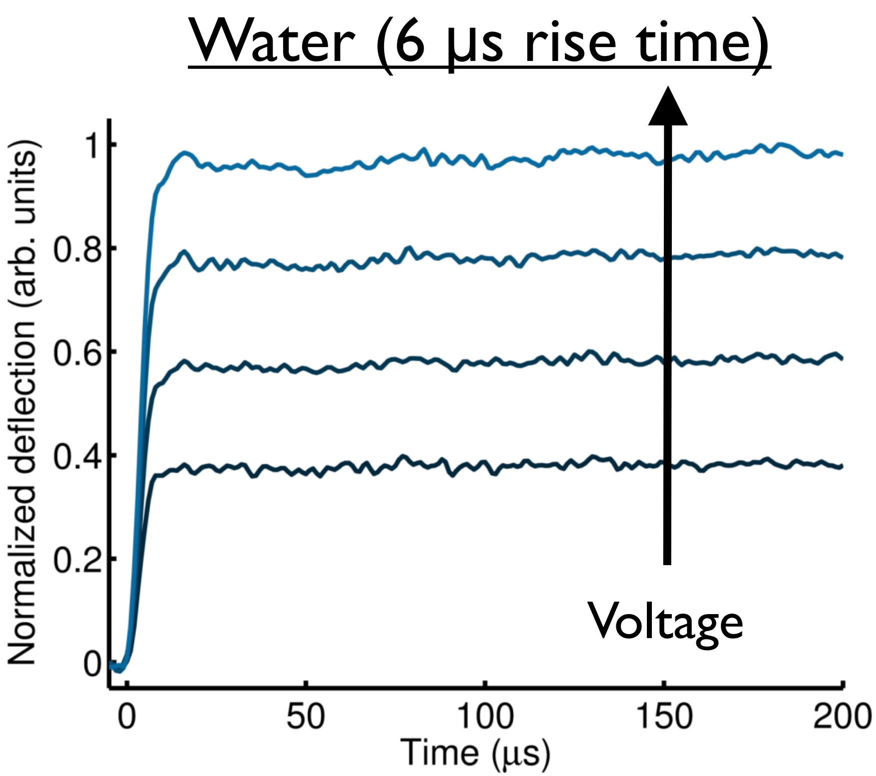
Piezoelectric films have good crystallinity

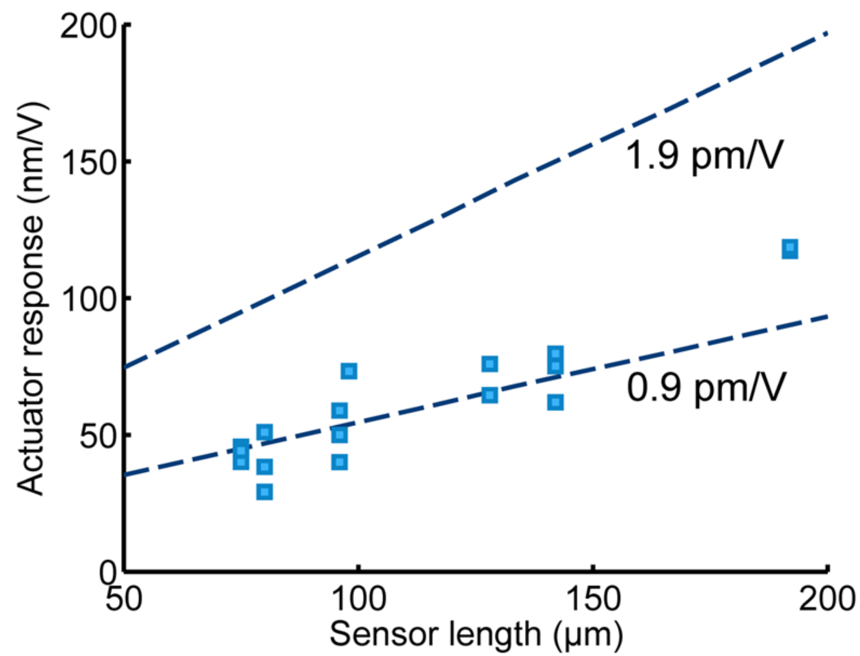






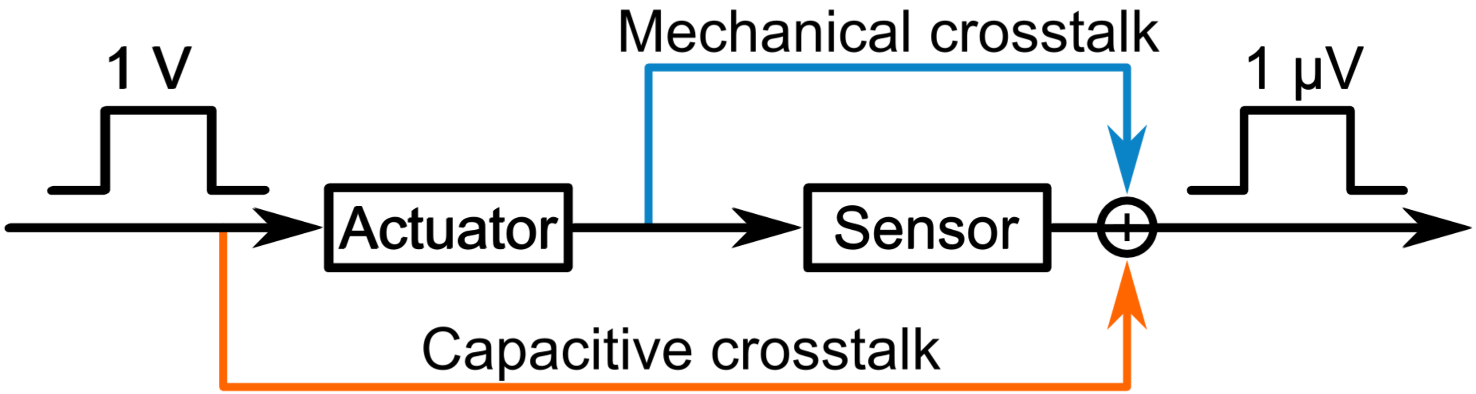
Piezoelectric actuation is fast

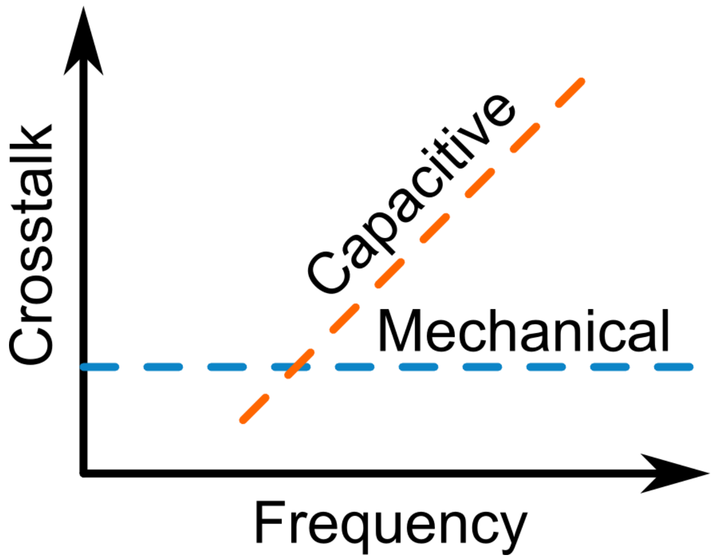




System integration
and
hair cell experiments

Actuator-sensor crosstalk

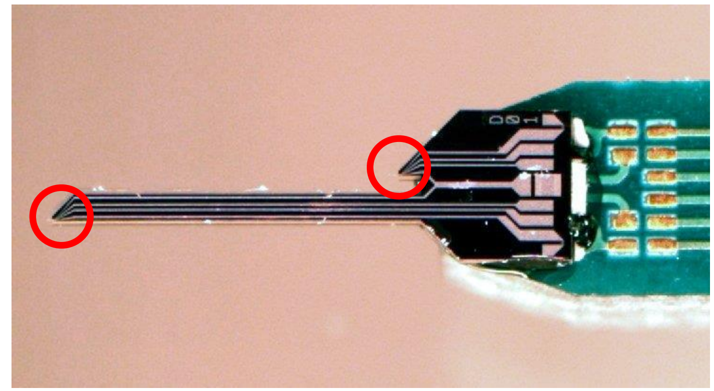




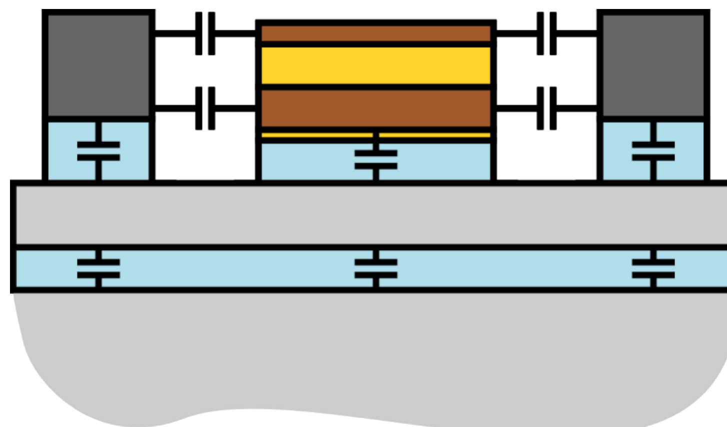
The actuator signal is 10^6-fold greater than the sensor signal

Crosstalk compensation

1) Identical compensation probe

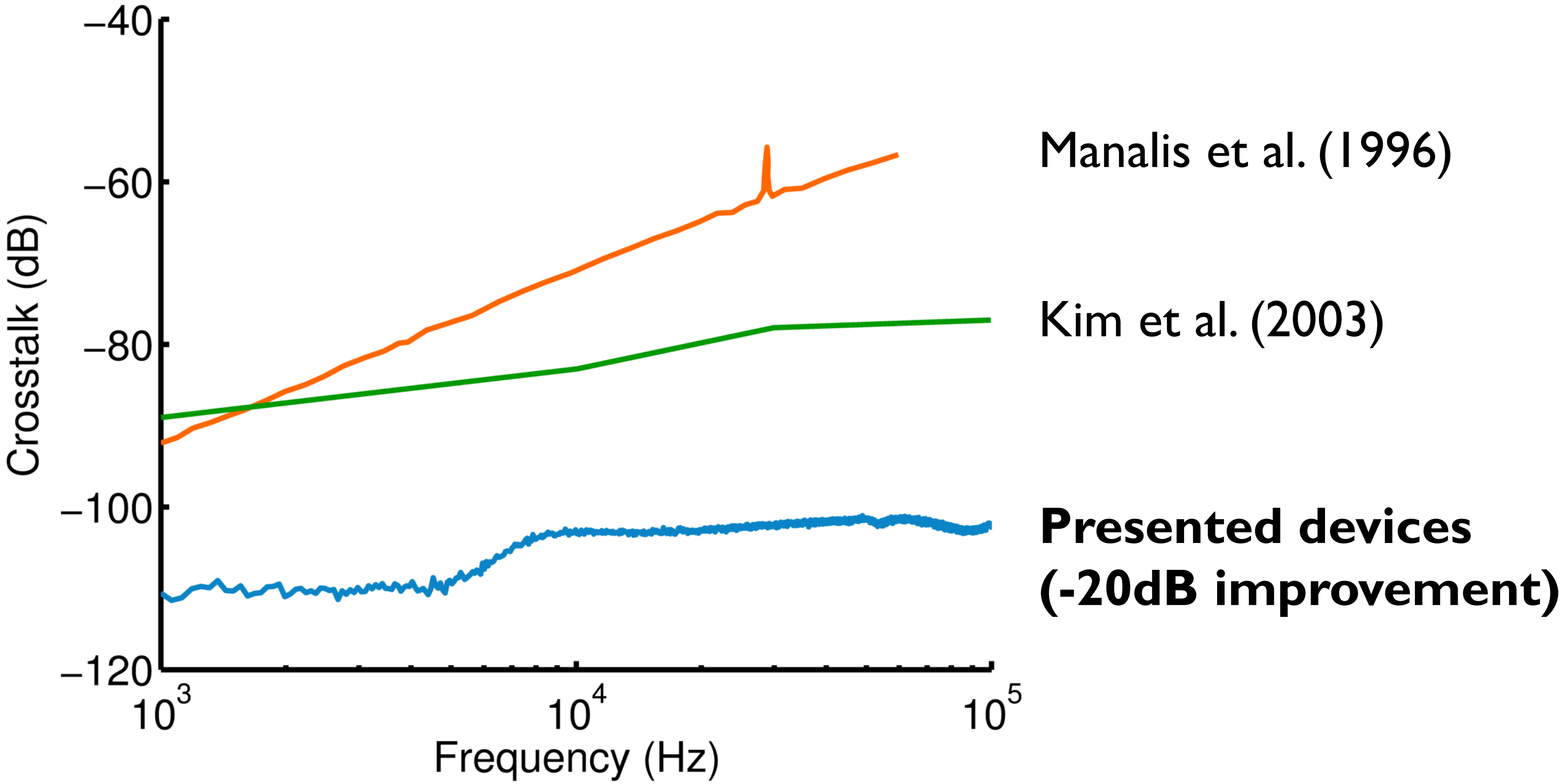


2) Diffusion well and isolation trench

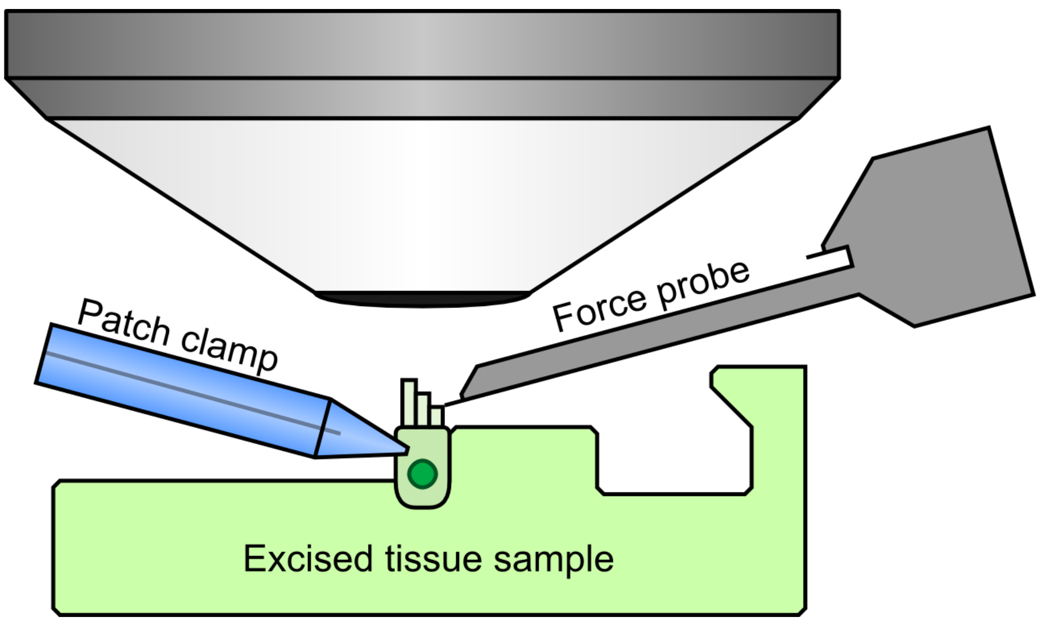


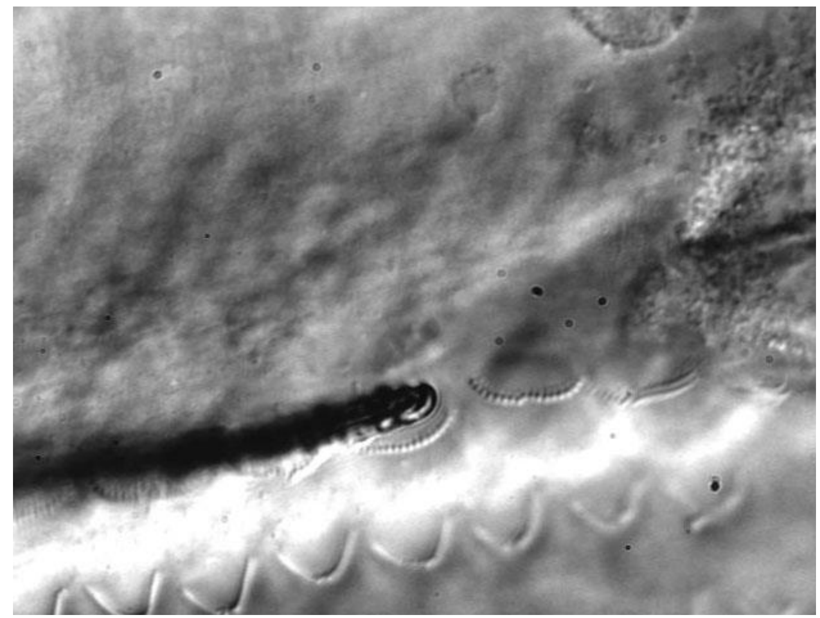
3) Circuit-level compensation (varcap)

Crosstalk is 10x smaller than previous work

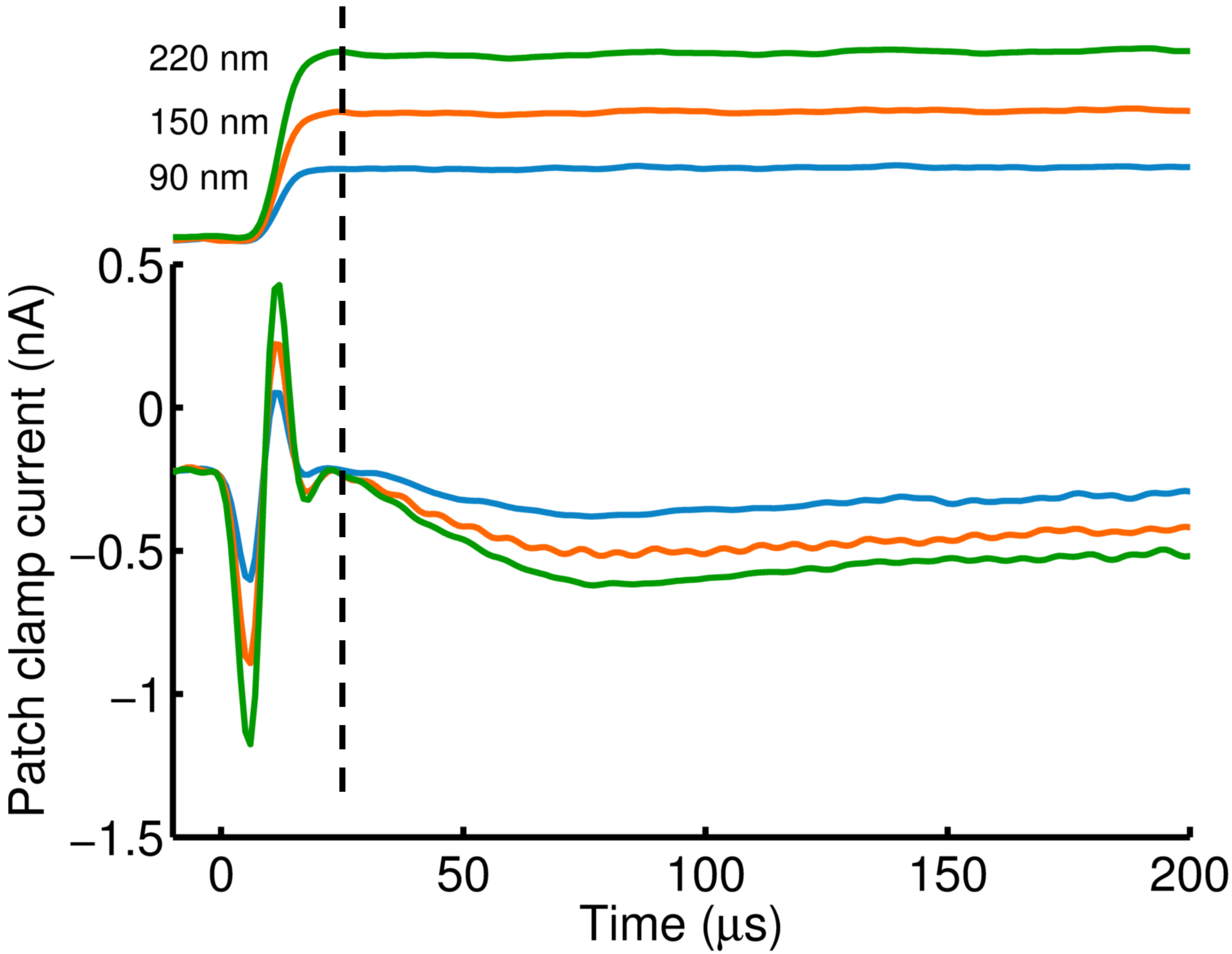


Measuring hair cell kinetics





Mammalian hair cell kinetics



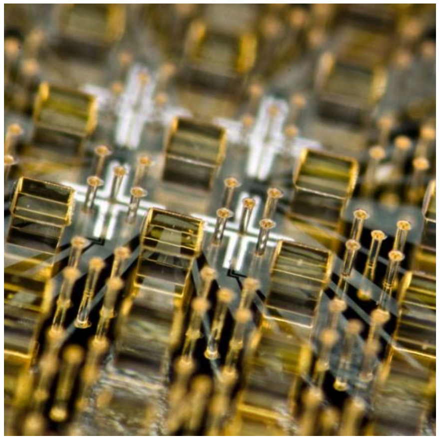
Contributions

1. Developed new techniques for piezoresistor design optimization

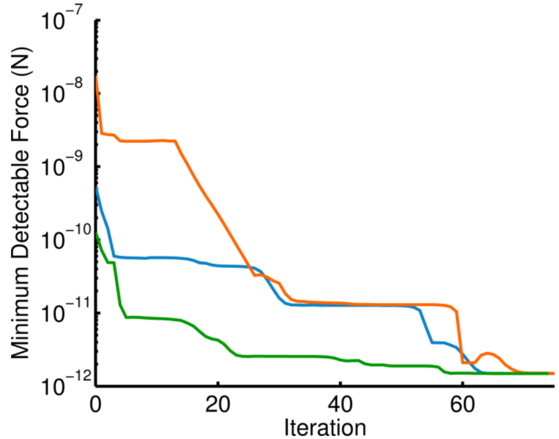
2. Fabricated force probes capable of detecting and applying pN forces at the μs timescale

3. Integrated the probes with simultaneous patch clamp measurements to study mammalian cochlear hair cells

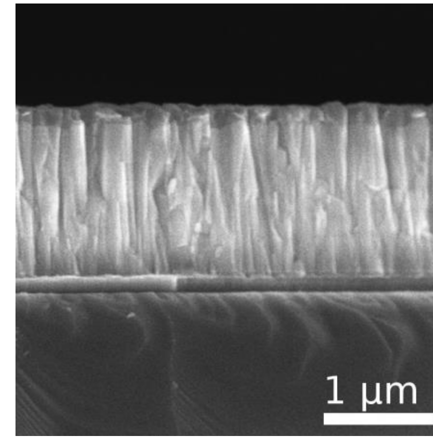
Other parts of the story…



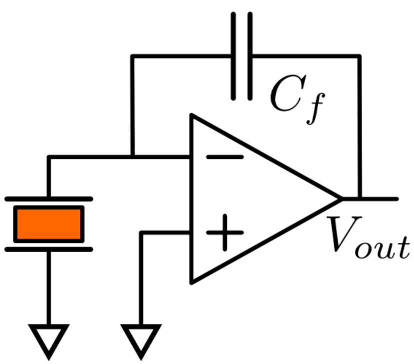
SU-8 force sensing pillar arrays
for biological measurements
Lab on a Chip (2009)



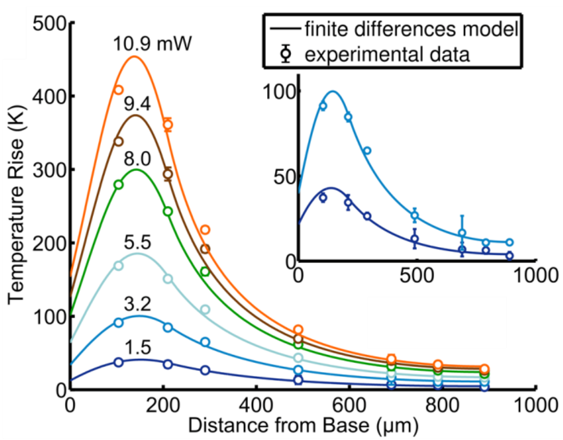
Design optimization of PR cantilevers
for force sensing in air and water
Journal of Applied Physics (2009)



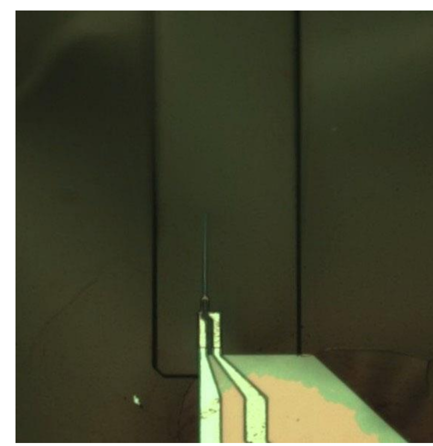
Aluminum nitride on titanium for CMOS
compatible piezoelectric transducers
JMM (2010)



Design of PR vs. PE scanning probes
JMM (2010)



Self-heating in piezoresistive cantilevers
Applied Physics Letters (2011)



Patterned cracks improve yield in the
release of microdevices from SOI wafers
JMM (2011)

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Prof. Miriam Goodman

Prof. Ellen Kuhl

Prof. Tony Ricci

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Ginel Hill
Rishi Kant
Tina Lamers
Eric Perozziello
J Provine
Gary Yama

+ many more

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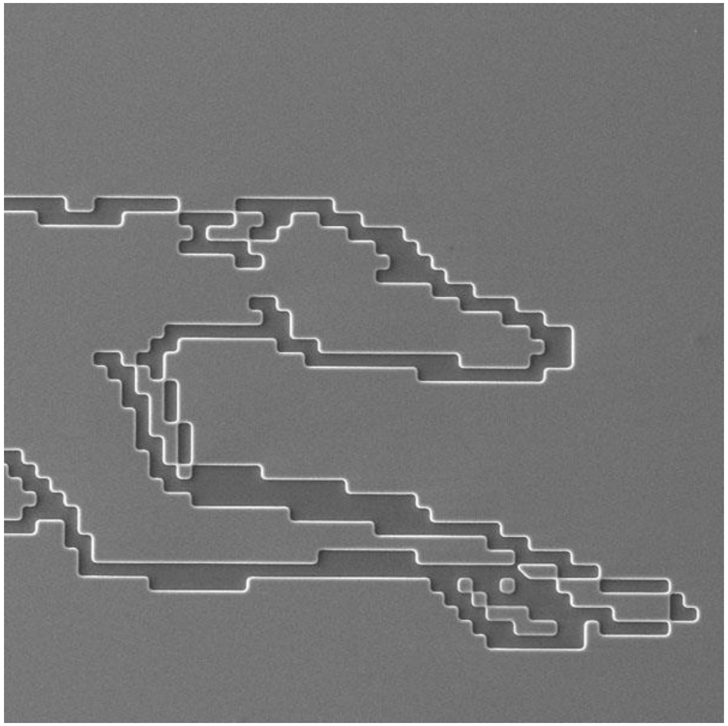
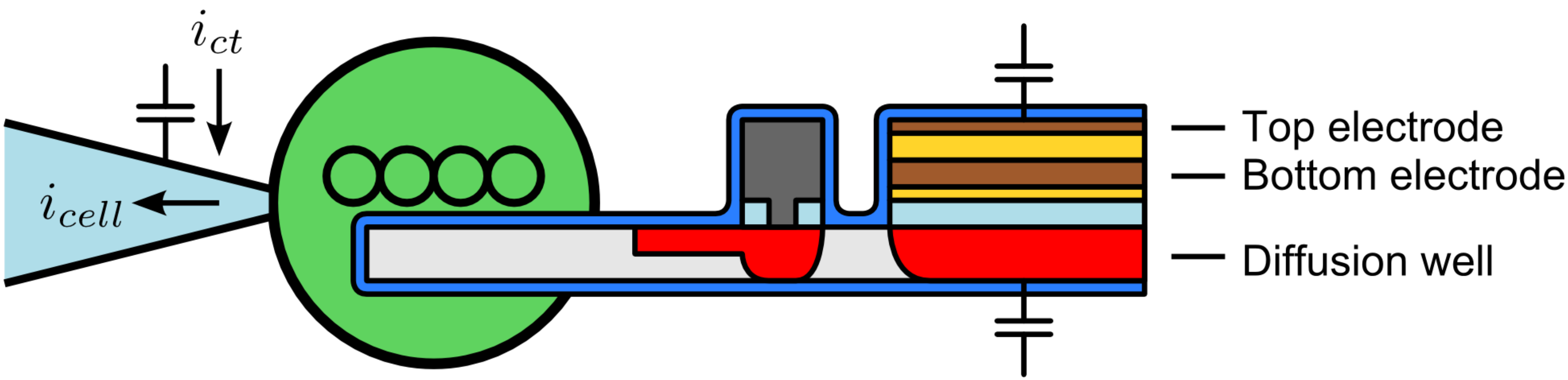


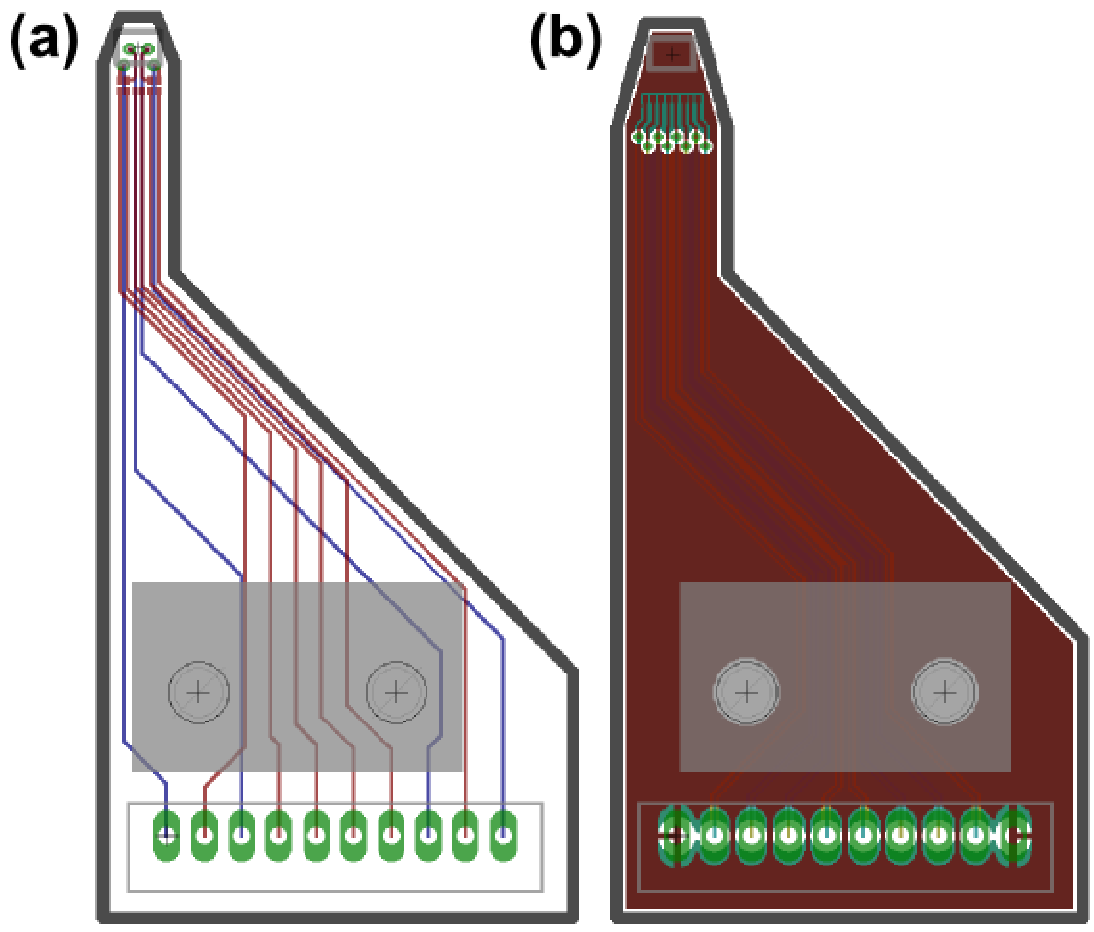
Thank you for listening!

Bonus slides

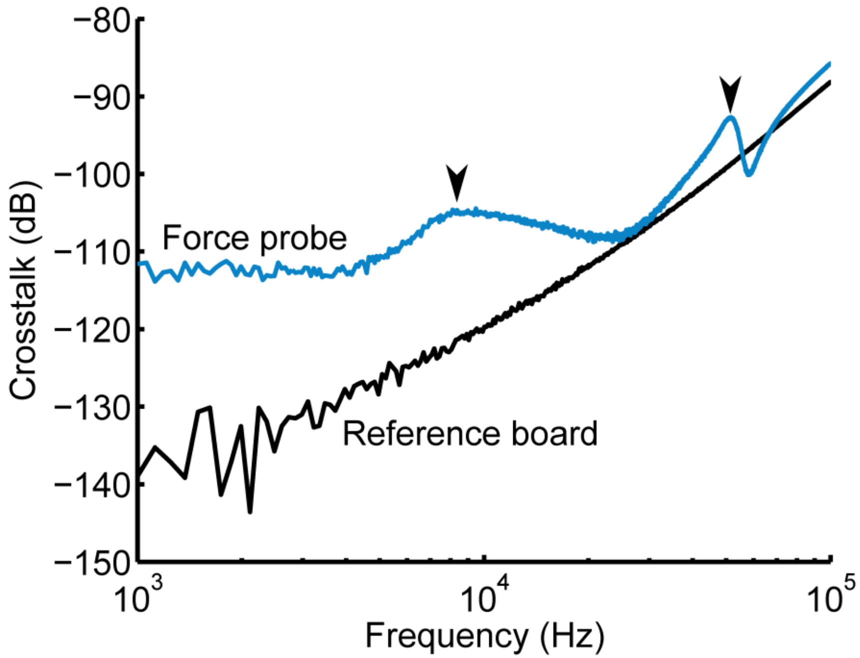
Patch clamp crosstalk

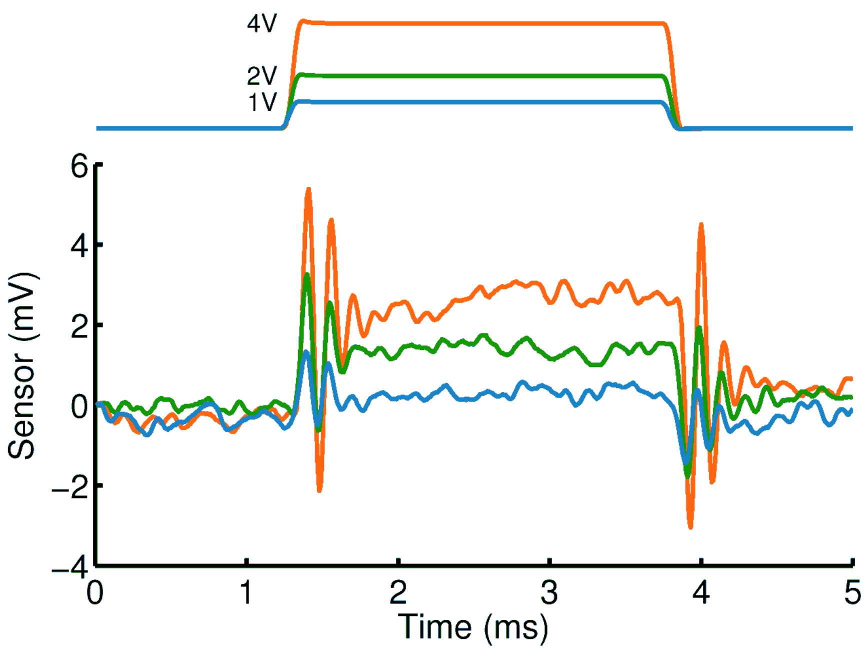


2- and 4- layer cantilever PCBs



Mechanical crosstalk

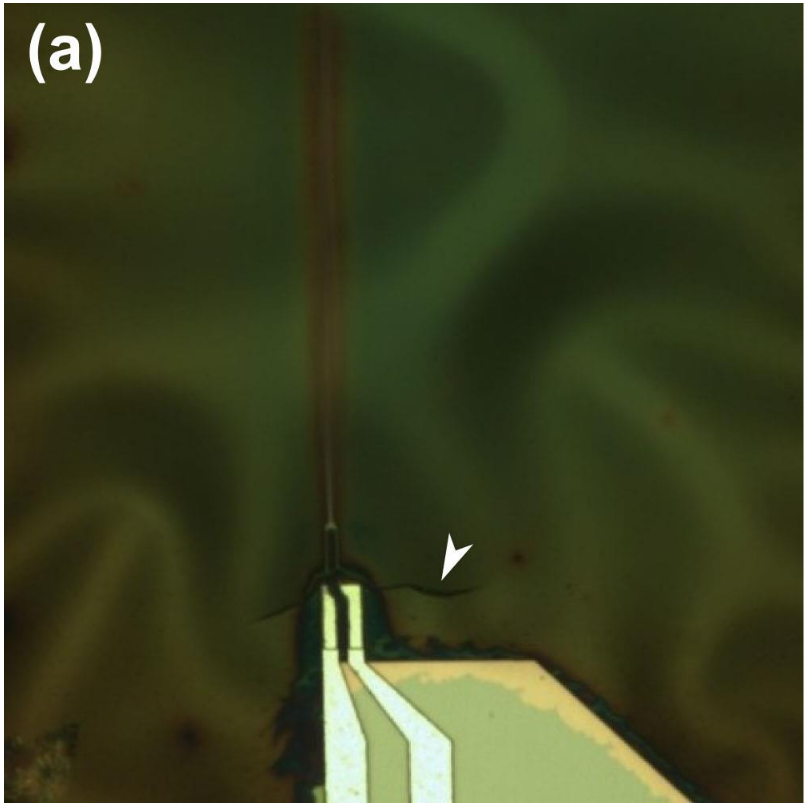




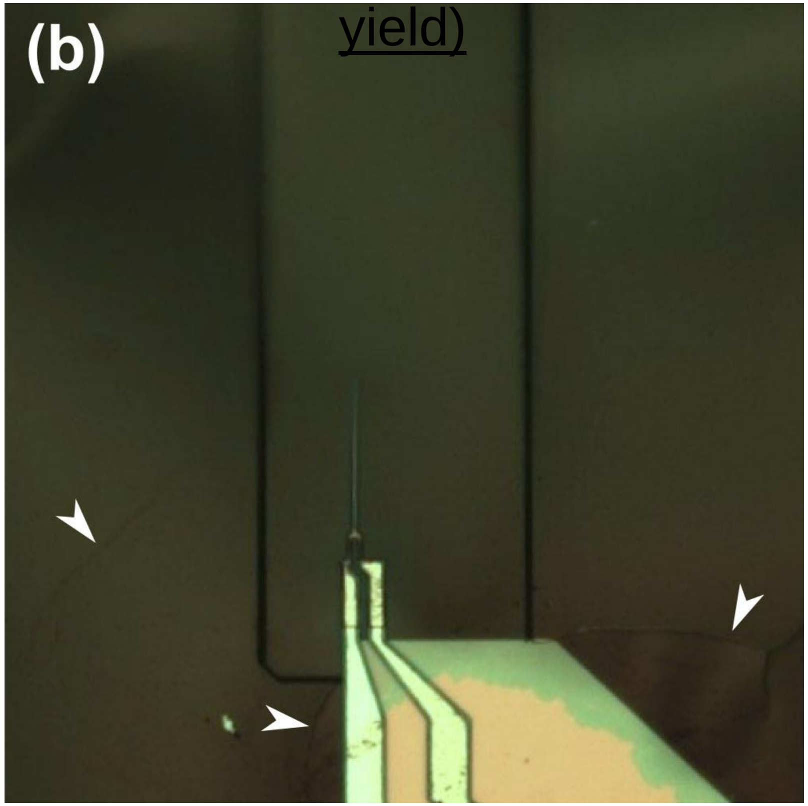
0.65 pN/nm (parylene coated)
7.3 kHz (in air)
75 nm/V deflection
1 mV = 0.2 pN

Patterned cracks doubled probe yield

Initial devices (16-50% yield)

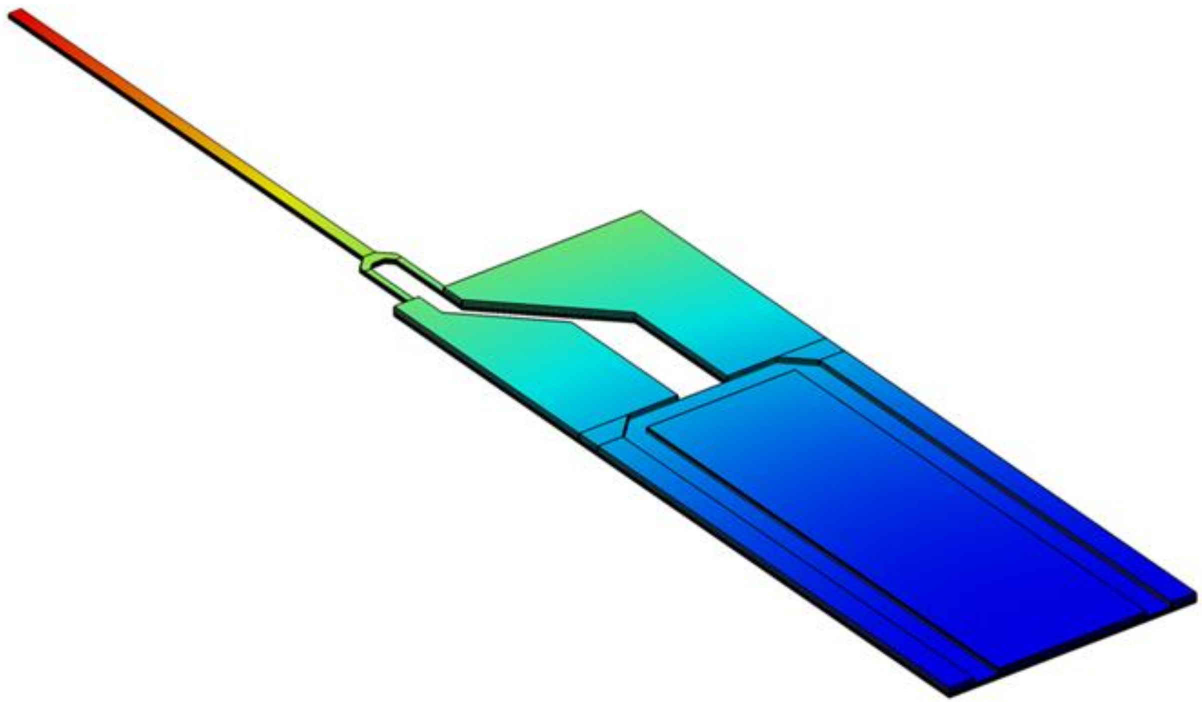


Patterned cracks (50-90% yield)



Patterned cracks improve yield in the release of compliant microdevices from SOI wafers
G.C. Hill, J.I. Padovani, J.C. Doll, B.W. Chui, D. Rugar, H.J. Mamin, N. Harjee, B.L. Pruitt
Journal of Micromechanics and Microengineering (2011)

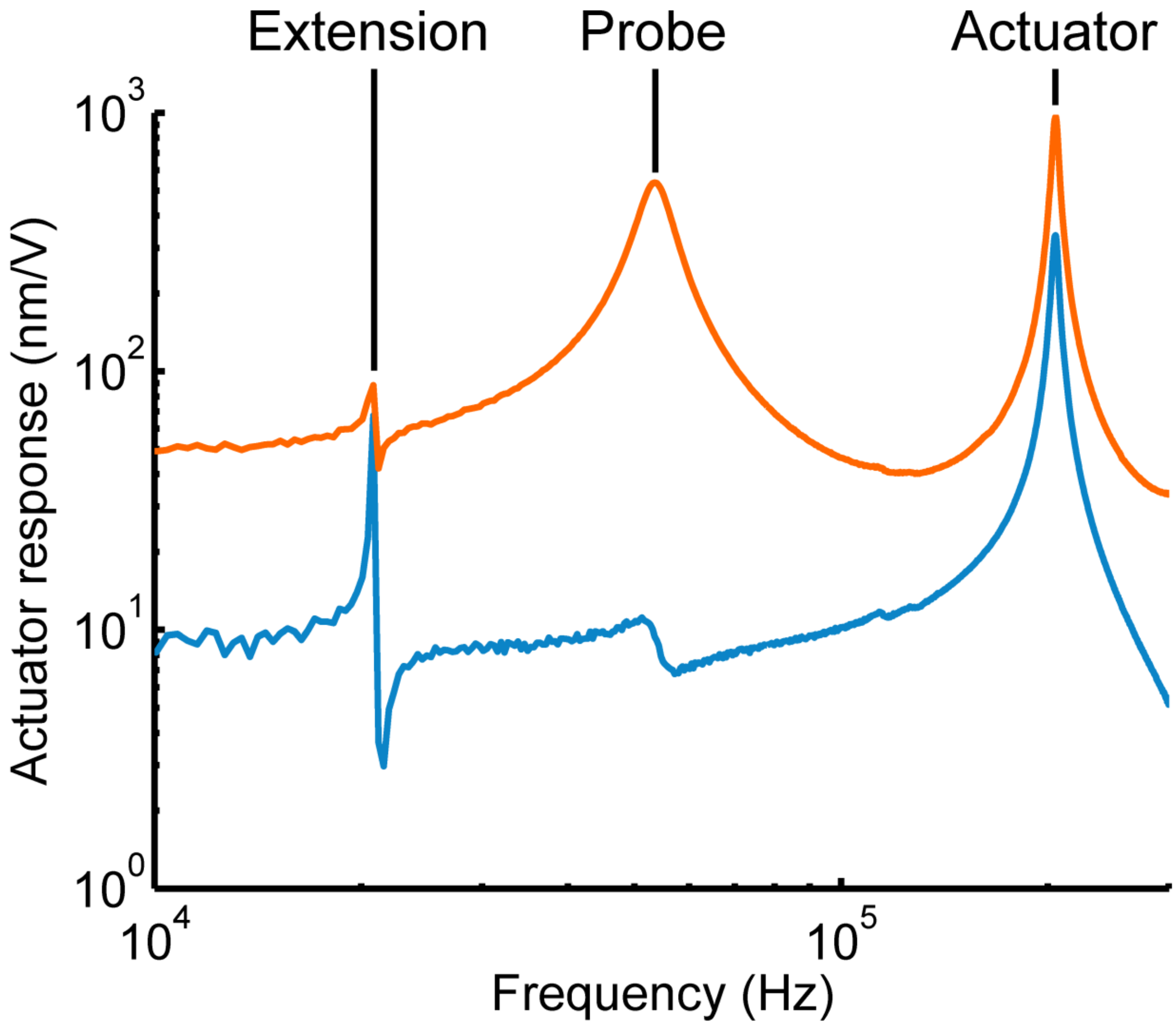
Actuator bandwidth



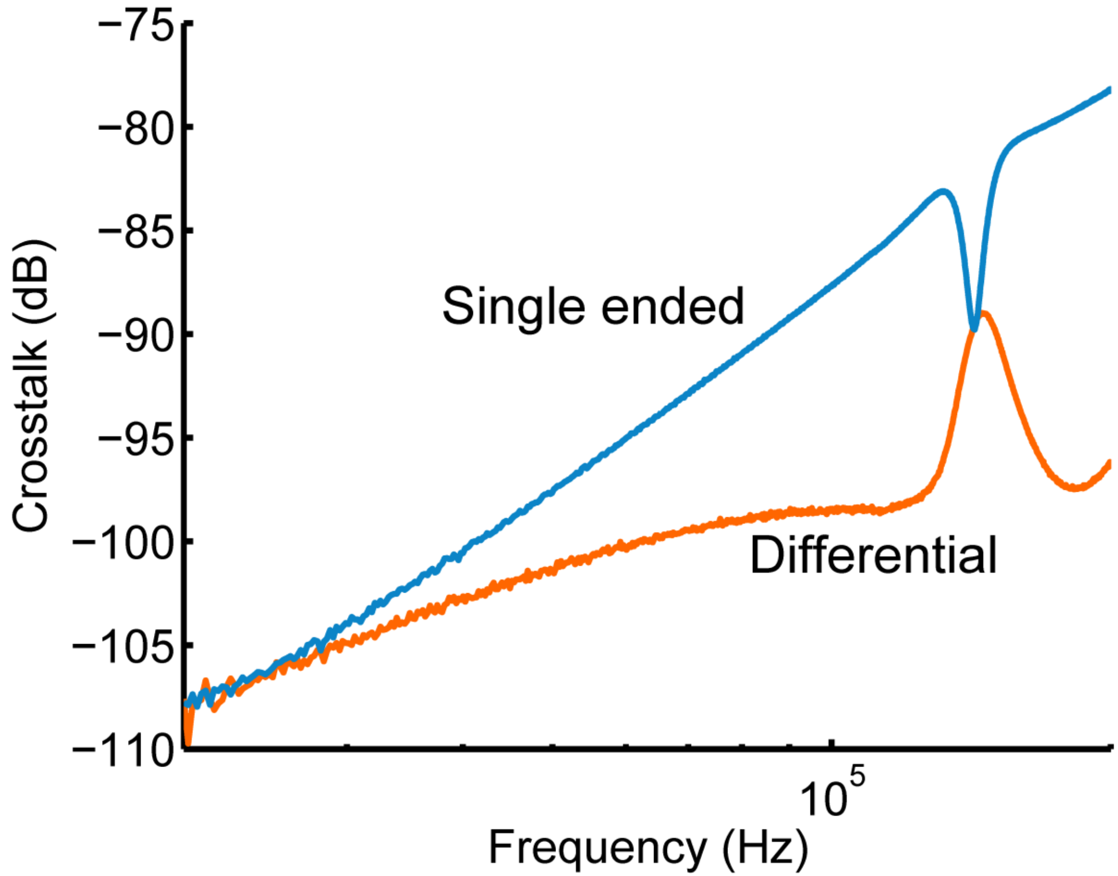
Calculation methods for k and f0:

1) 1D numerical (i.e. Rayleigh-Ritz)
2) FEA (Comsol) for spot checks

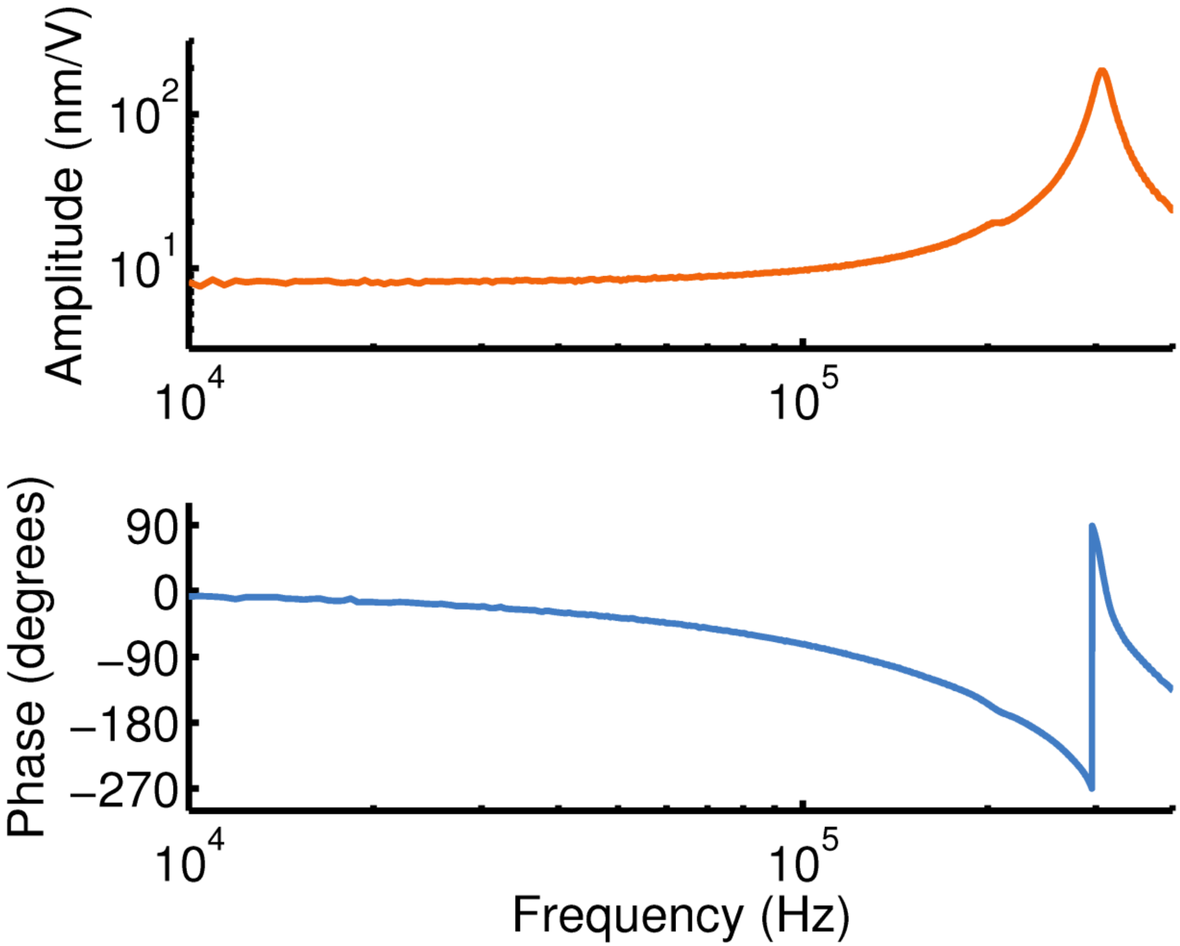
Actuator bandwidth



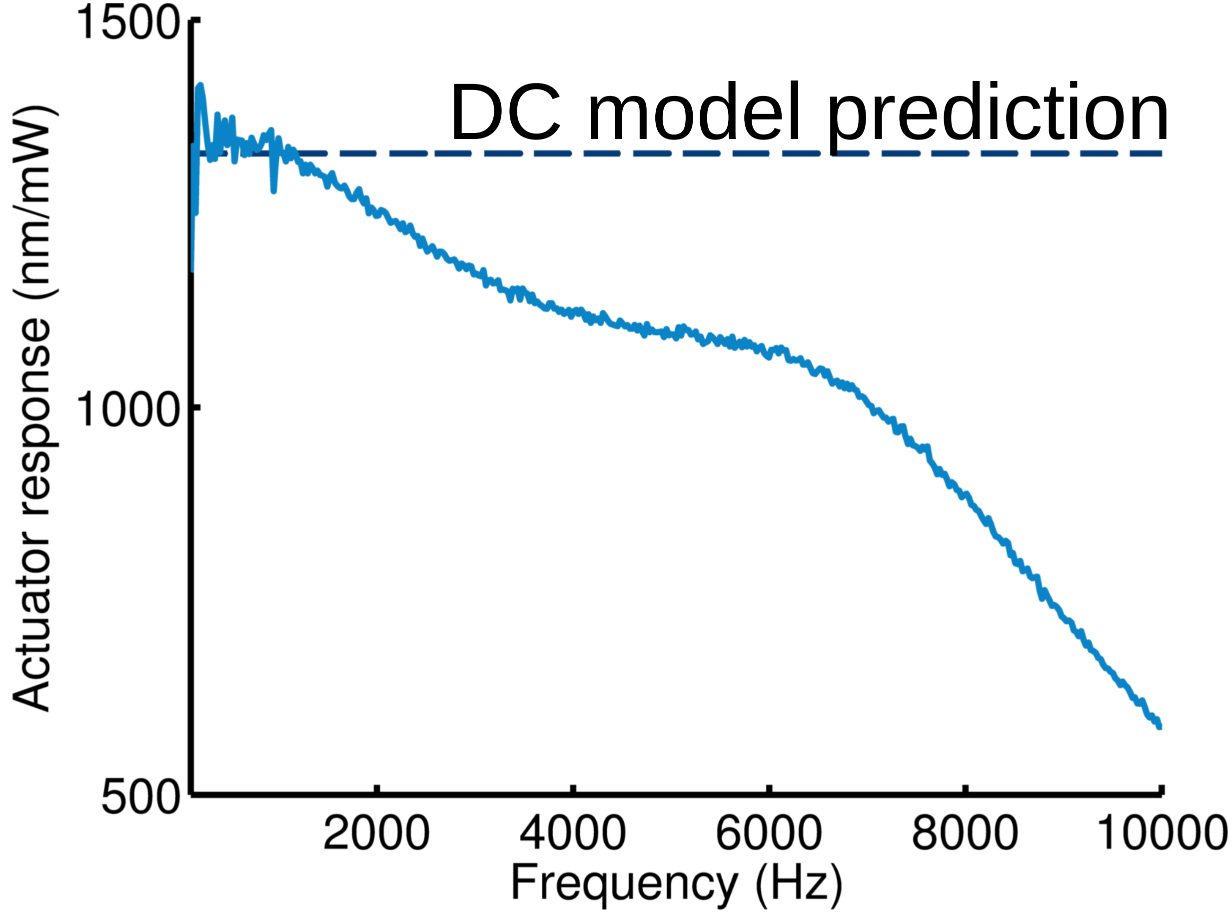
Single ended vs. differential drive

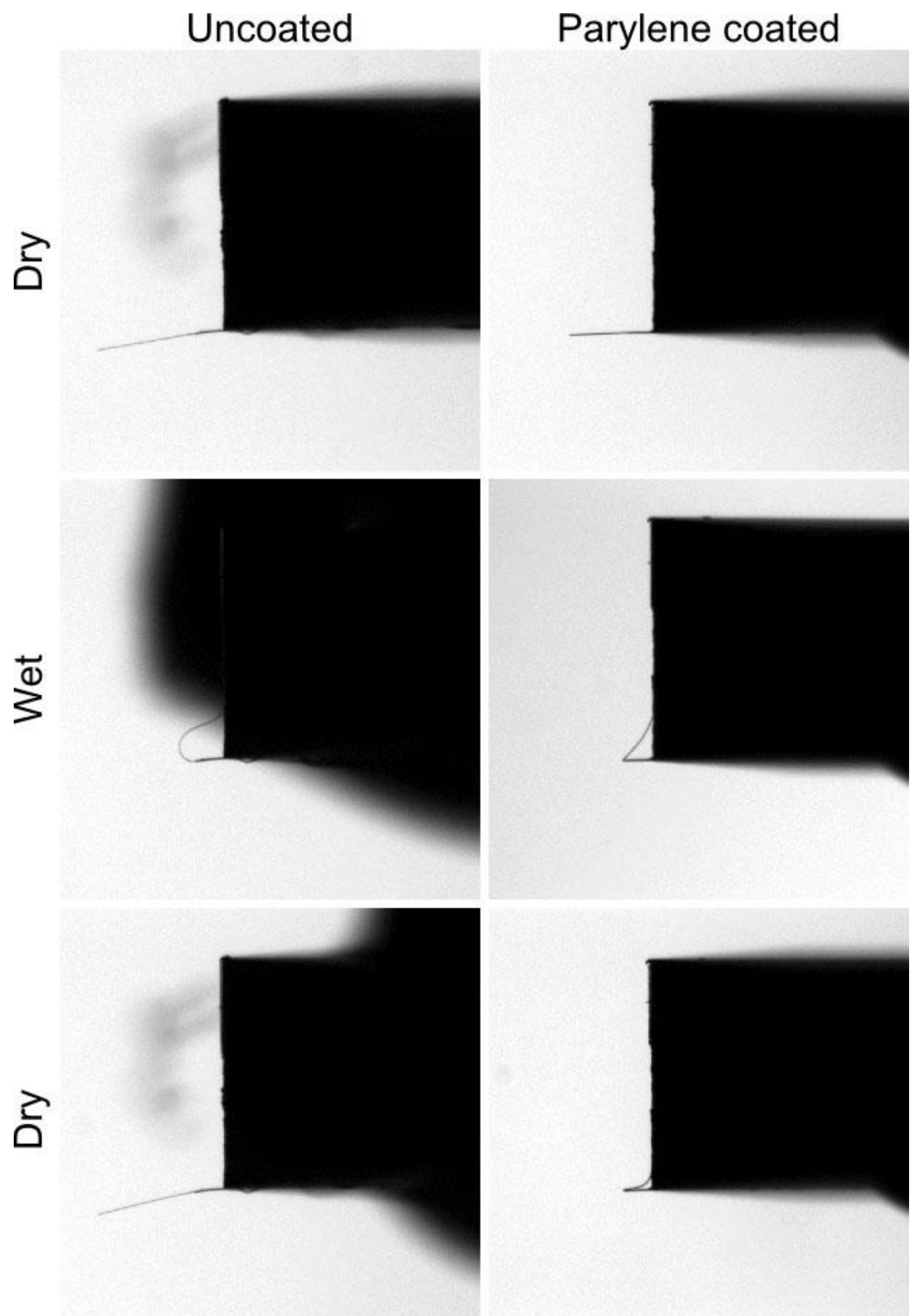


Piezoelectric actuator bandwidth



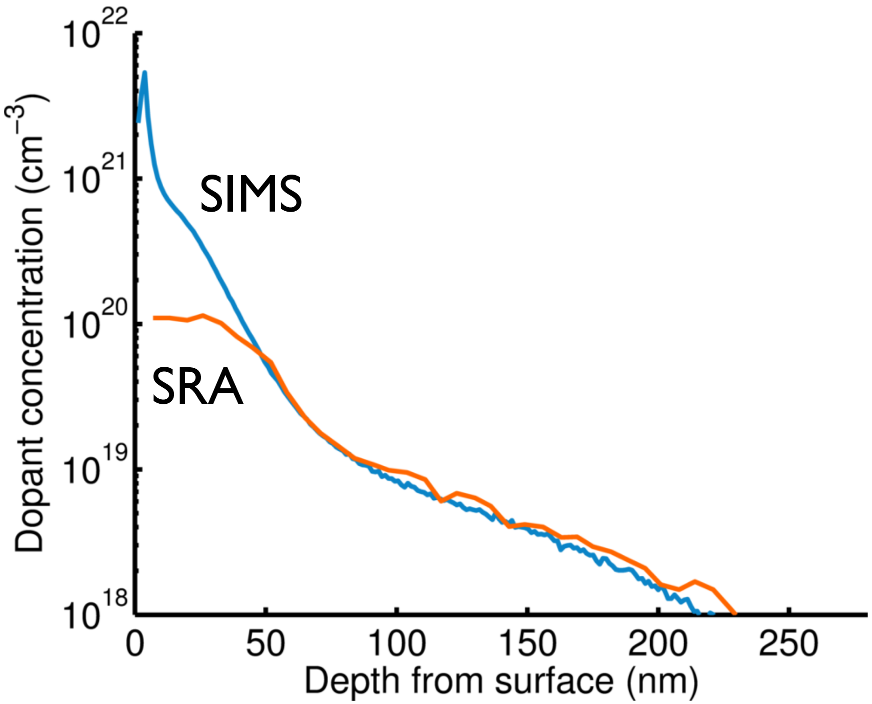
Thermal actuator frequency response

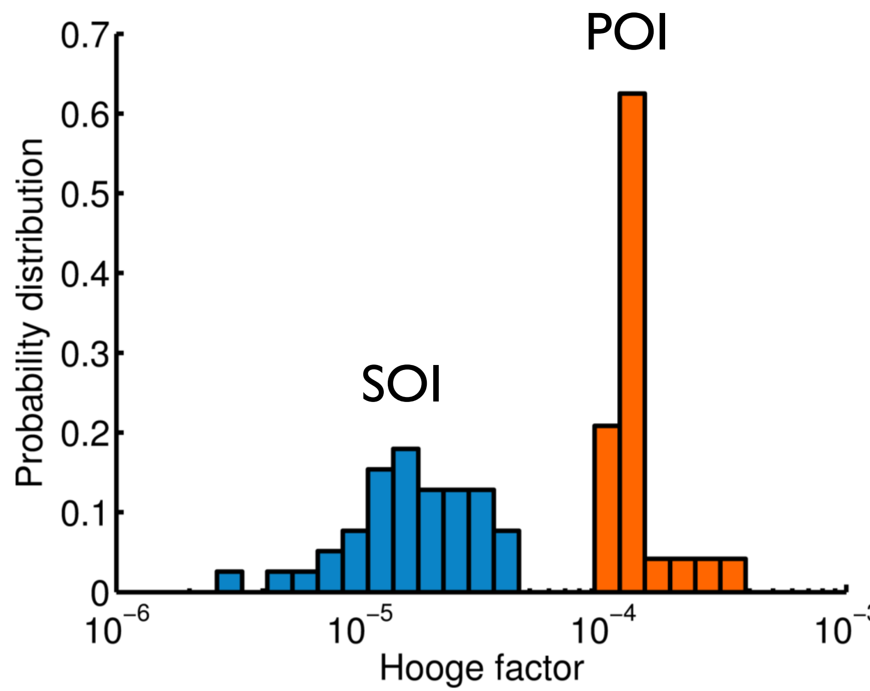




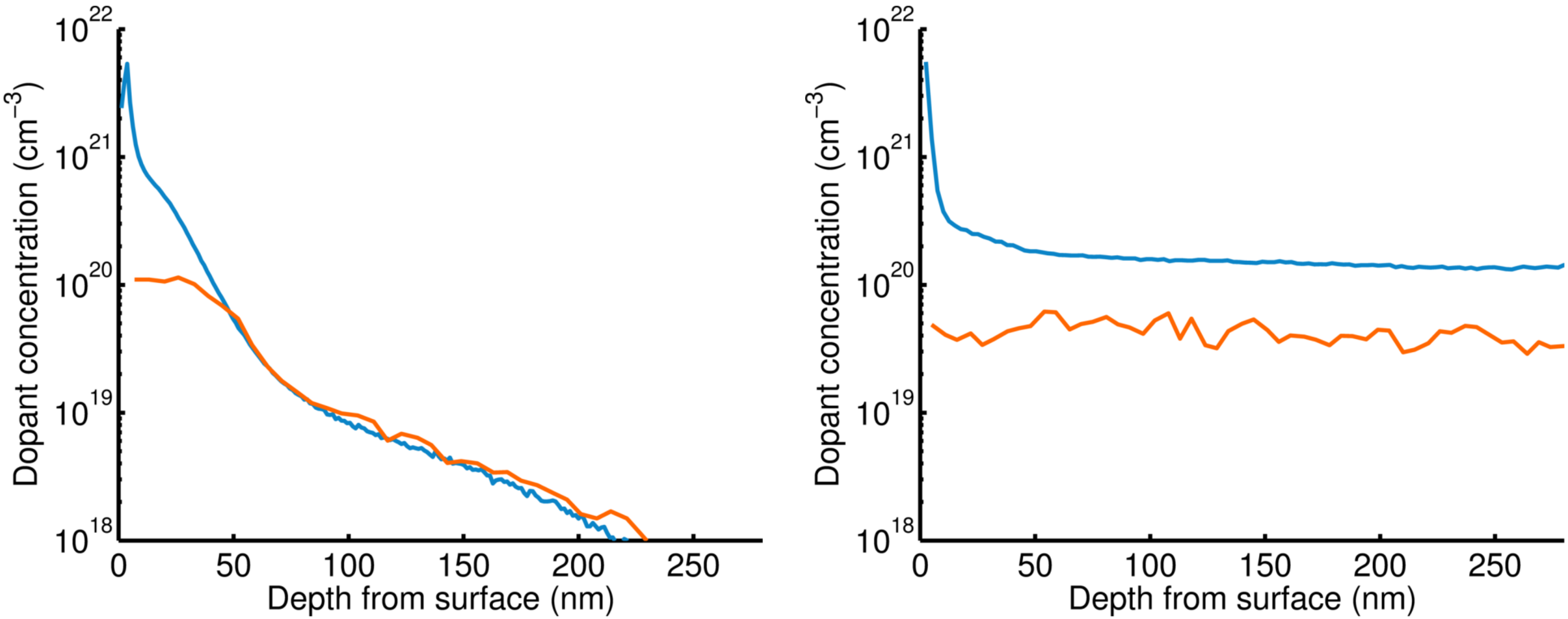
Uncoated
Parylene coated
Dry
Wet
Dry

Piezoresistor noise

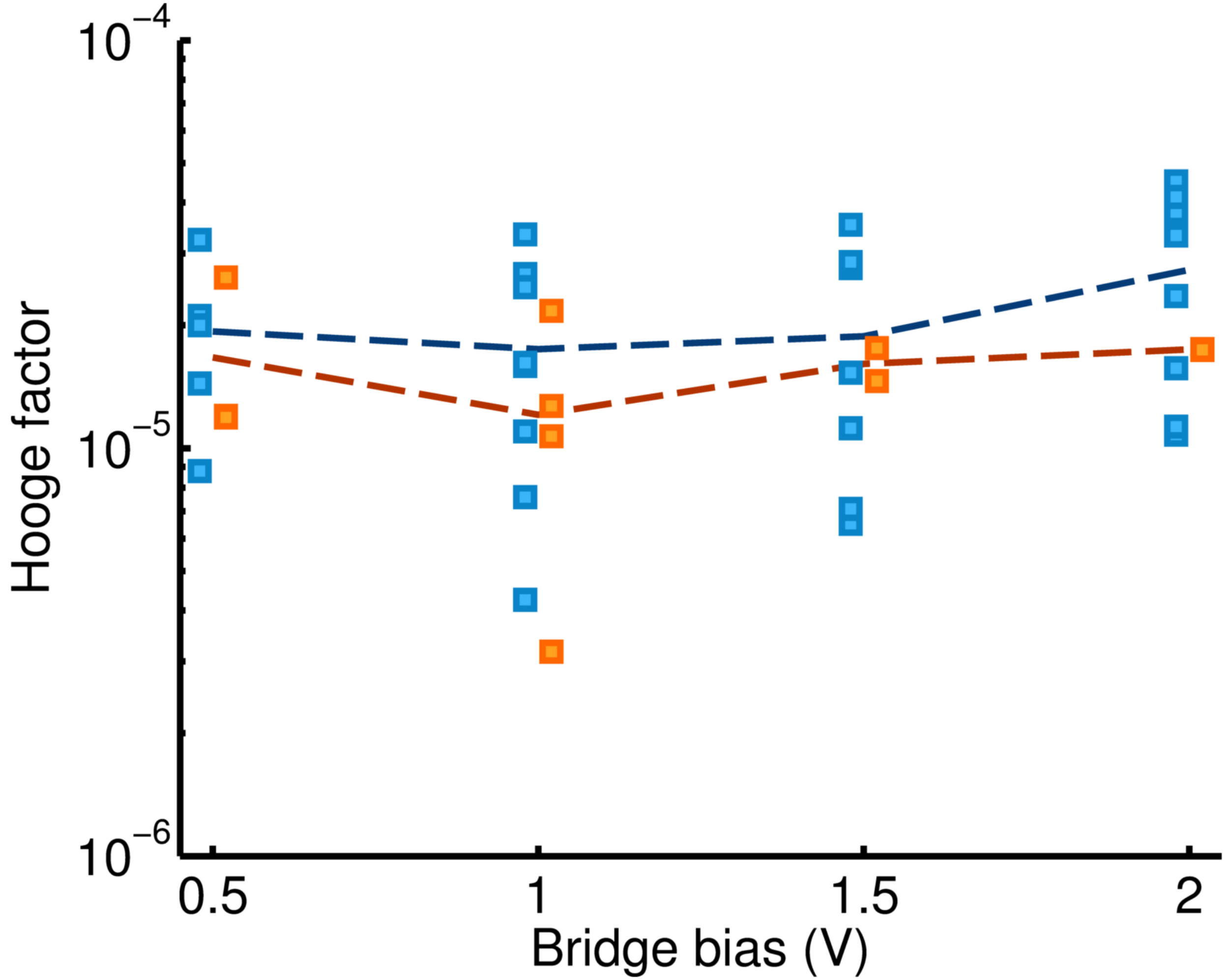




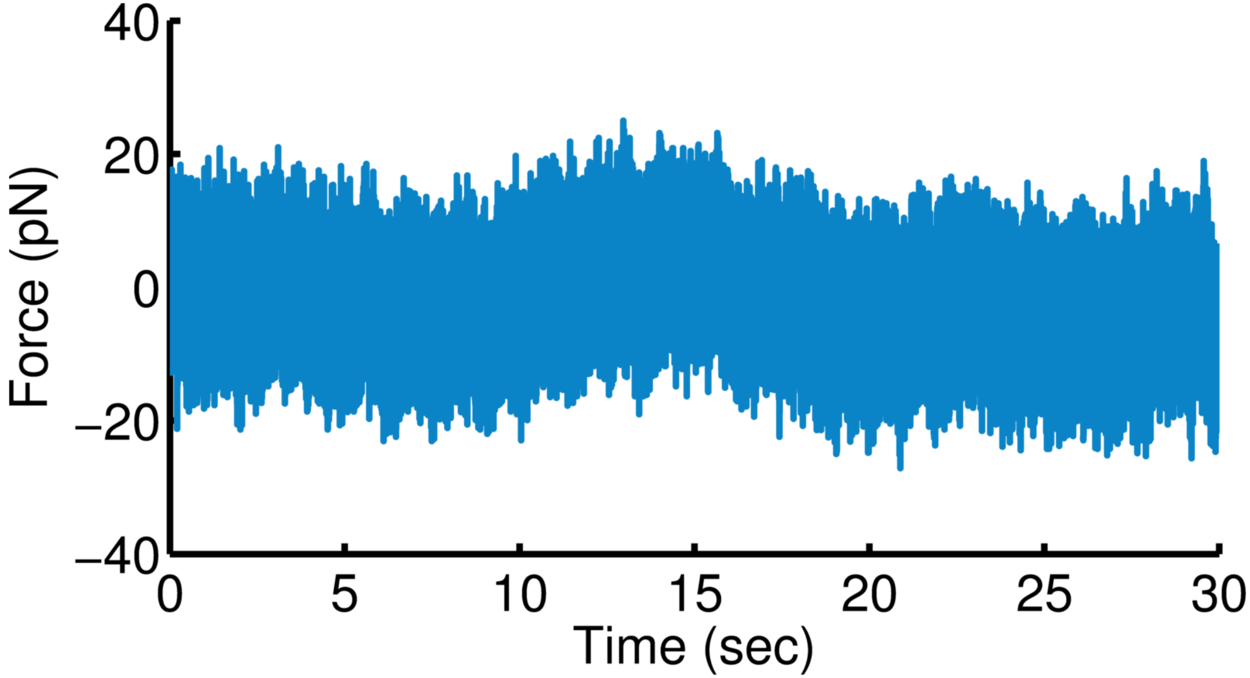
c-Si vs. poly concentration profiles



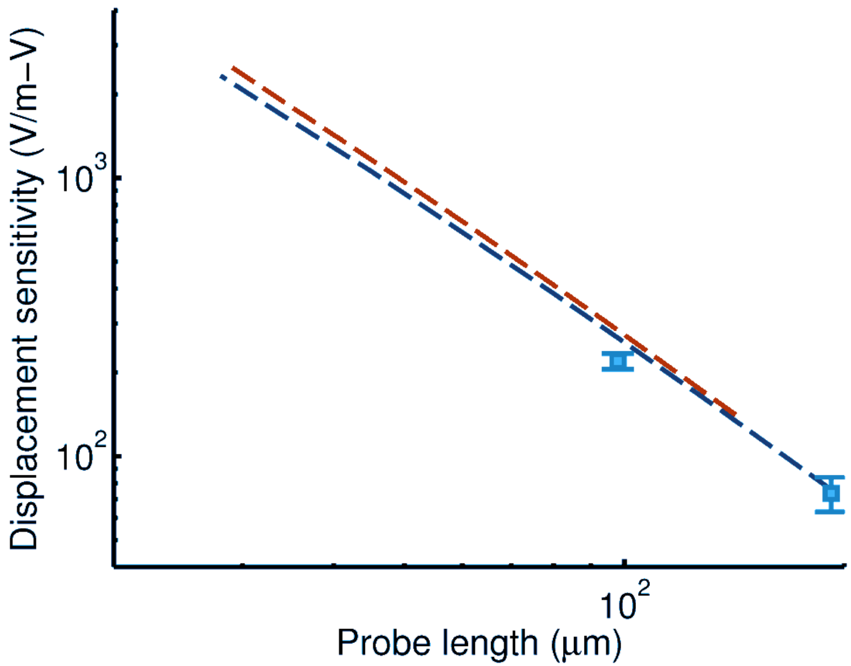
Piezoresistor noise



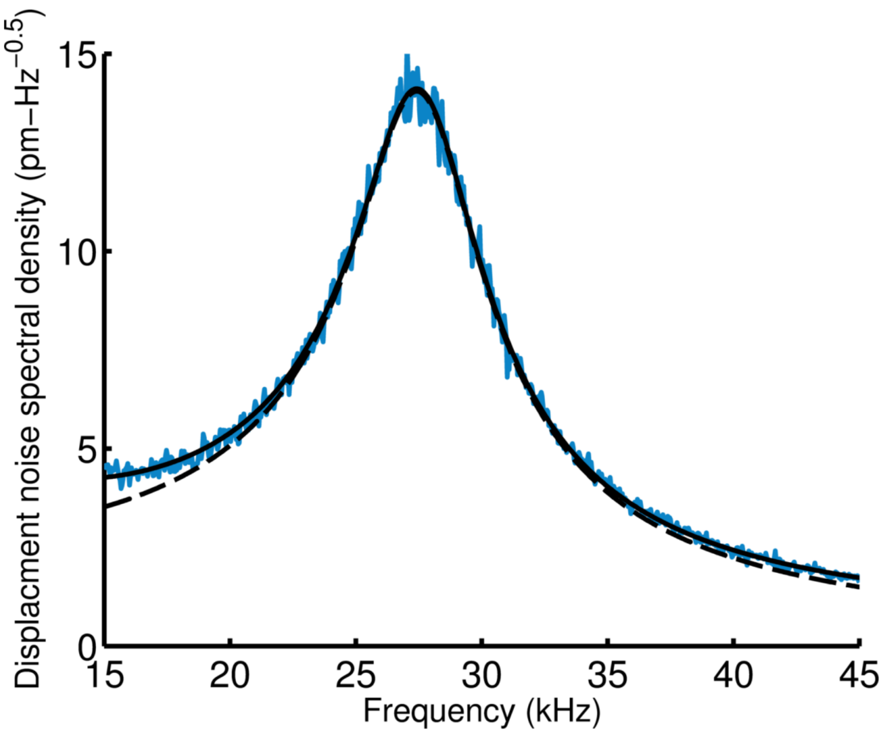
Piezoresistor noise

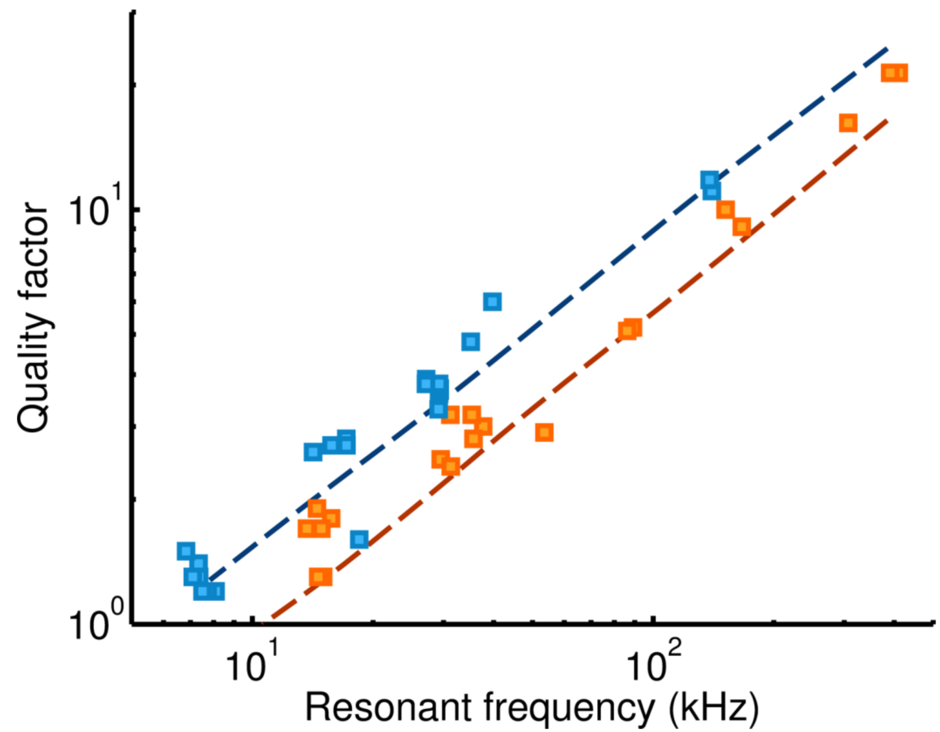


Sensitivity measurements

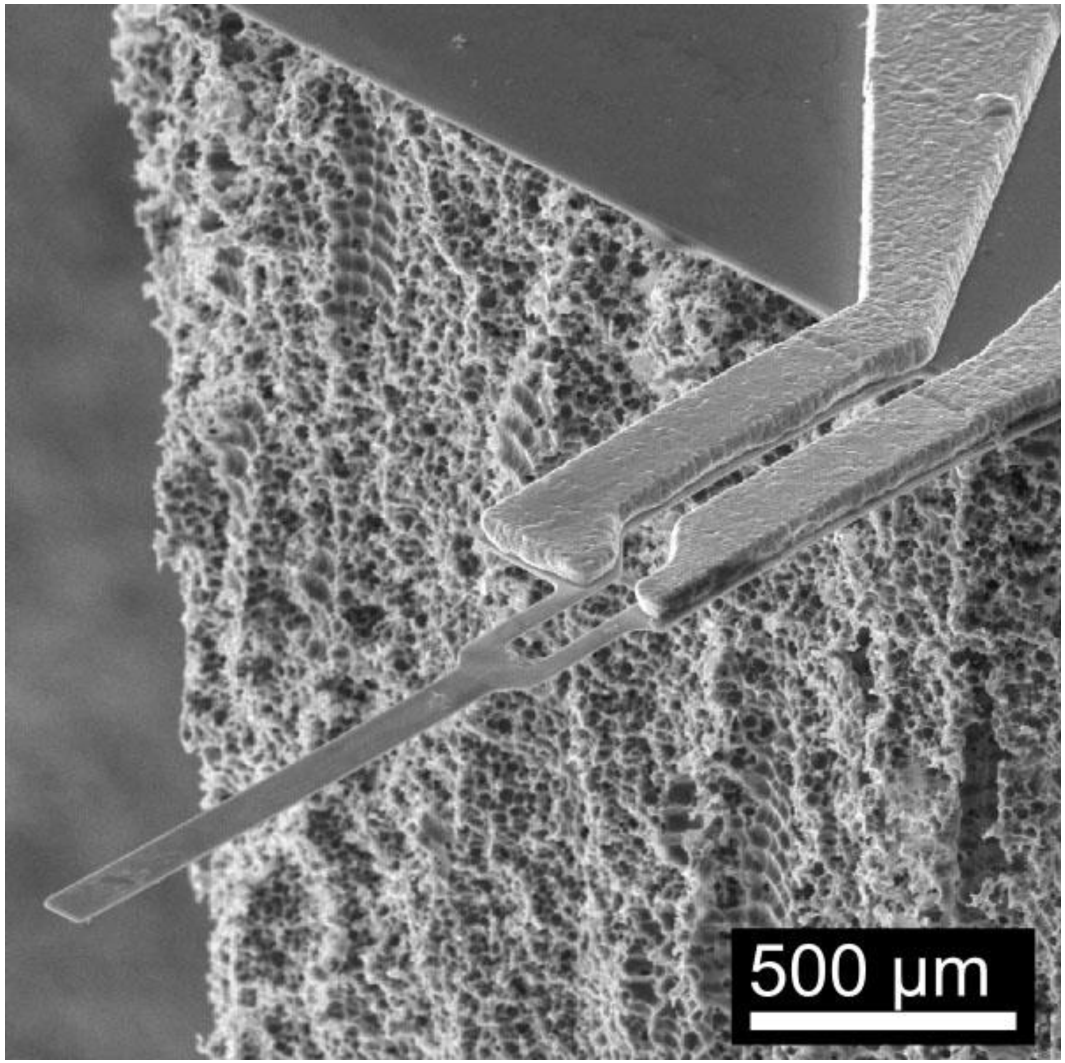


TMN and quality factor scaling

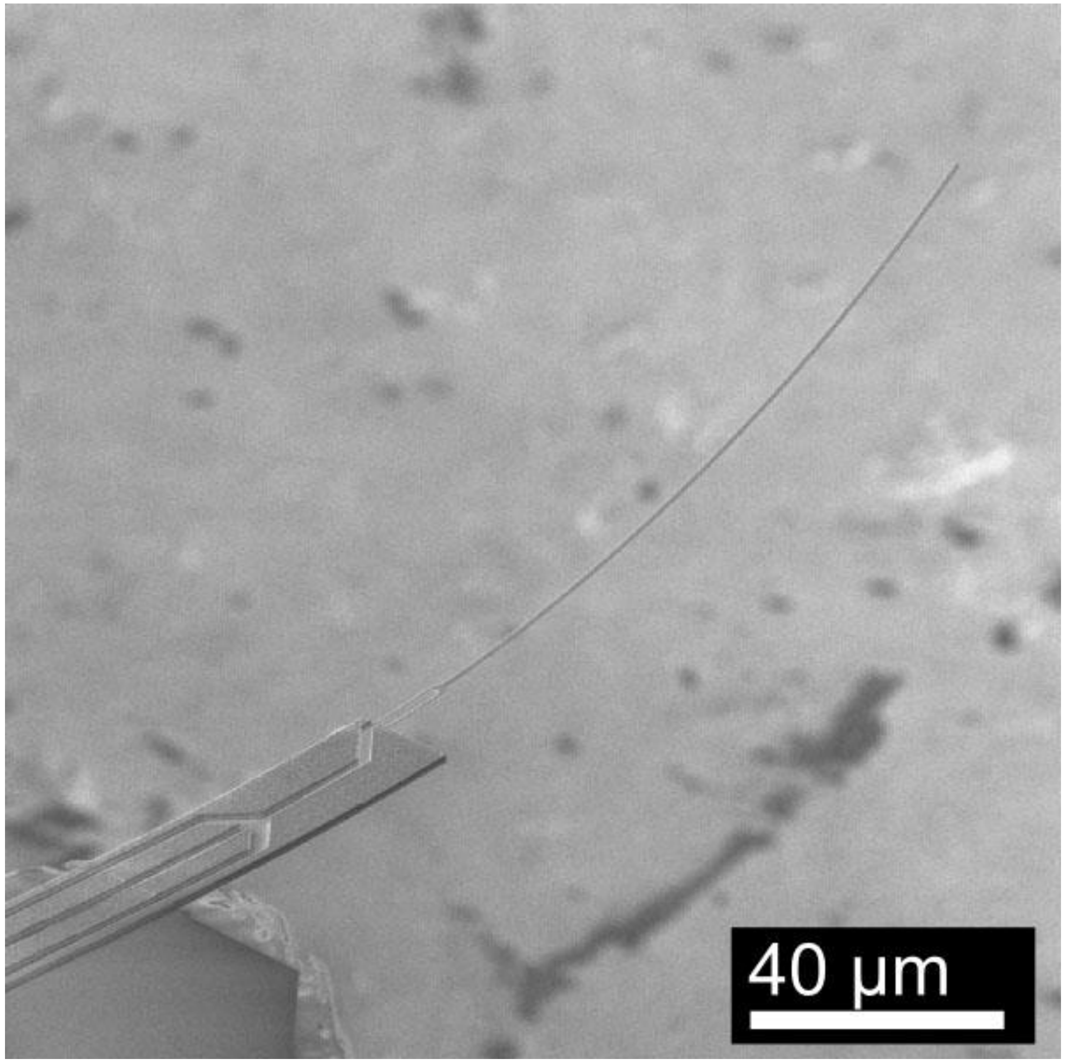




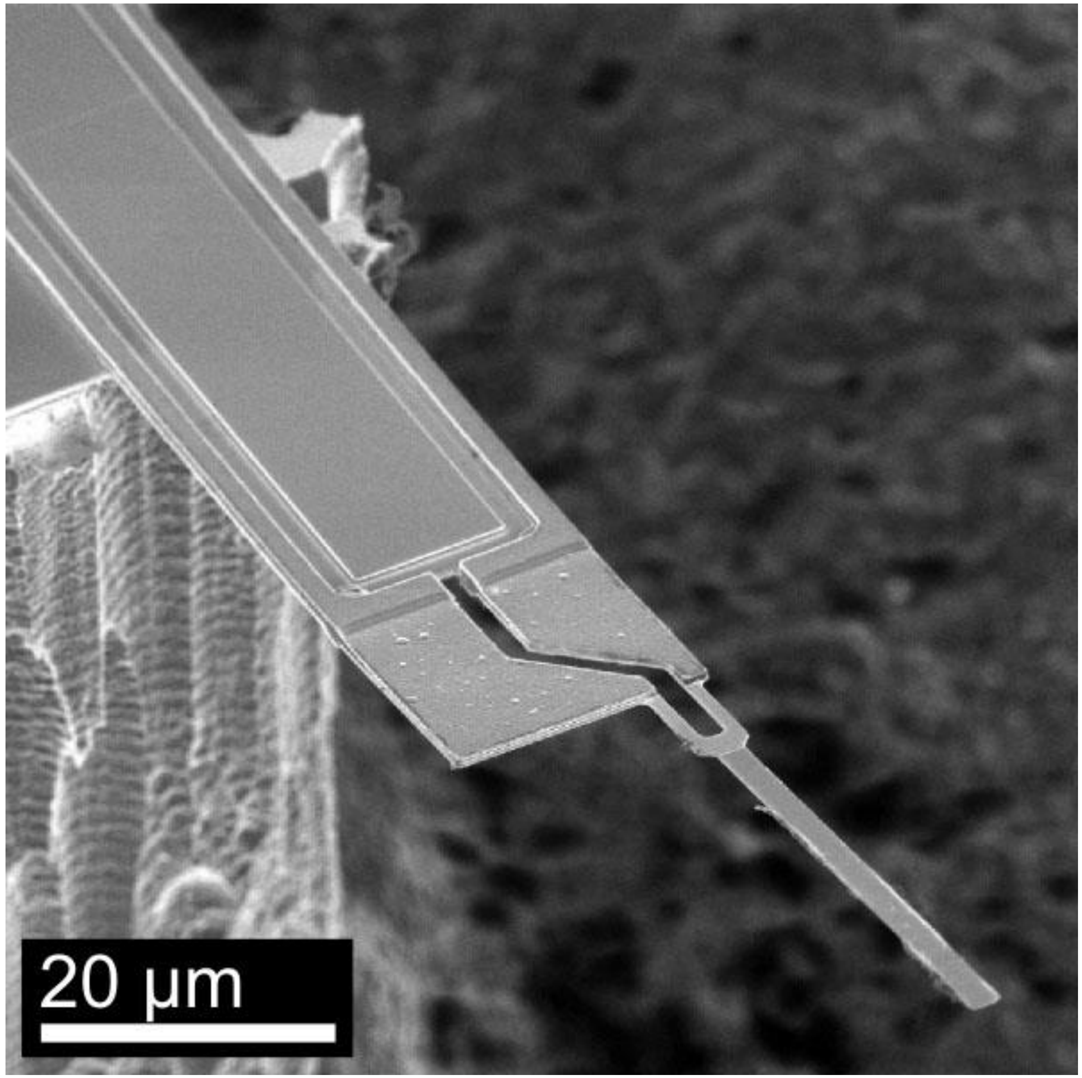
Finished Device SEMs



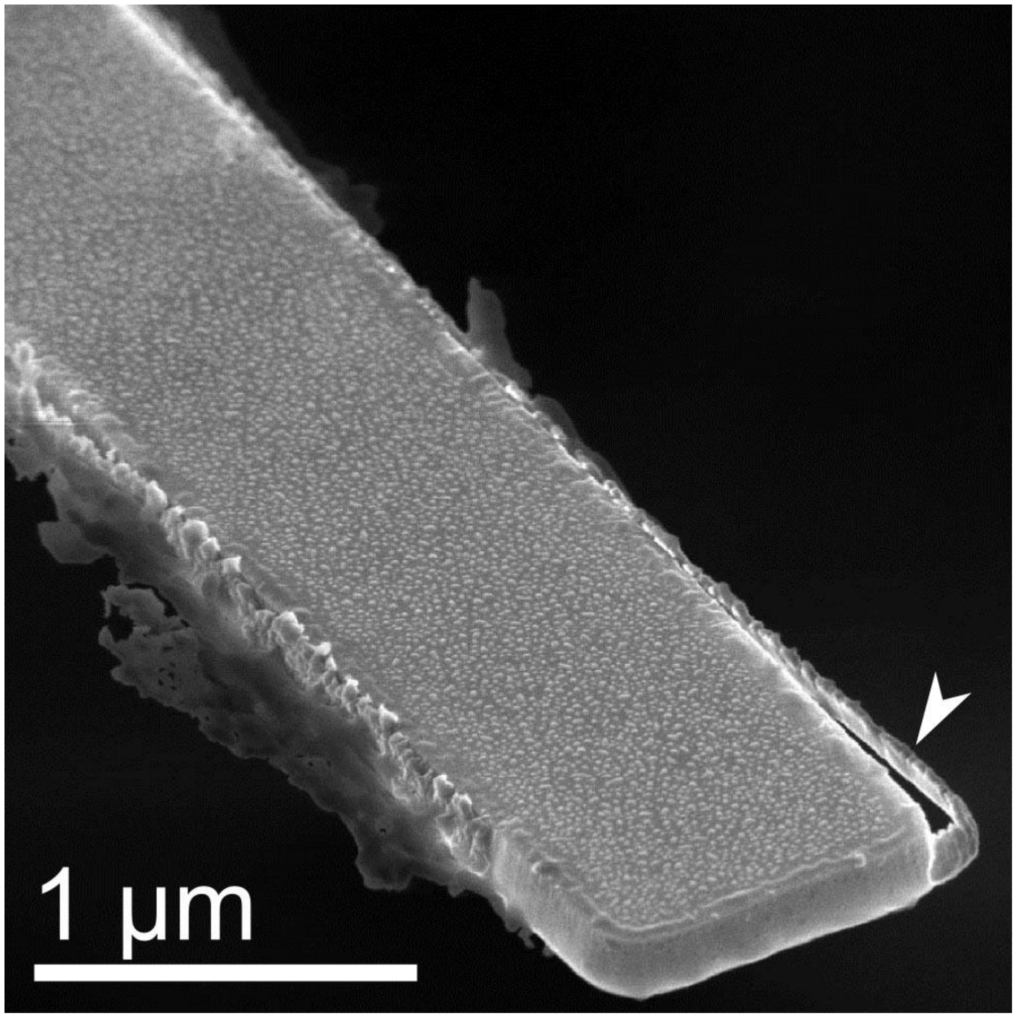
Finished Device SEMs



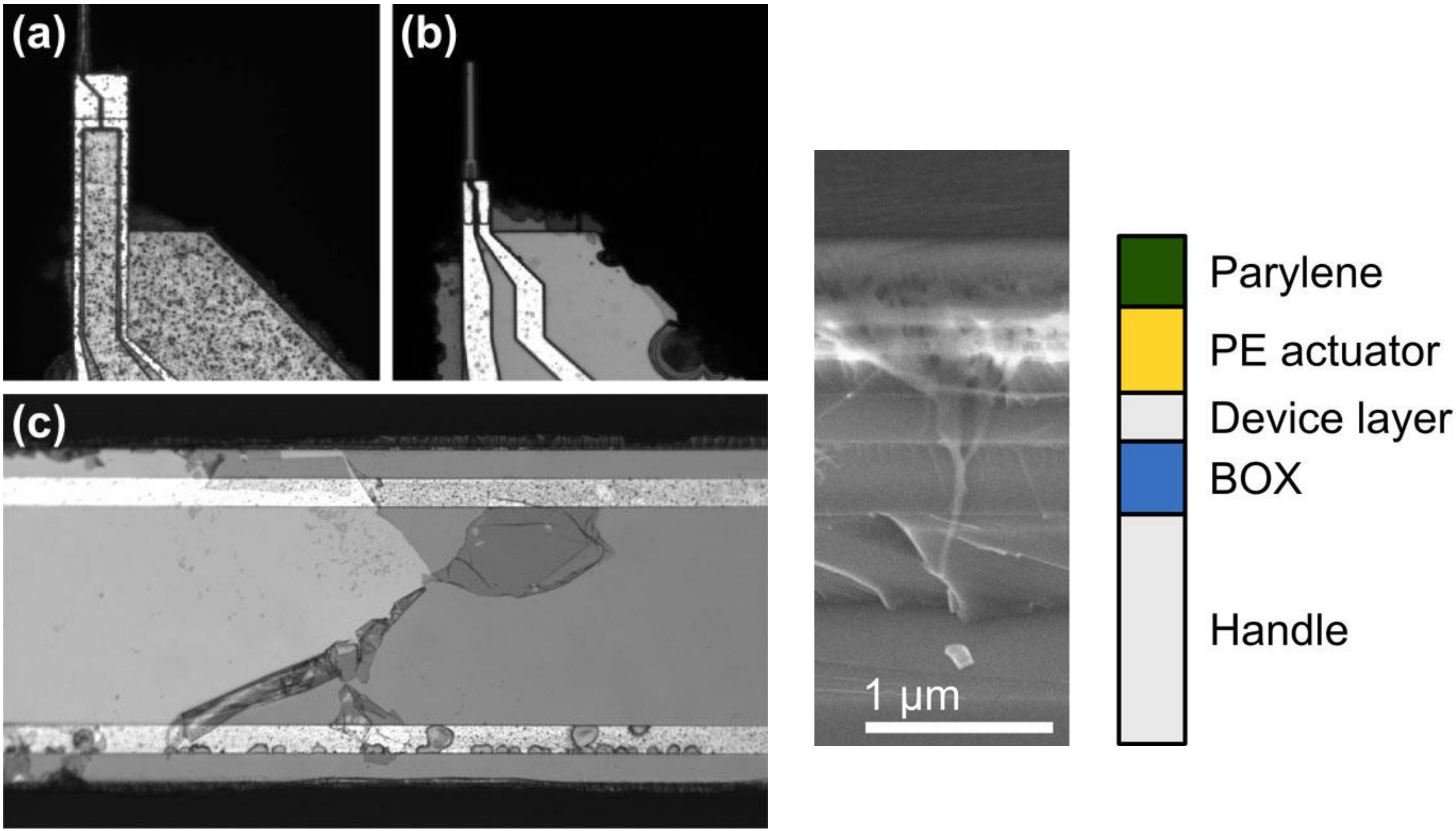
Finished Device SEMs



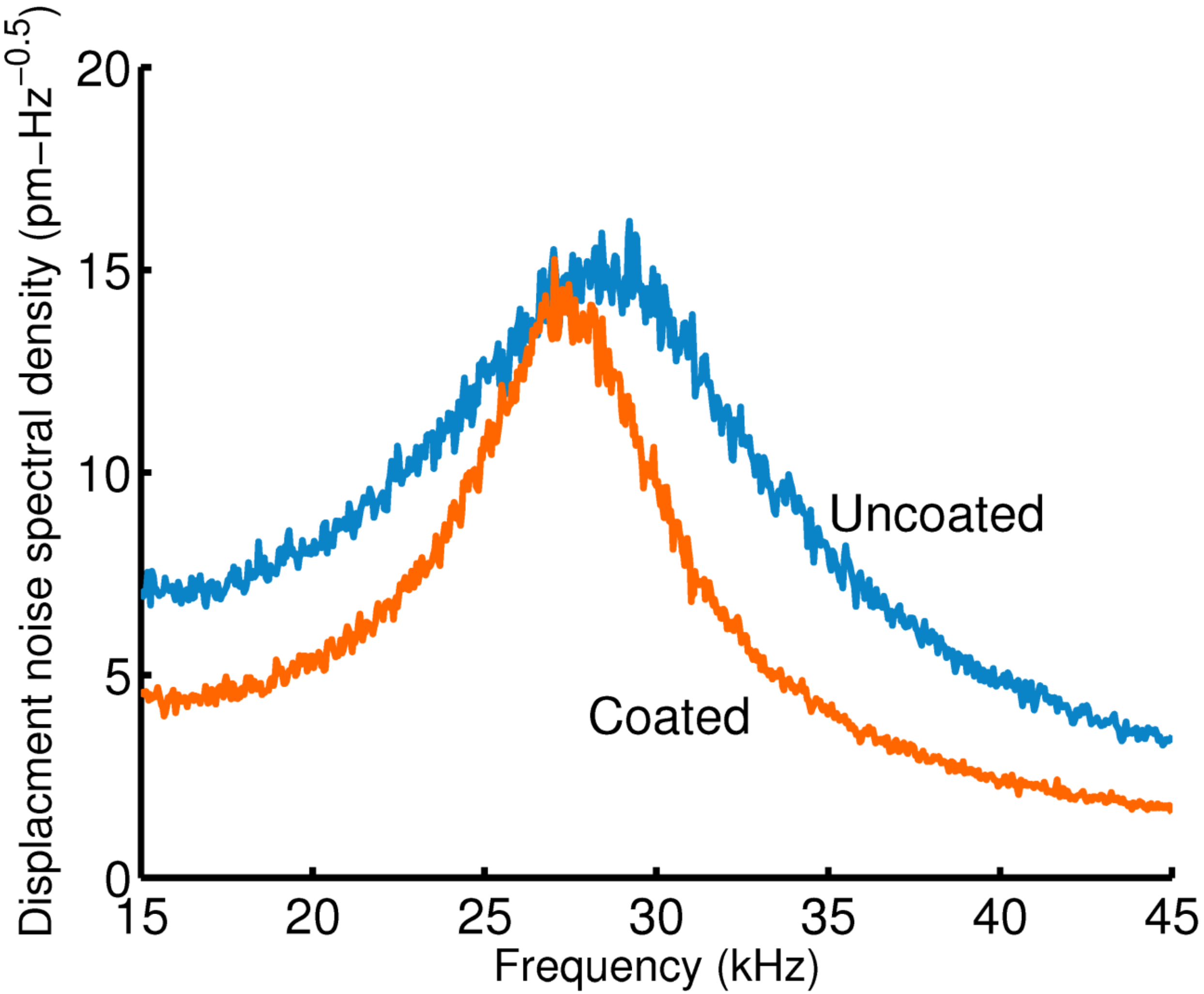
Stringers



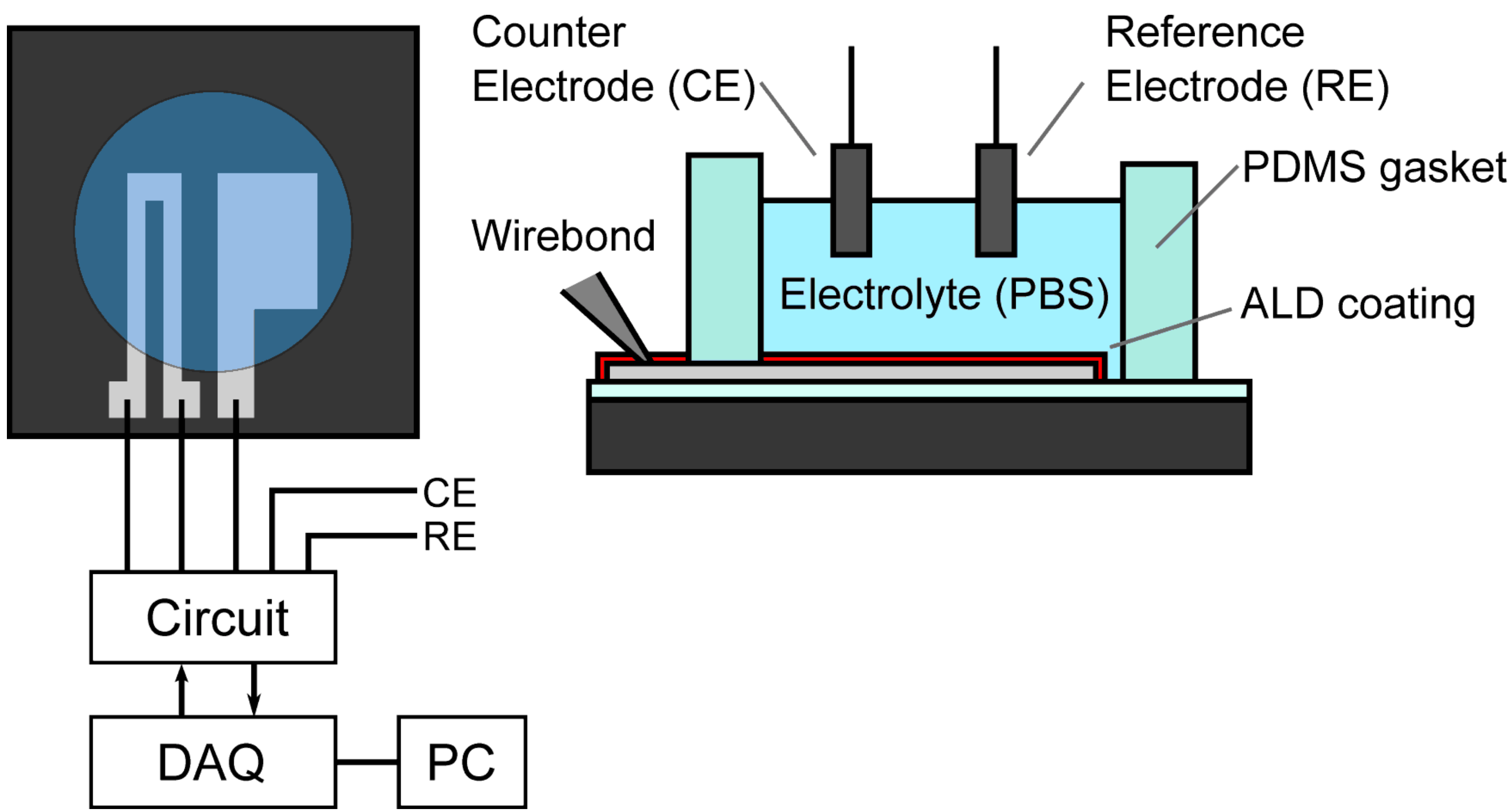
Parylene passivation



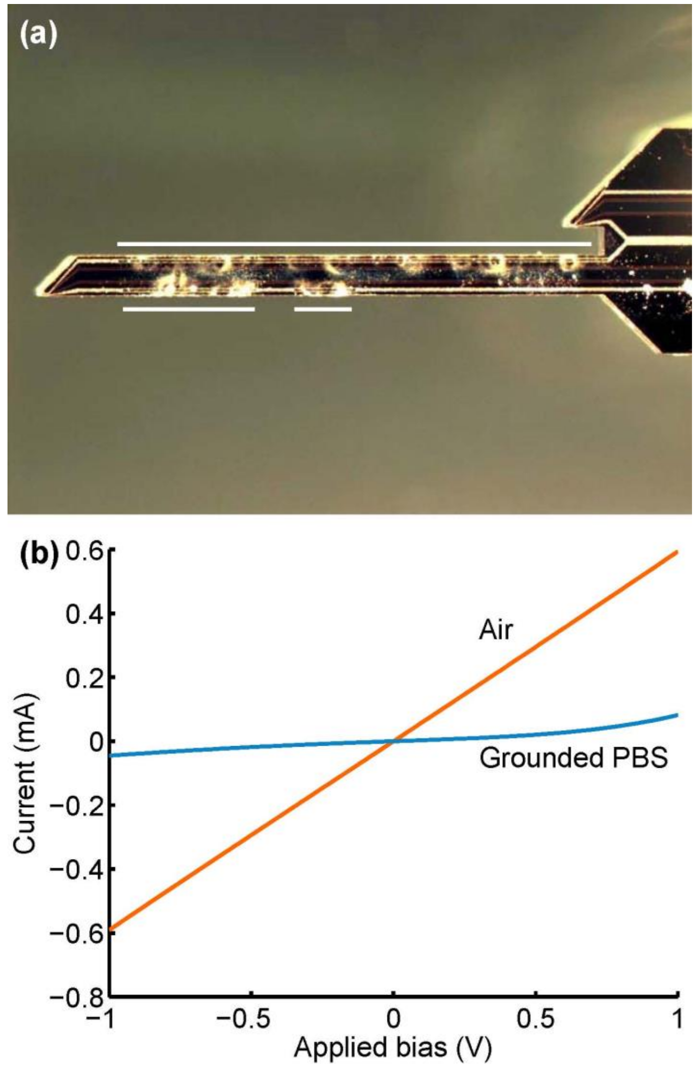
Parylene passivation



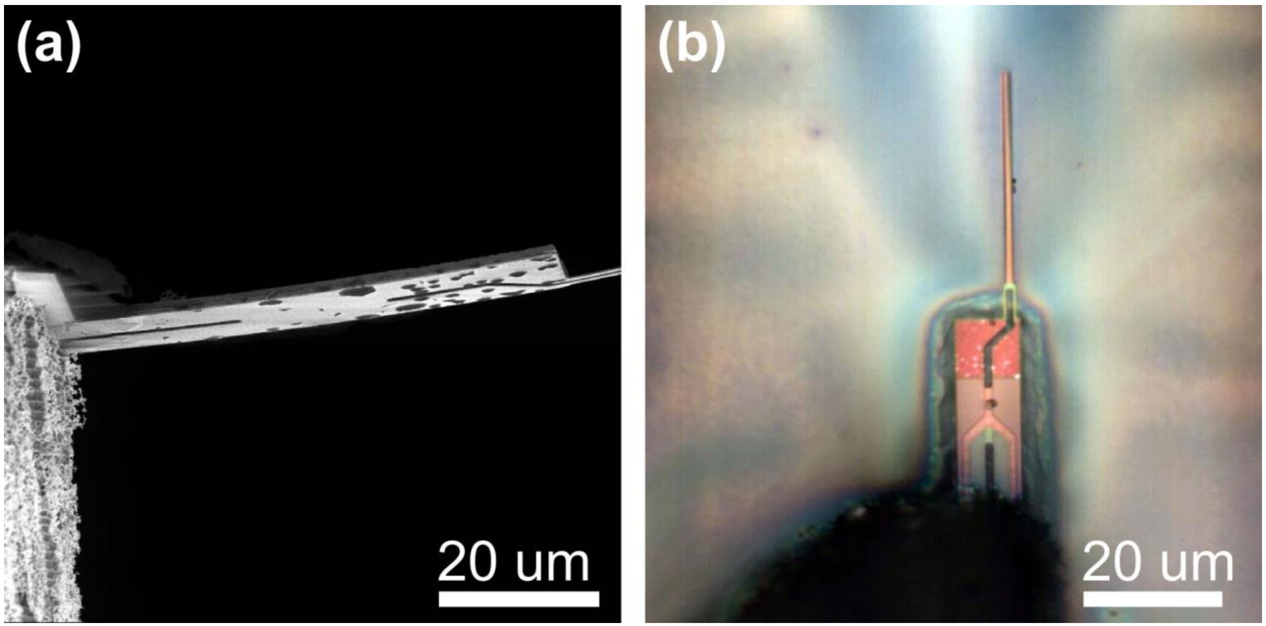
ALD passivation



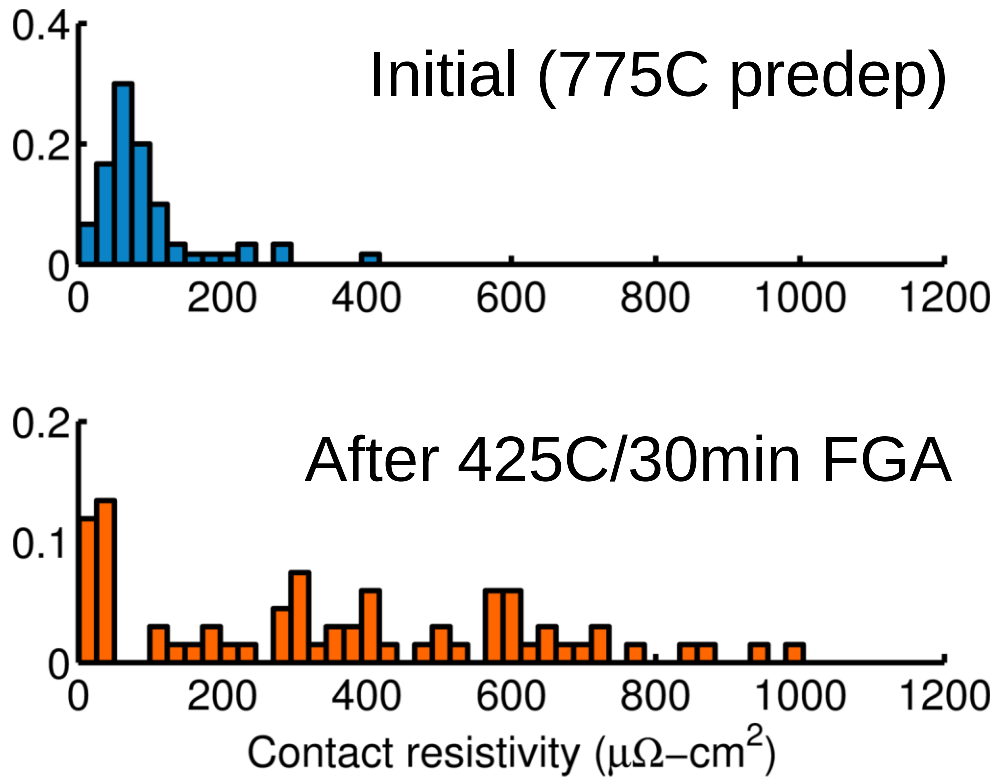
ALD passivation



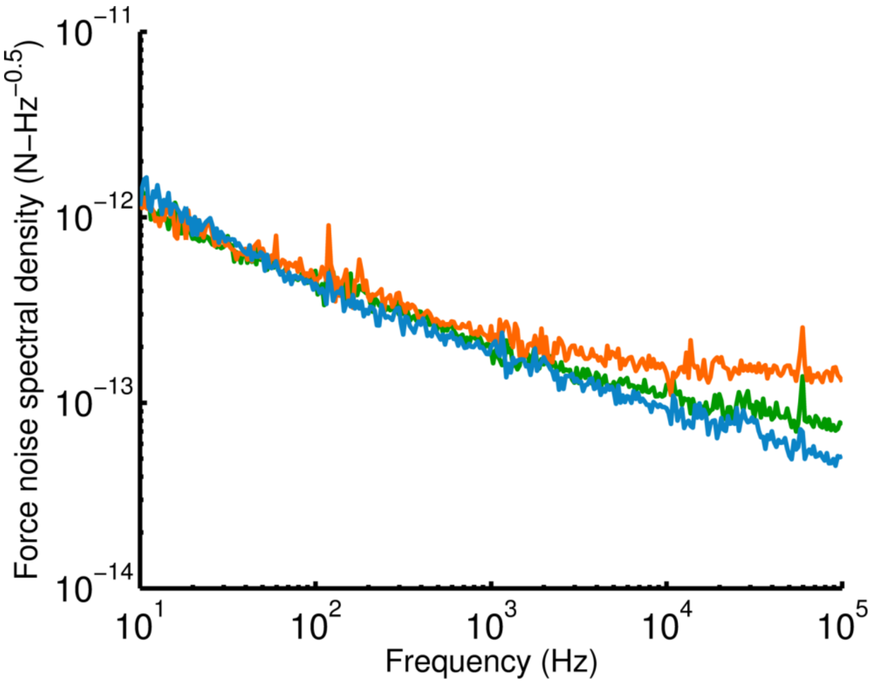
FGAs are bad (for thin, n-type piezos)

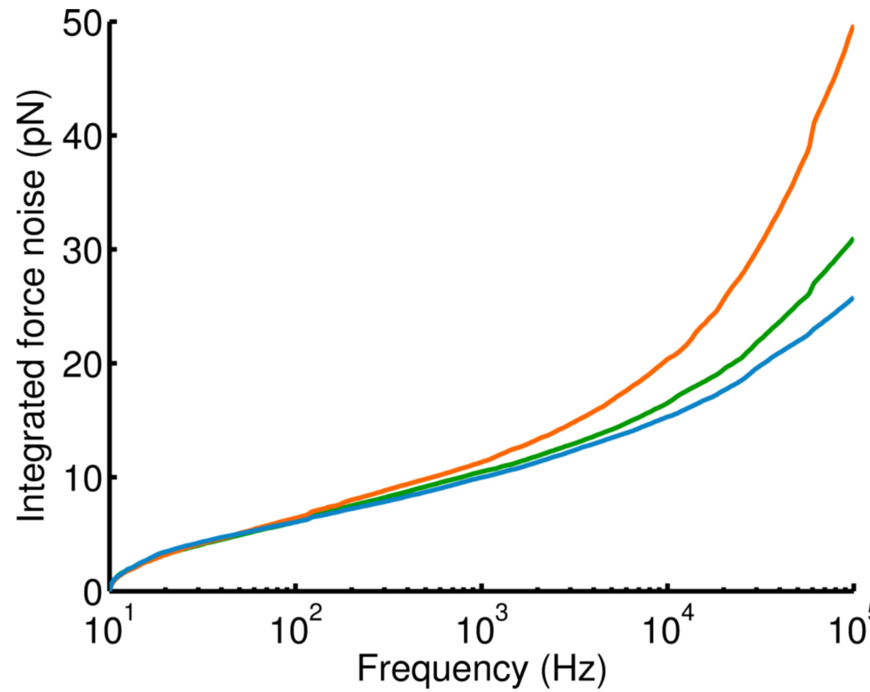


FGAs are bad (for thin, n-type piezos)

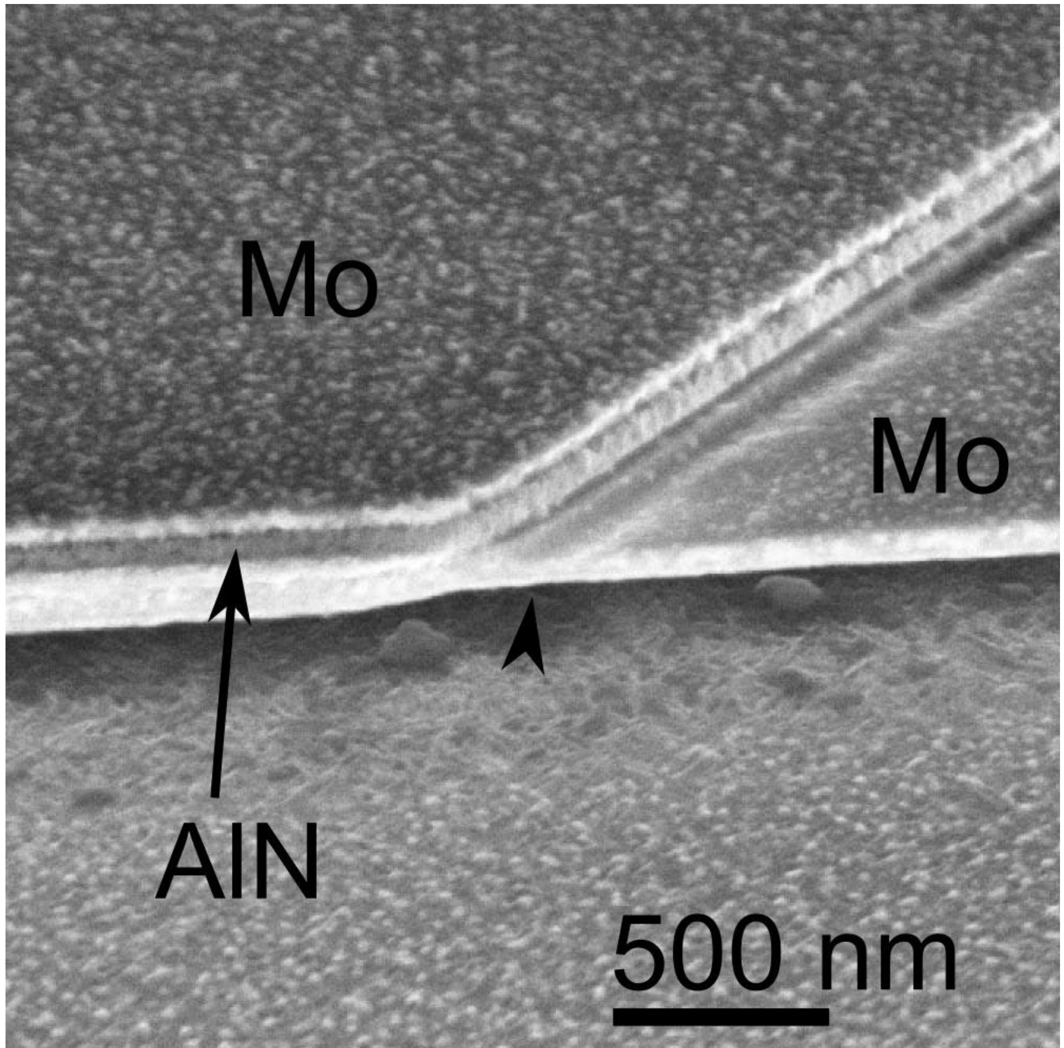


Effect of bridge bias

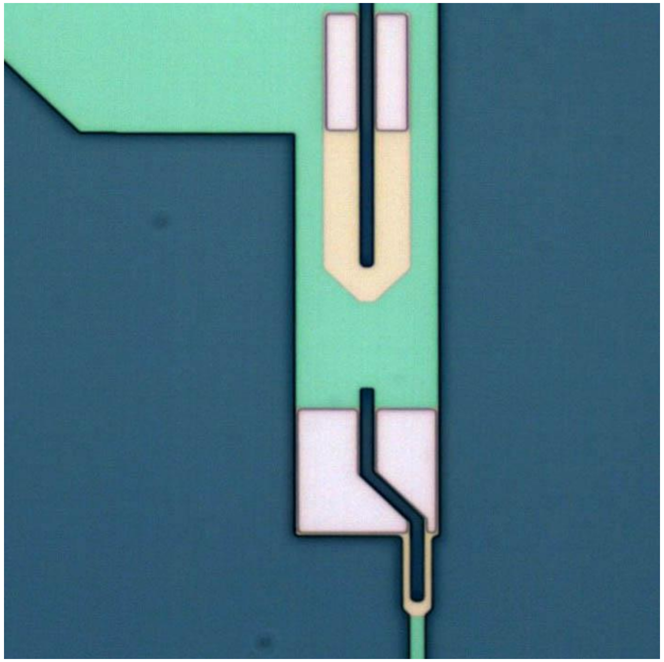


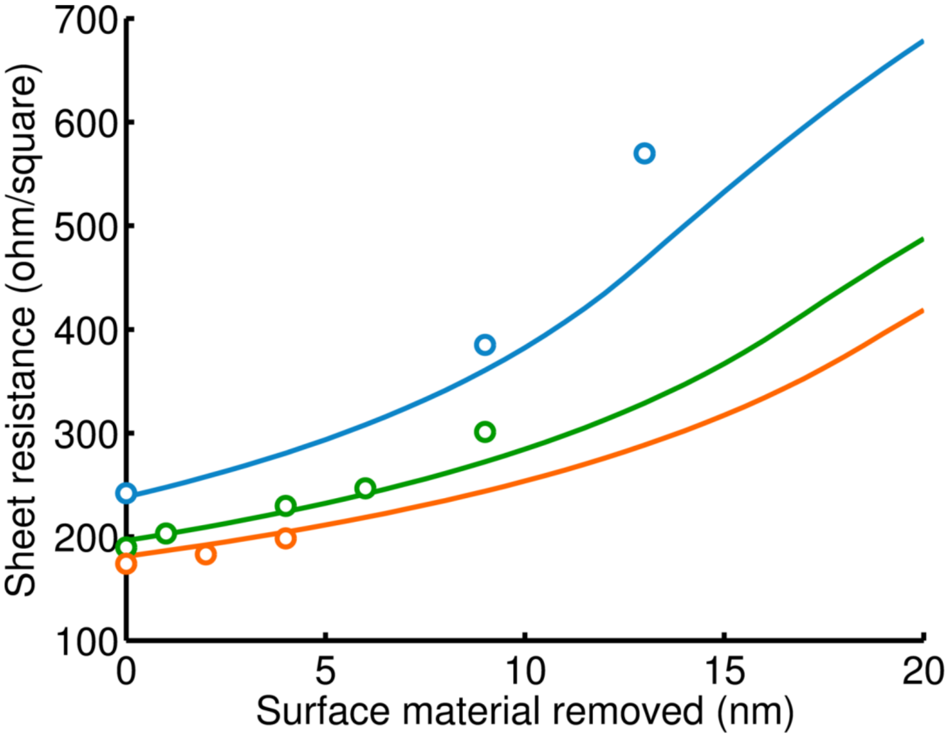


Etching the AlN/Mo stack

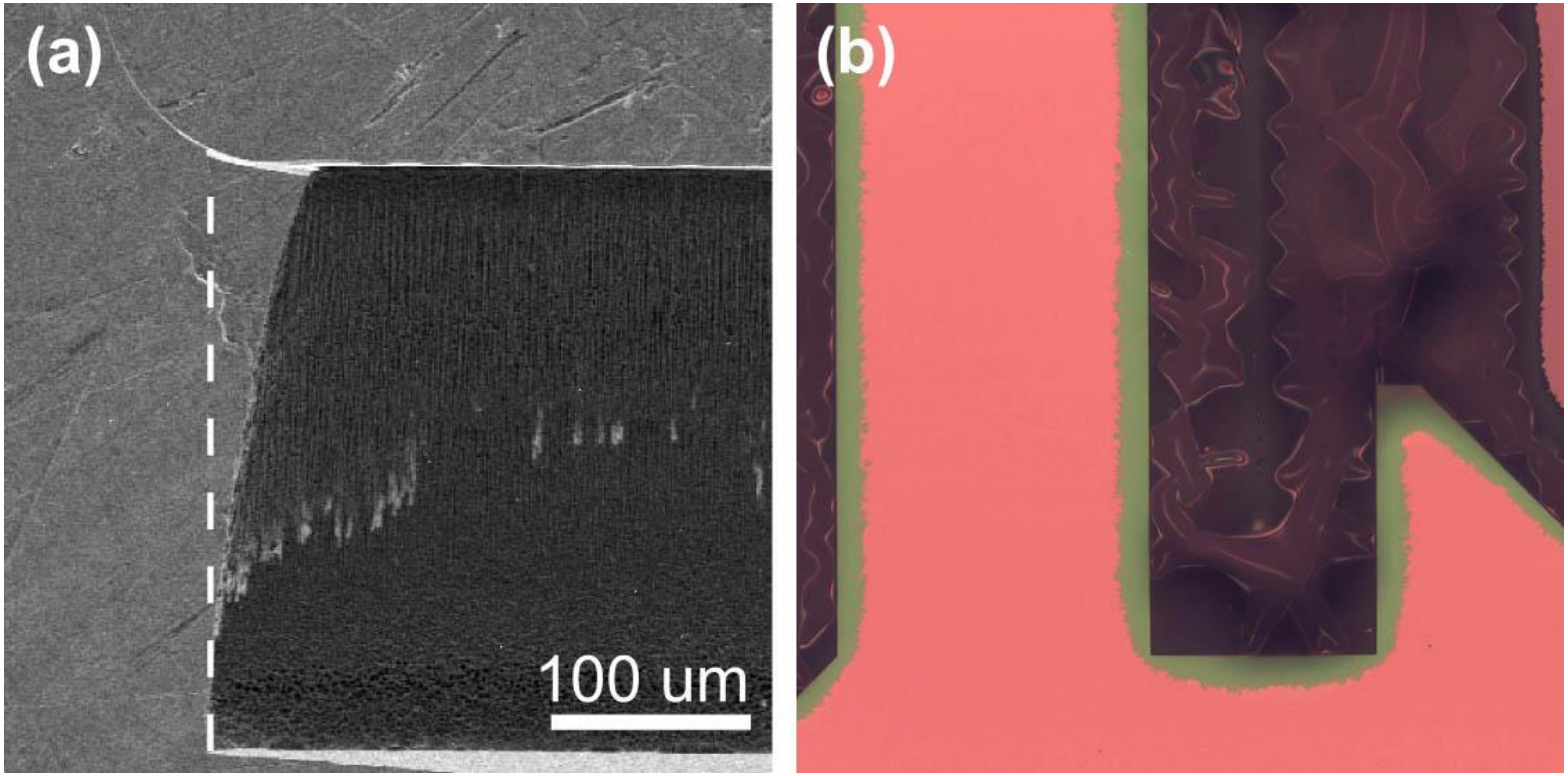


Fabricating thin devices

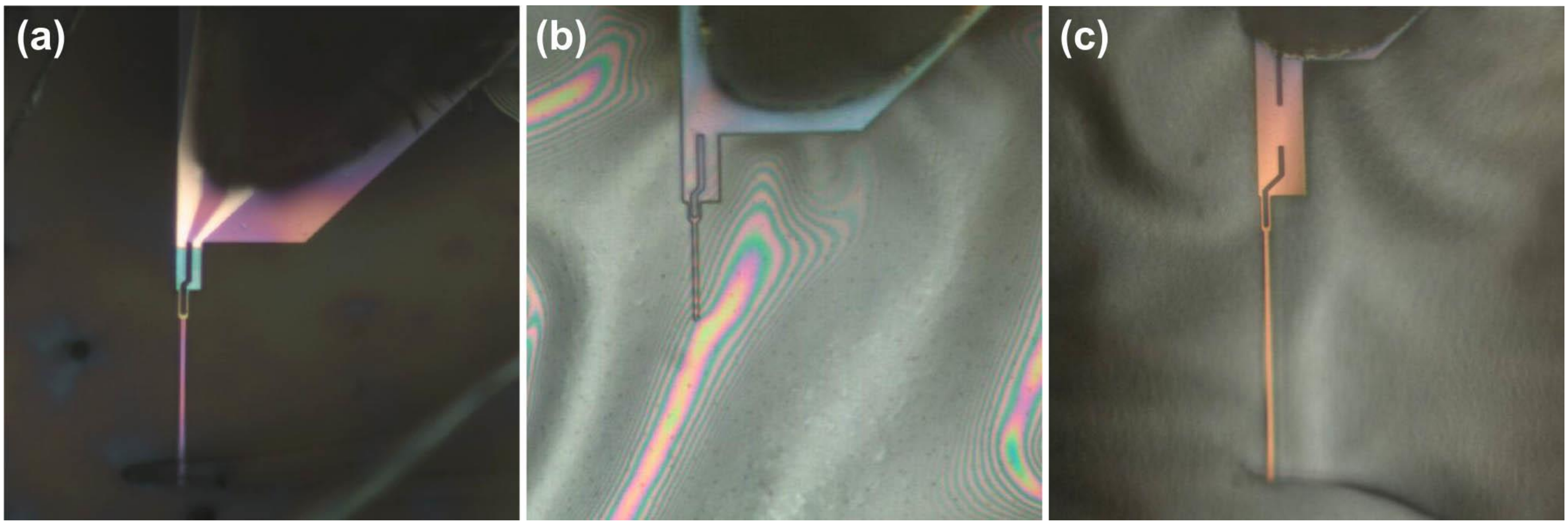




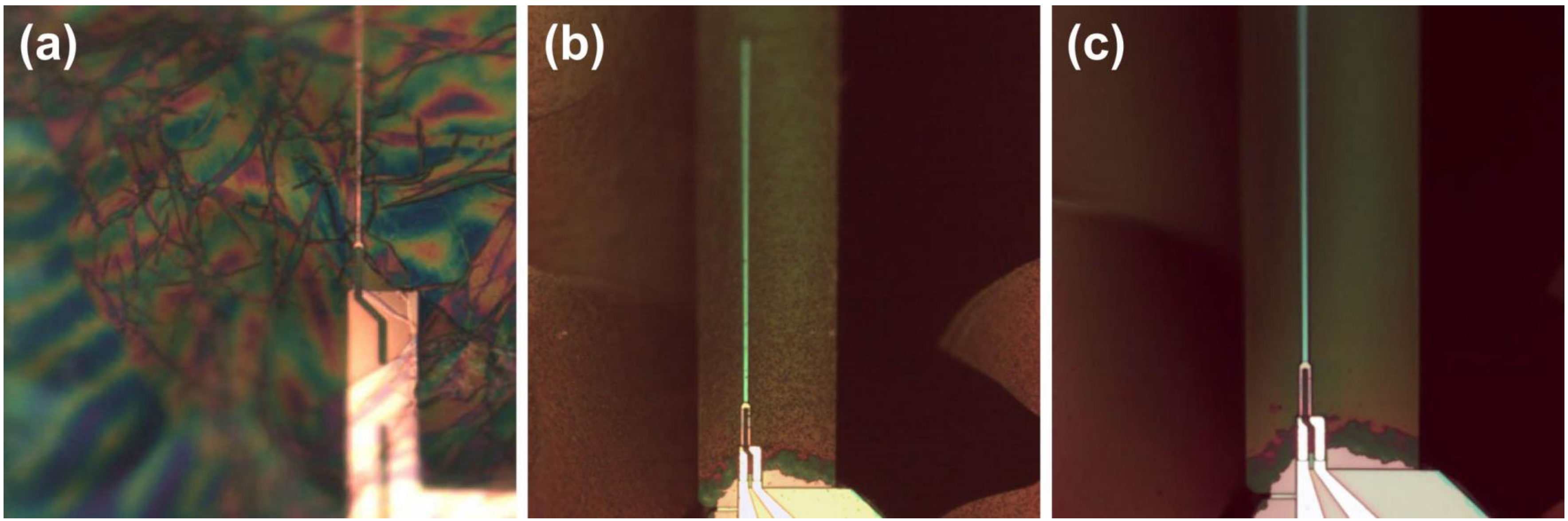
DRIE Issues



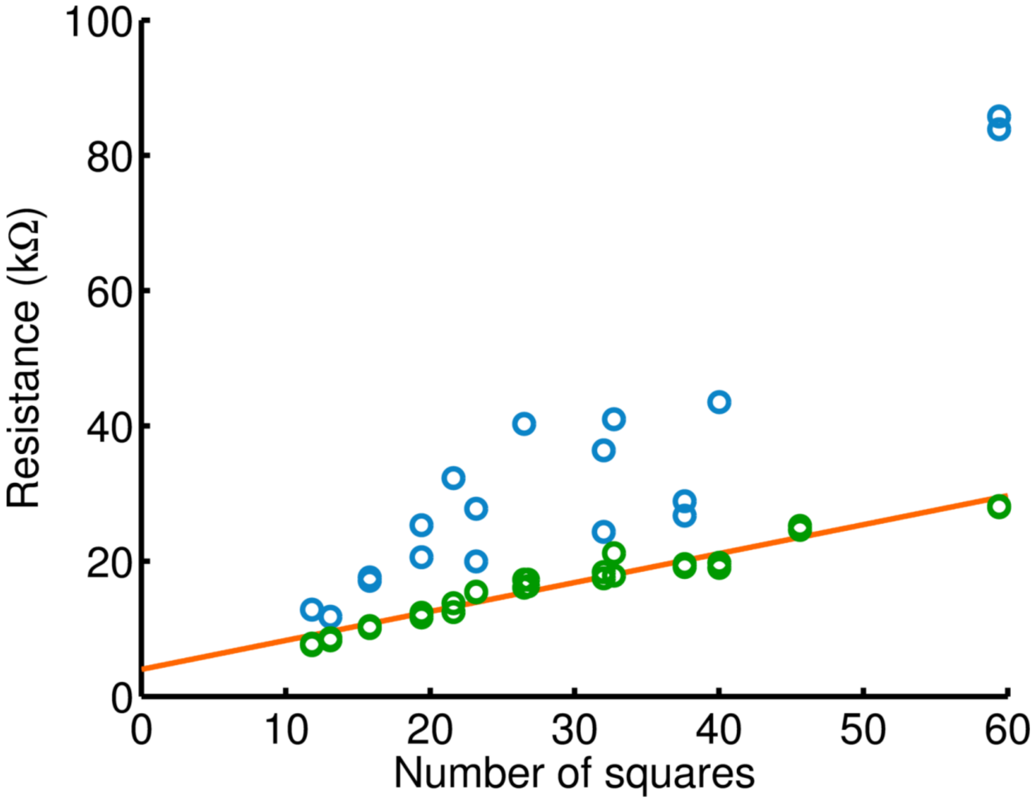
DRIE undercut vs. trench width

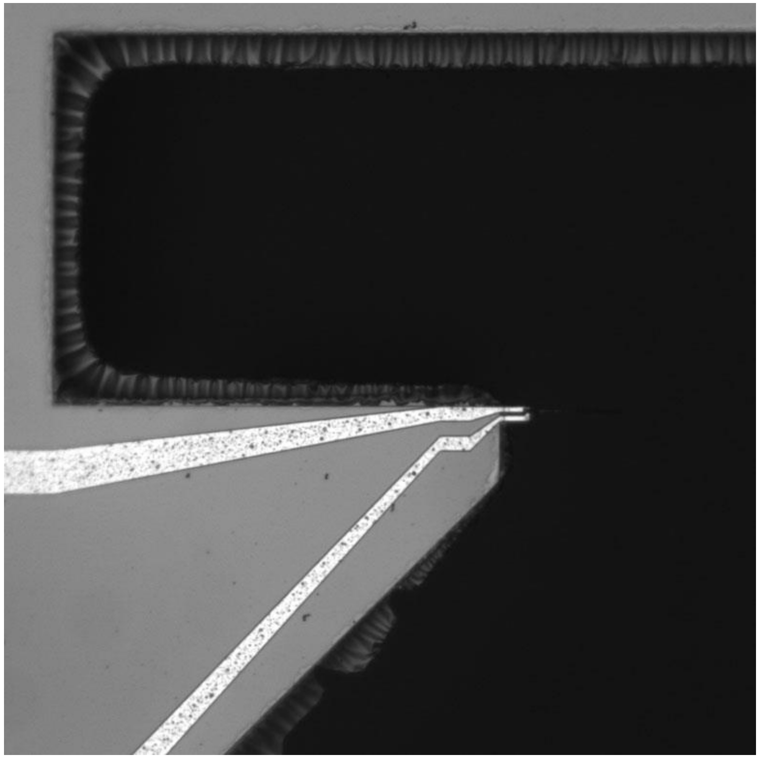


DRIE polymer cleanup

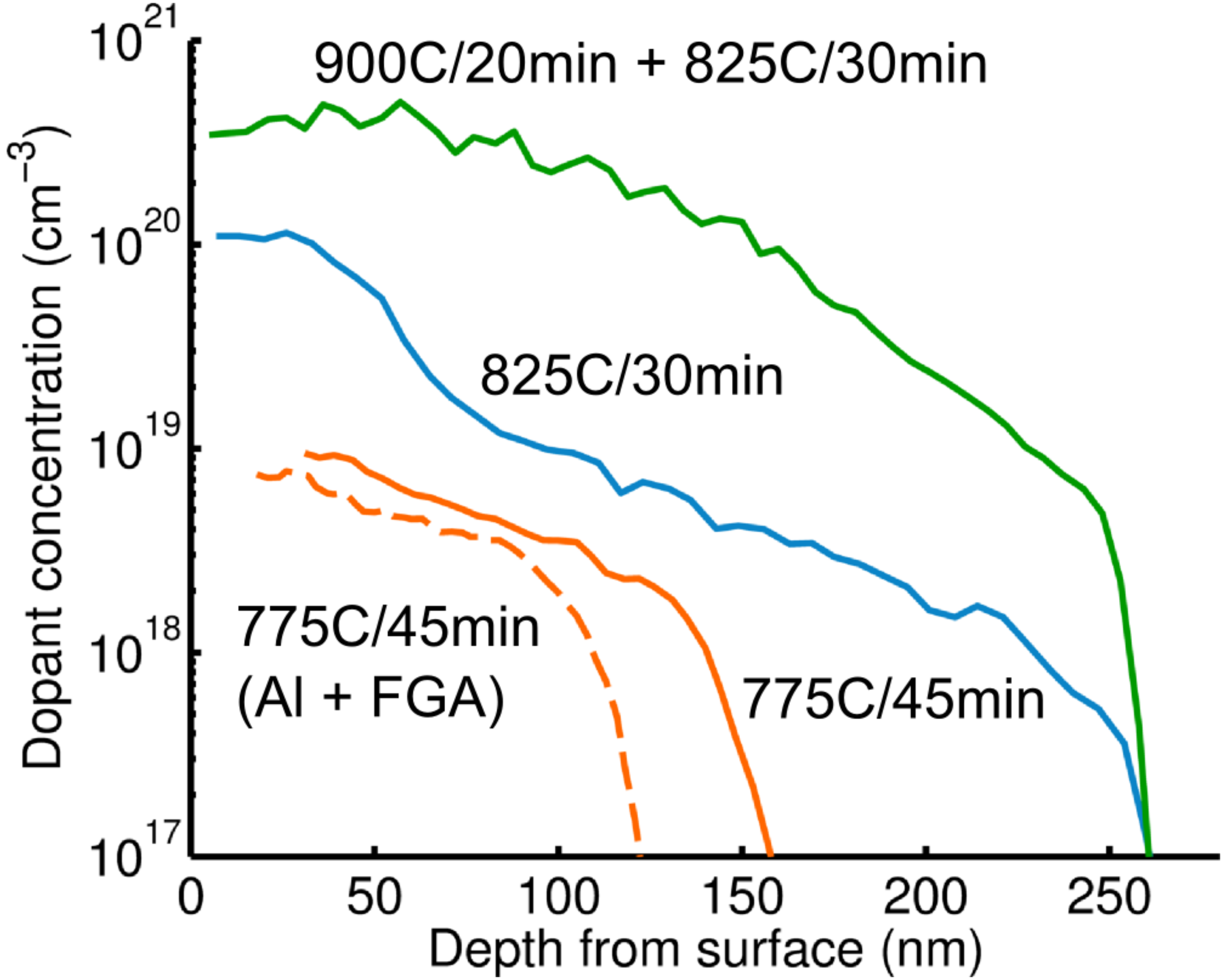


RIE BOX release issues

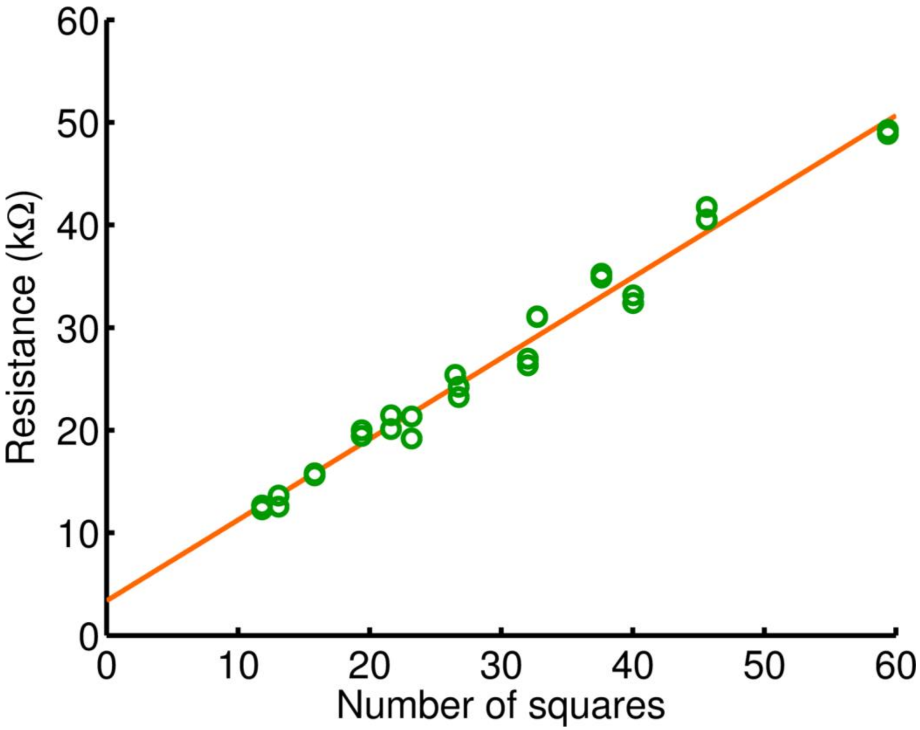


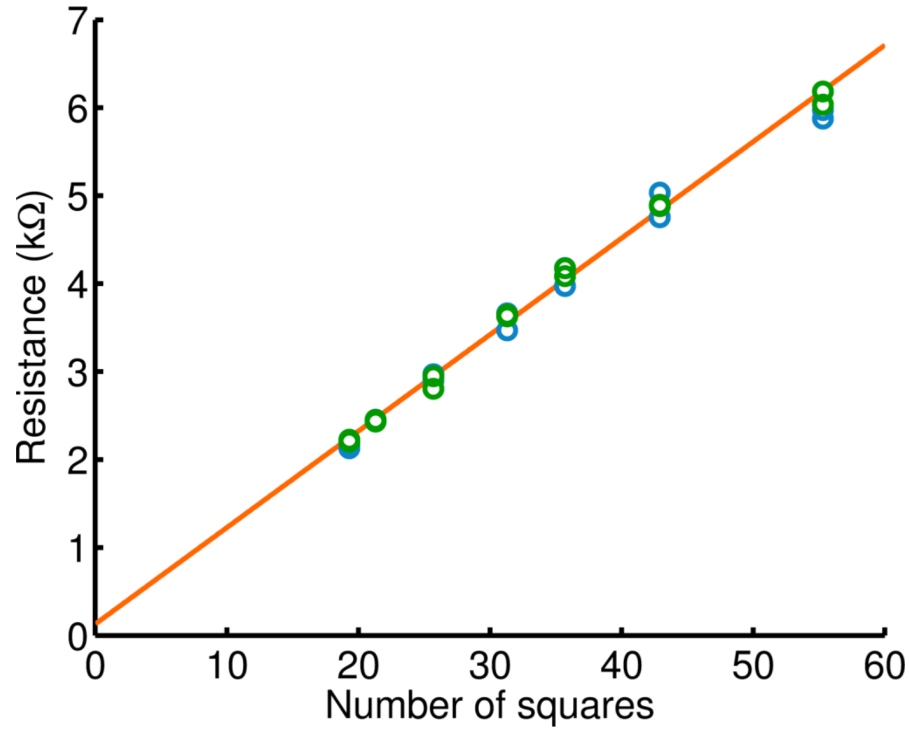


Why the extra doping step?

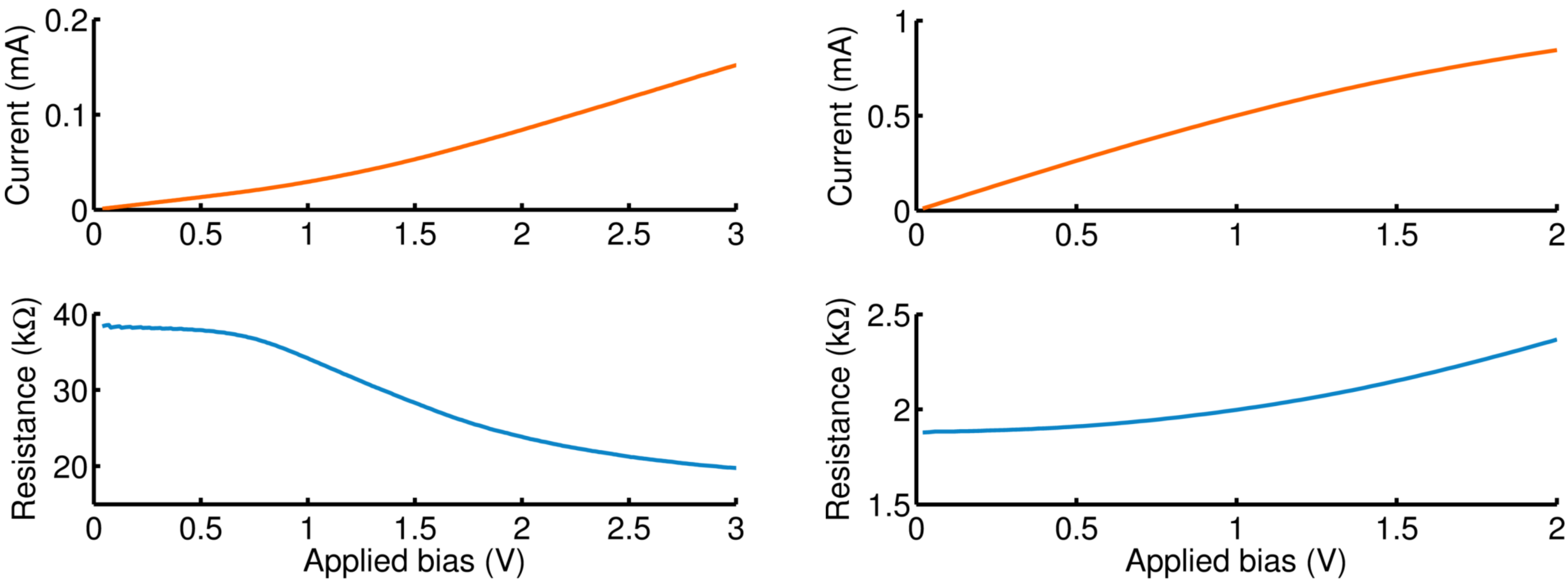


Initial vs. optimized PR processes

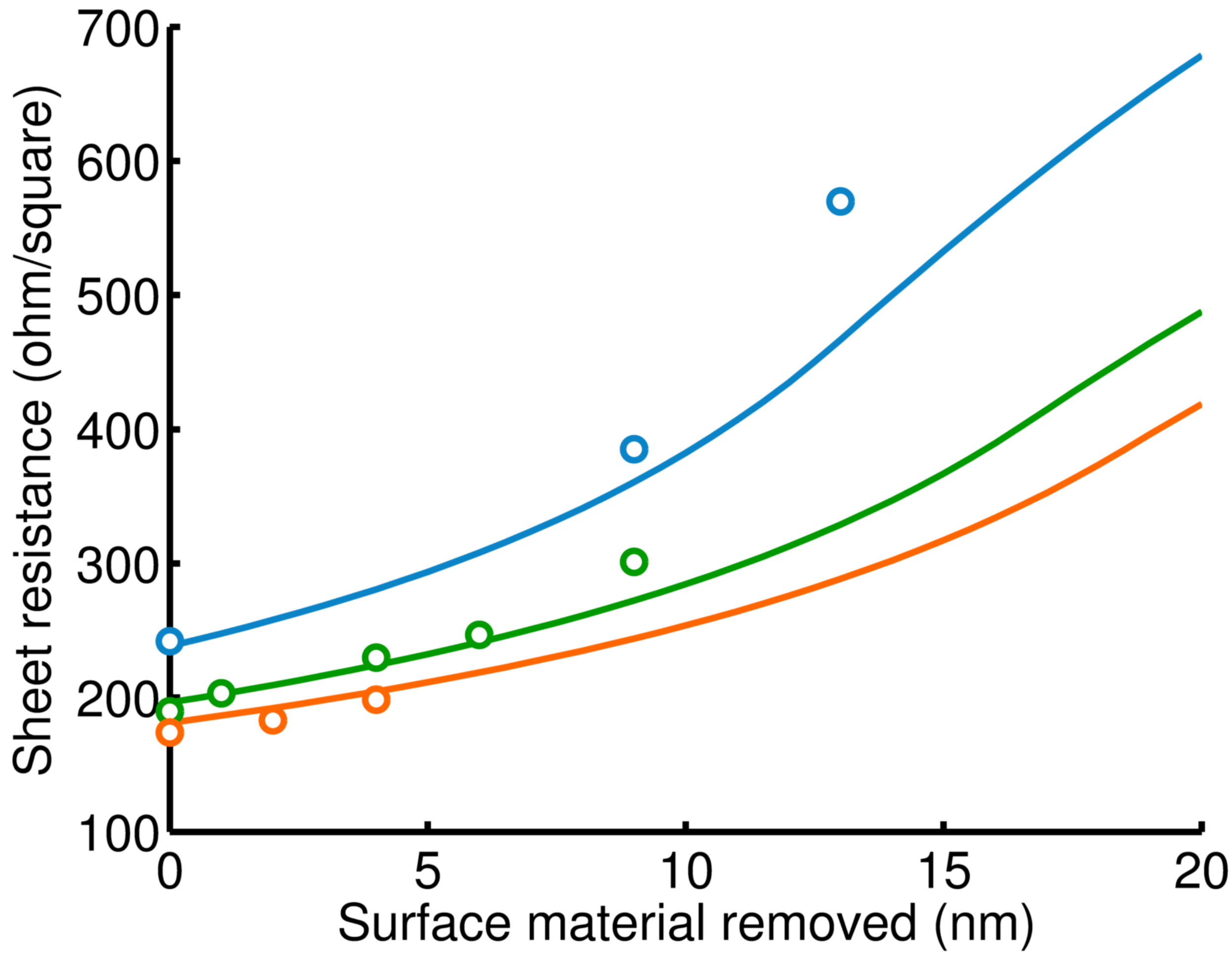




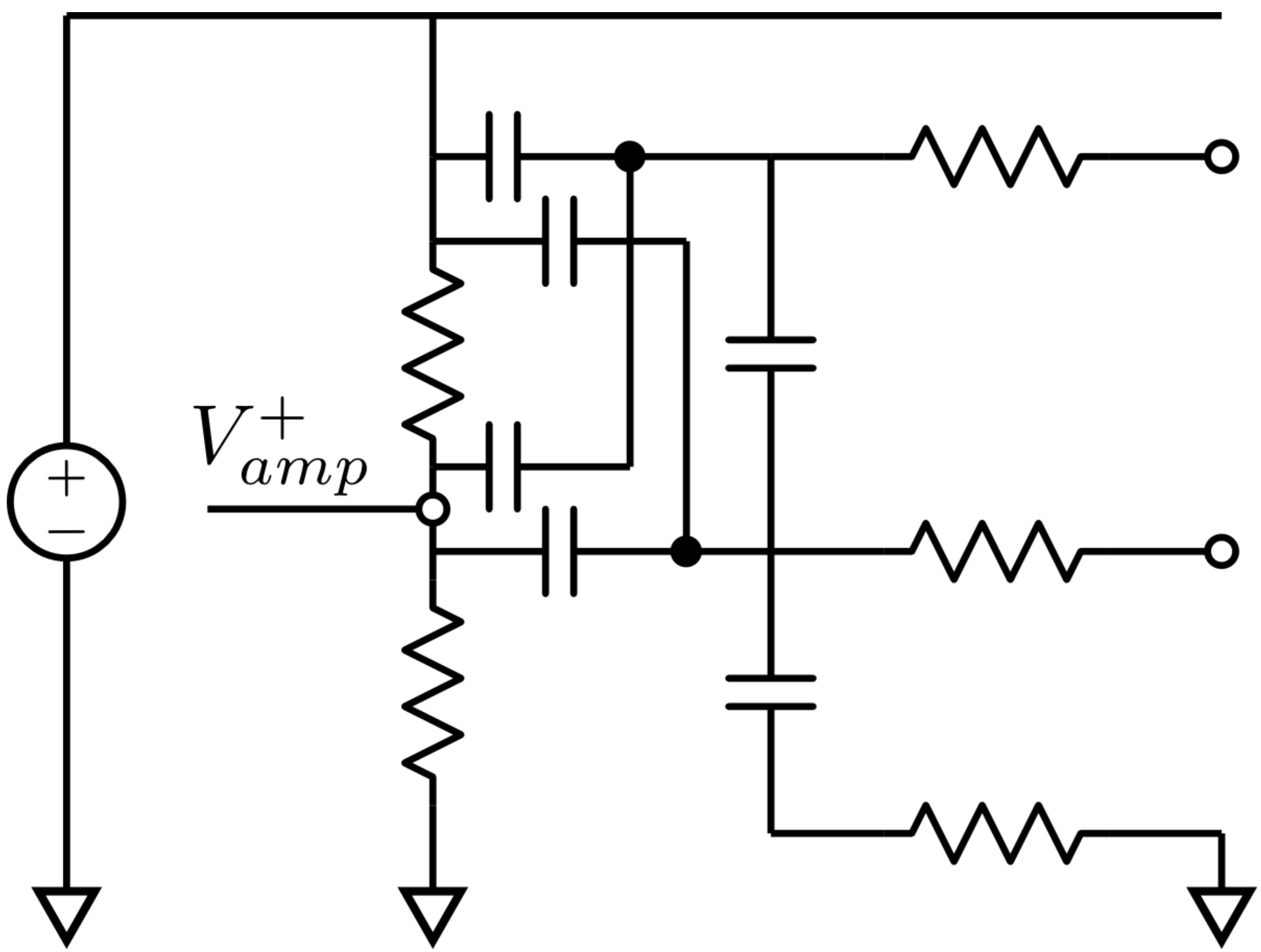
Initial vs. optimized PR process



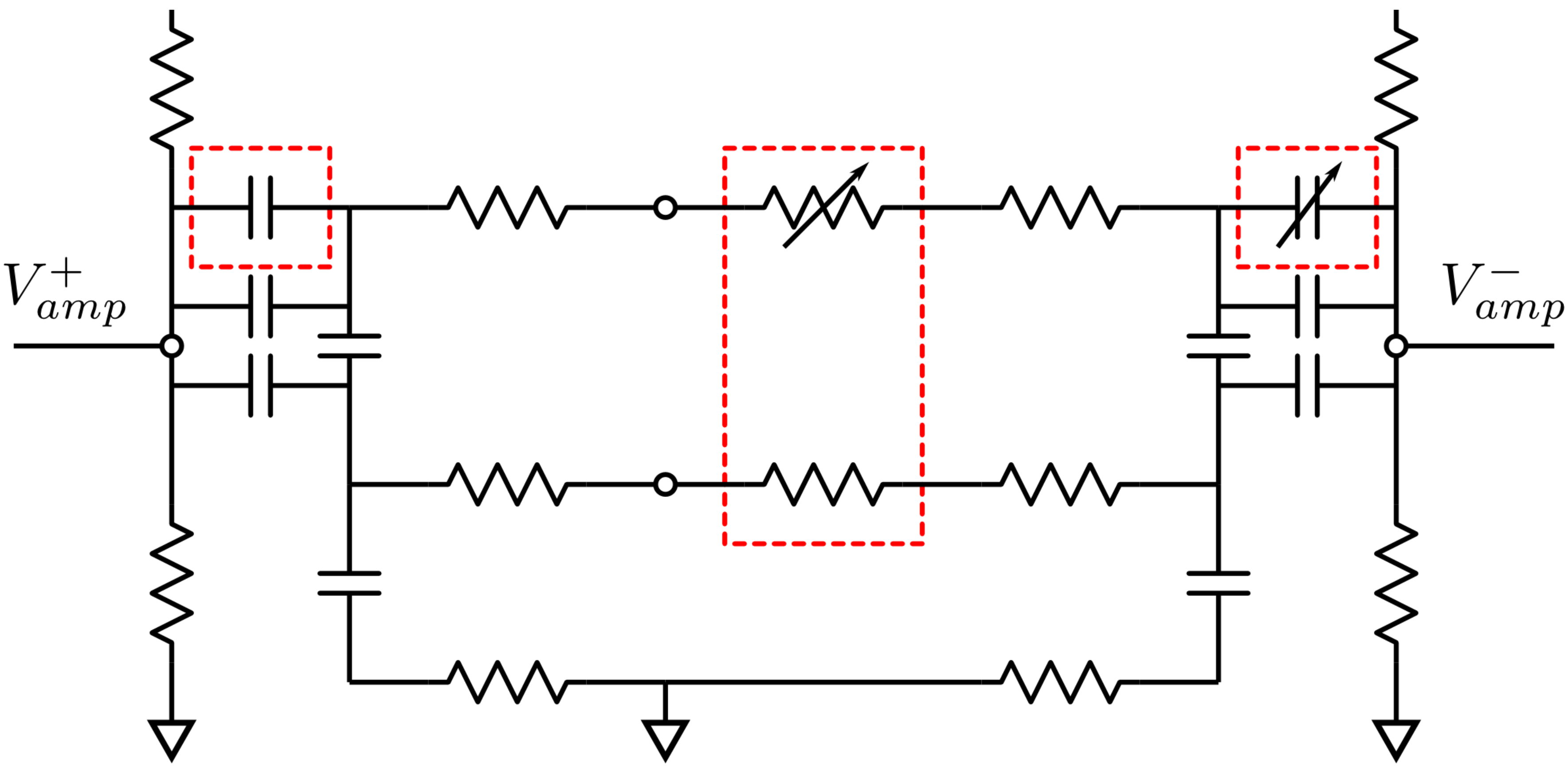
The trouble with thin piezoresistors



Crosstalk compensation



Crosstalk compensation



Actuator-patch crosstalk