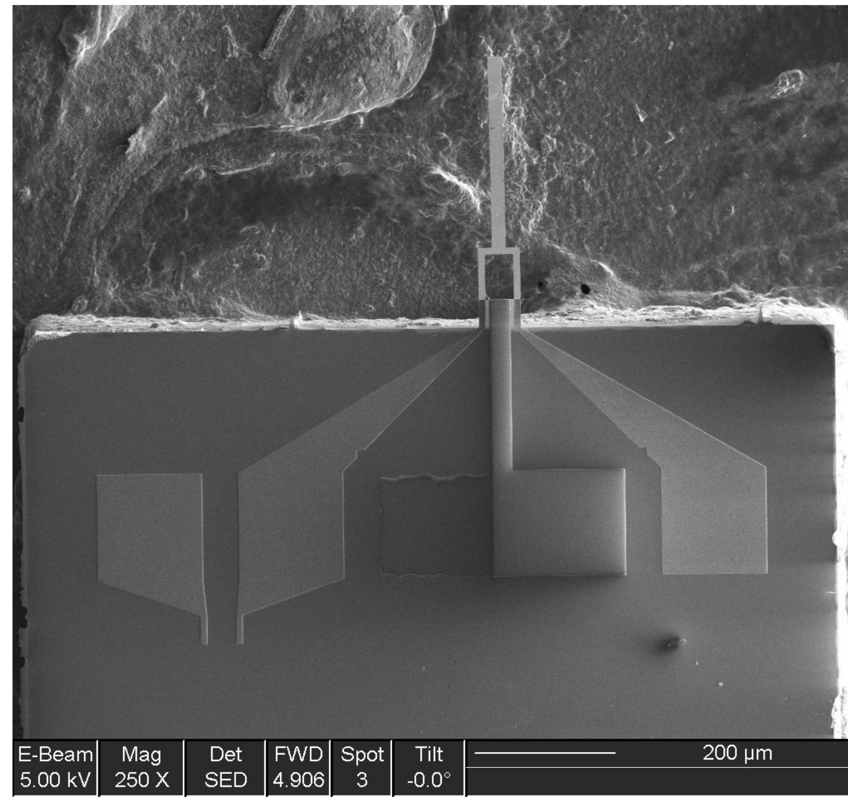
Research update: feedback control, device testing, and more

Joey Doll

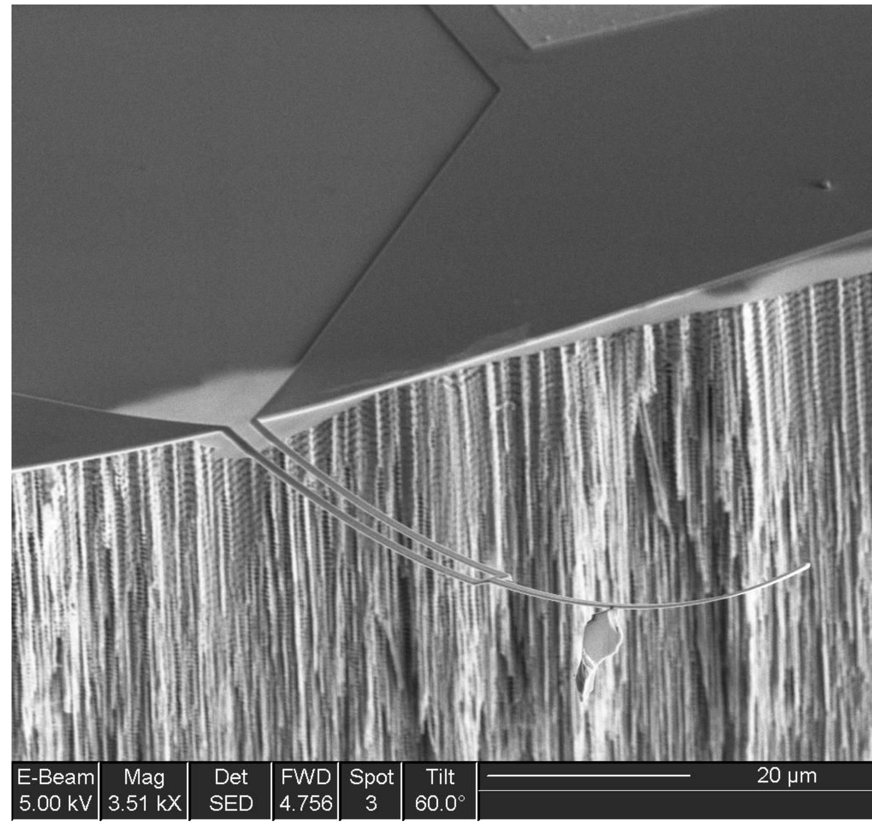
Group Meeting

11/4/2009

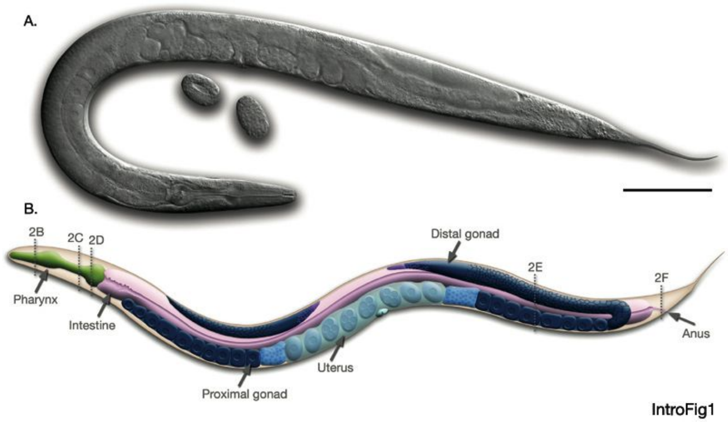


Today

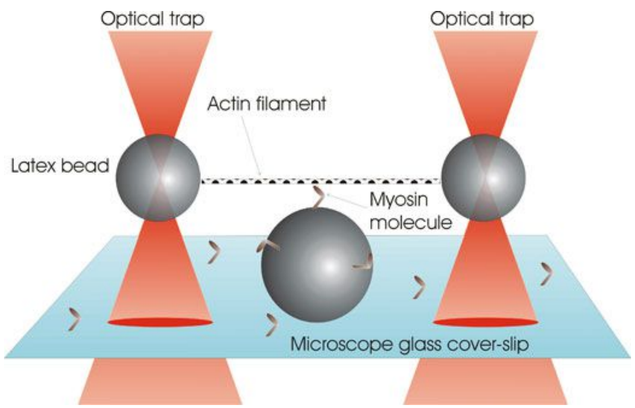
- Amplifier and feedback circuitry
- Combined PR+PE testing
- Cantilever bending stress



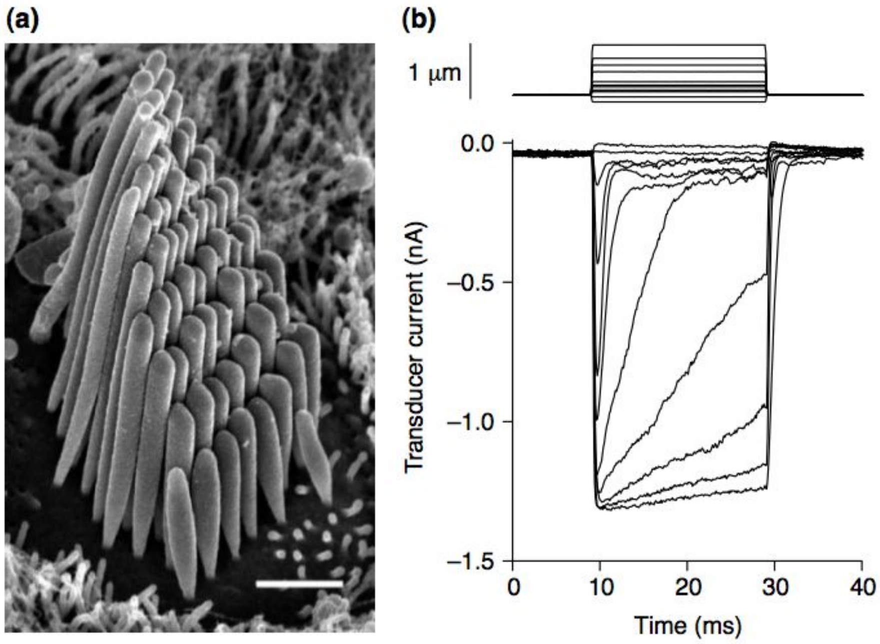
Motivation



Sense of touch (TRNs)



Protein conformational changes



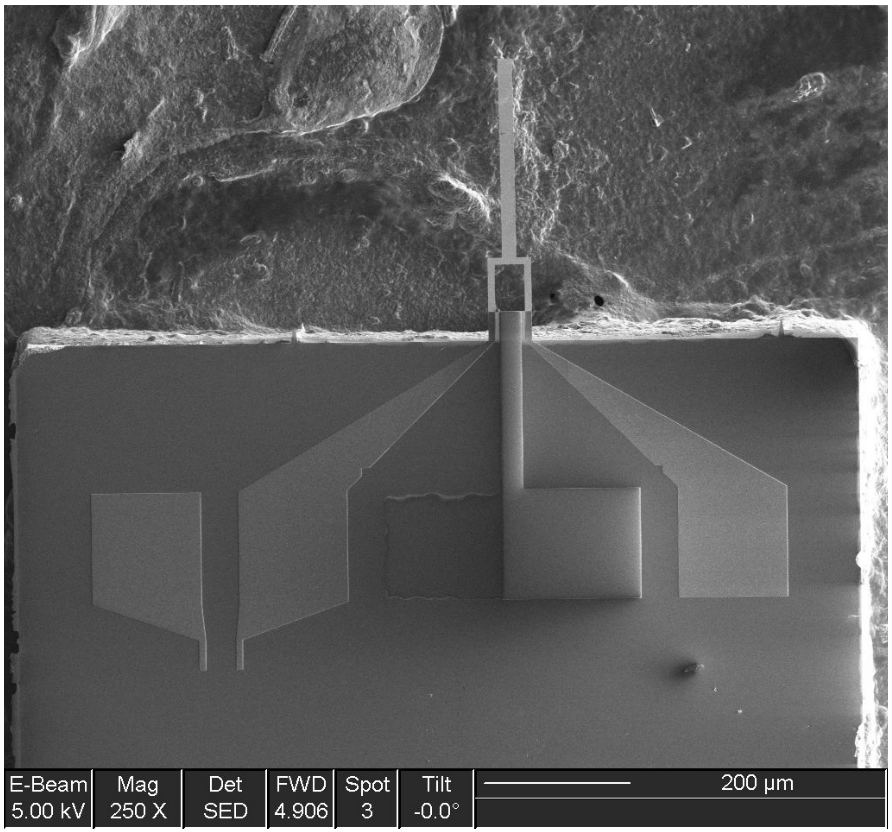
Sense of hearing (hair cells)

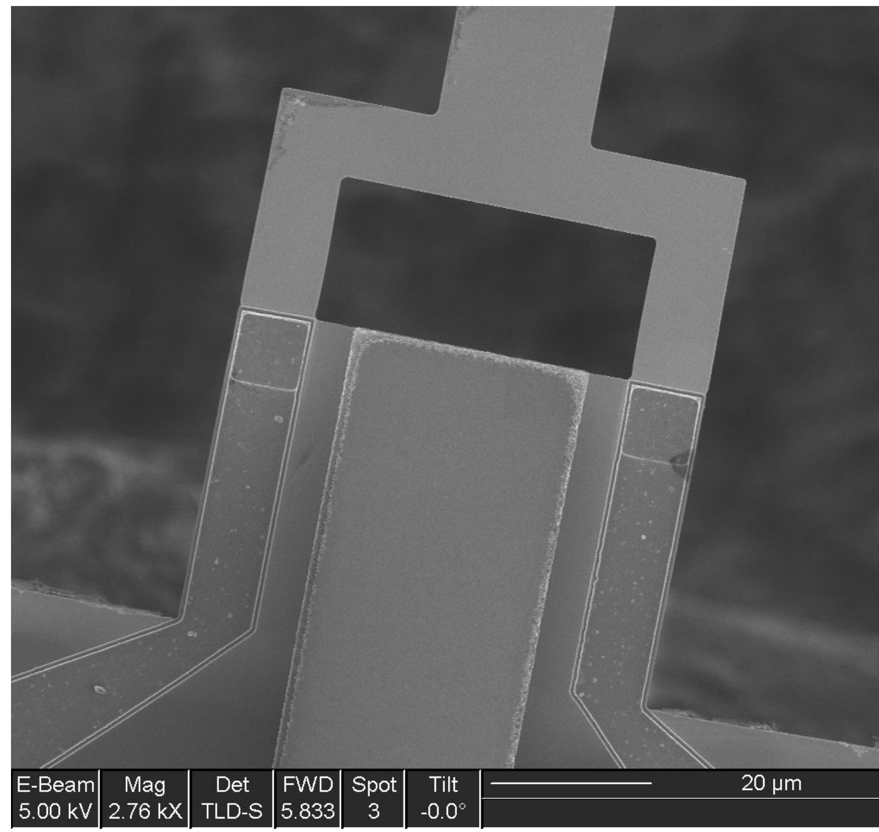
Images from Worm Atlas, http://www.scienceinschool.org/print/210 and
Clues to the cochlear amplifier from the turtle ear, Fettiplace, Ricci and Hackney, 2001

Performance Goals

- Rise time
  - 10 microseconds (turtle hair cell)
  - 1 microsecond (mammalian hair cell)
- Force resolution
  - 50 pN, 1 Hz – 30 kHz (turtle)
  - 50 pN, 1 Hz – 300 kHz (mammalian)
  - 30 pN, 1 Hz – 10 kHz (TRN, single molecule)
- Closed loop force control
- Operation in fluid

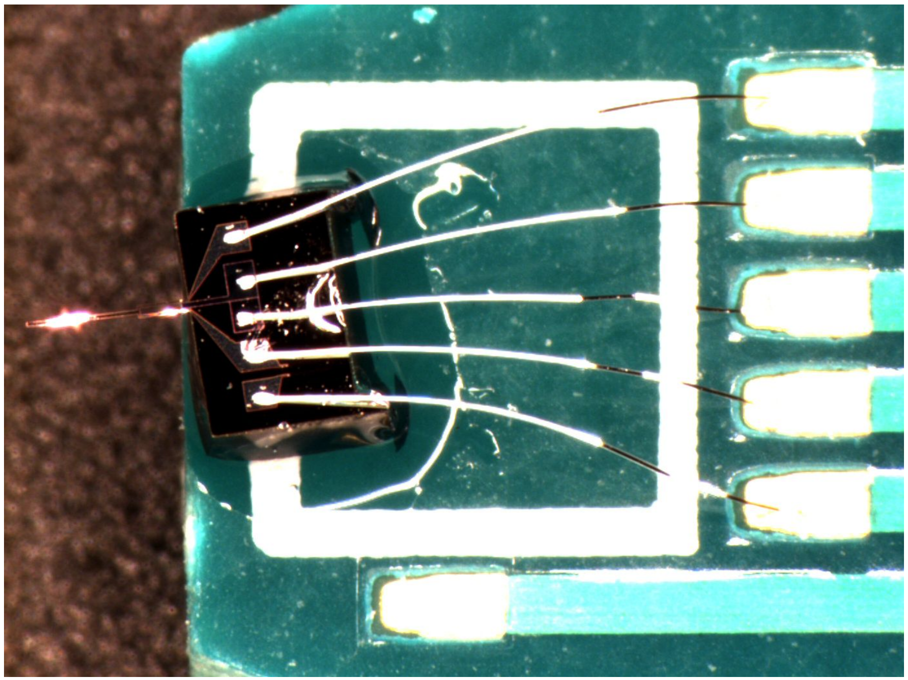
The Device

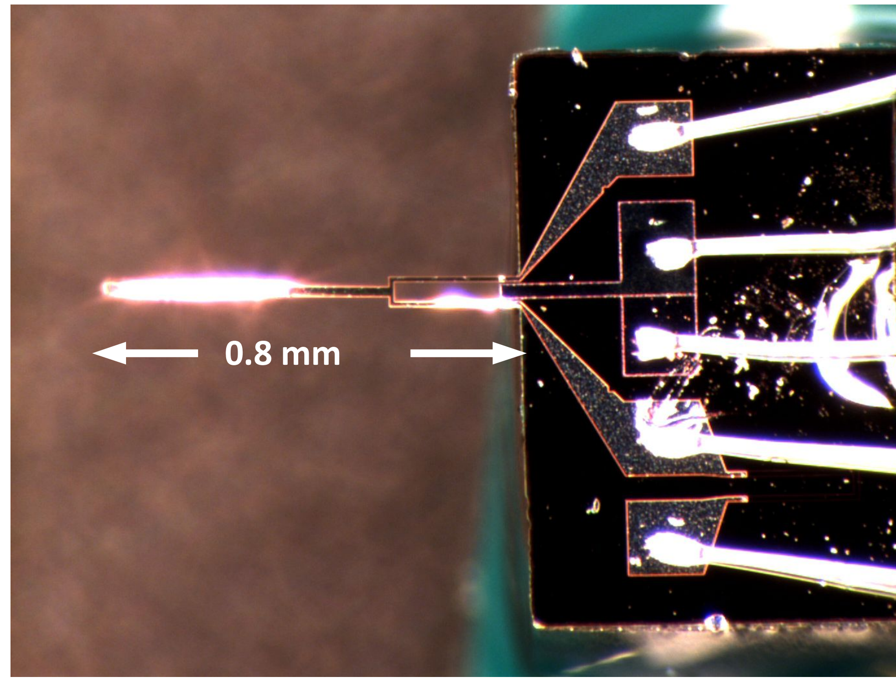




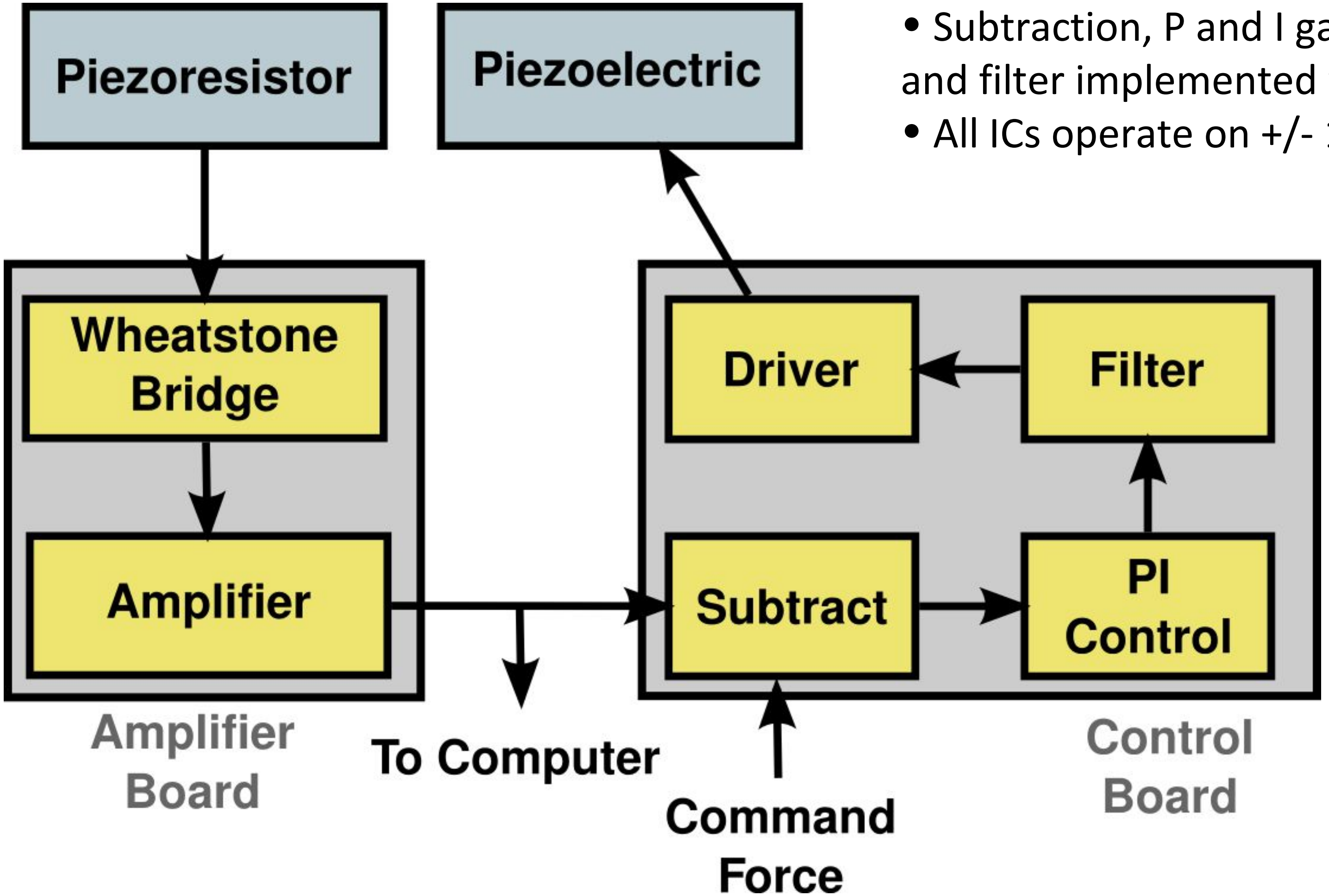
Piezoresistive force detection
Piezoelectric actuation

The Device



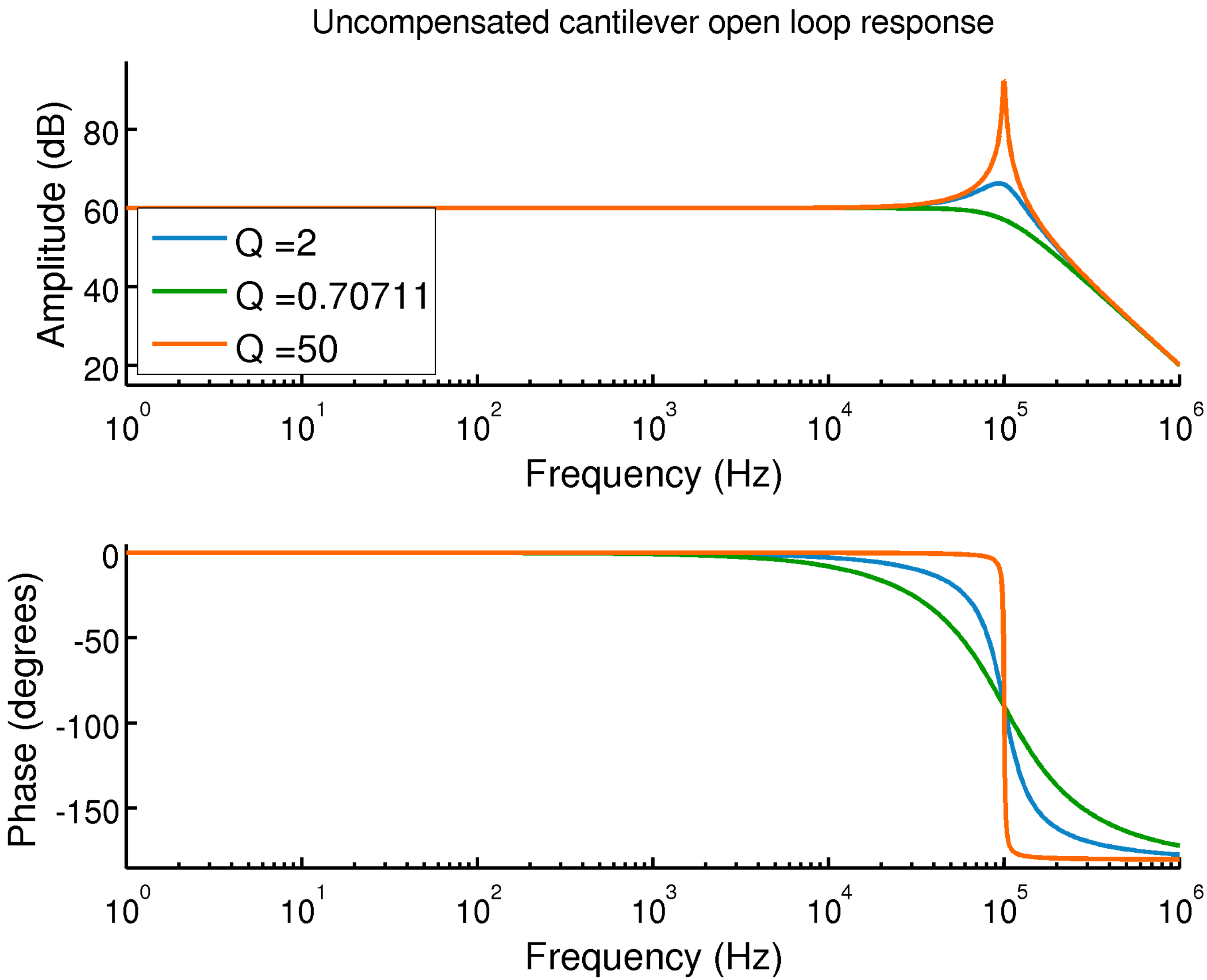


Feedback Circuit

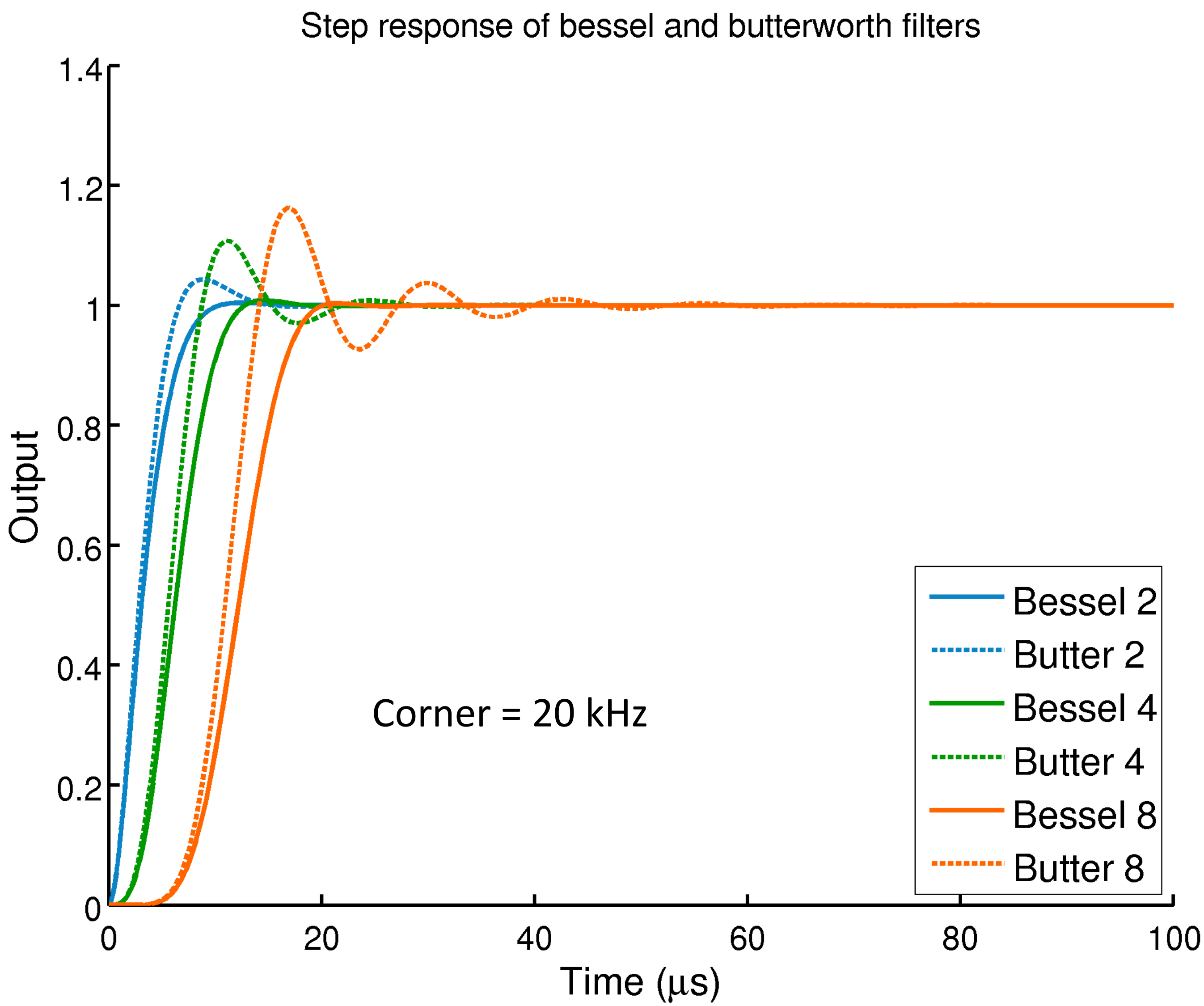


- Amplifier = INA103 or AD8221
- Subtraction, P and I gains, summation and filter implemented with op-amps
- All ICs operate on +/- 15V

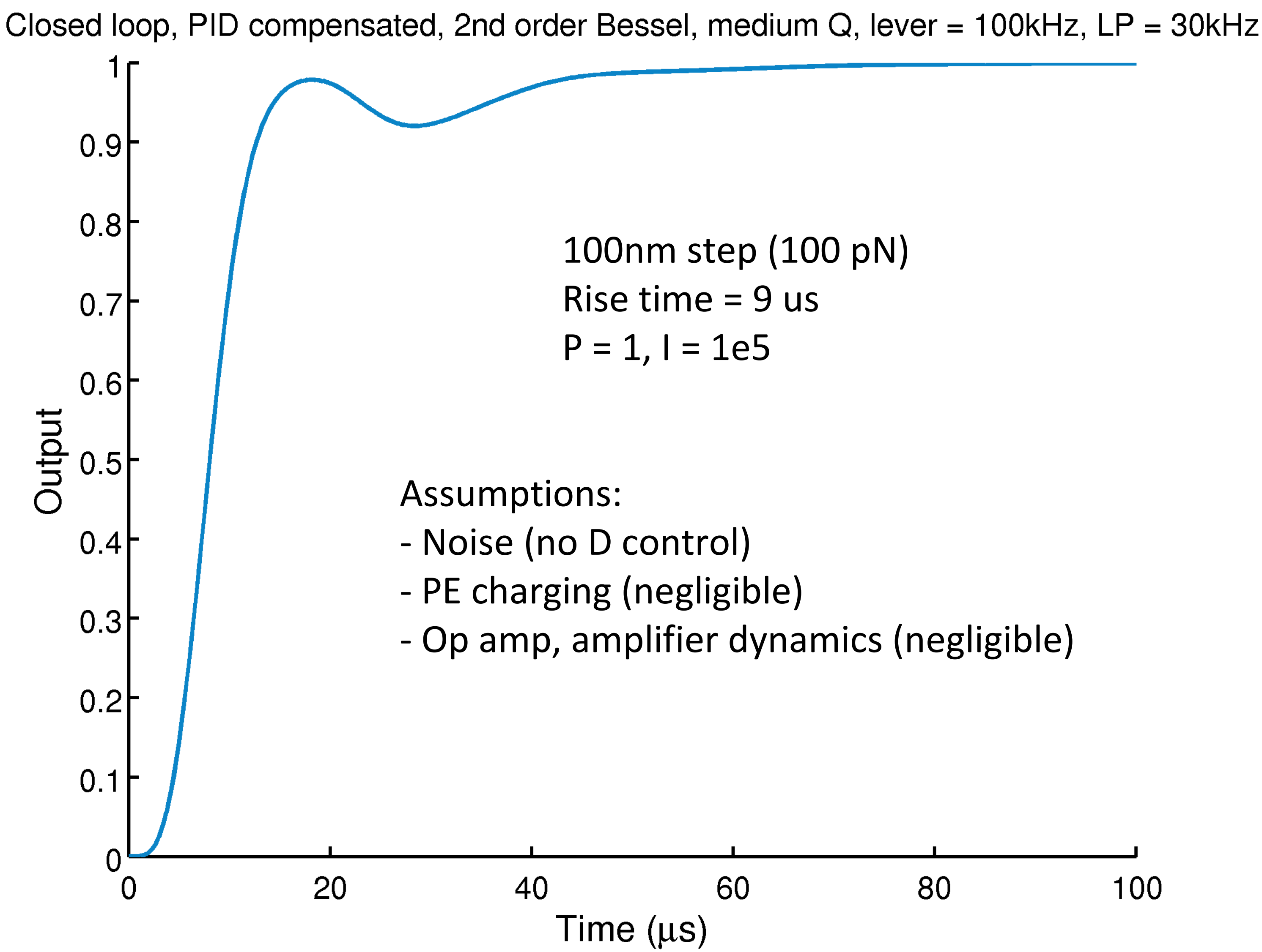
Feedback Modeling



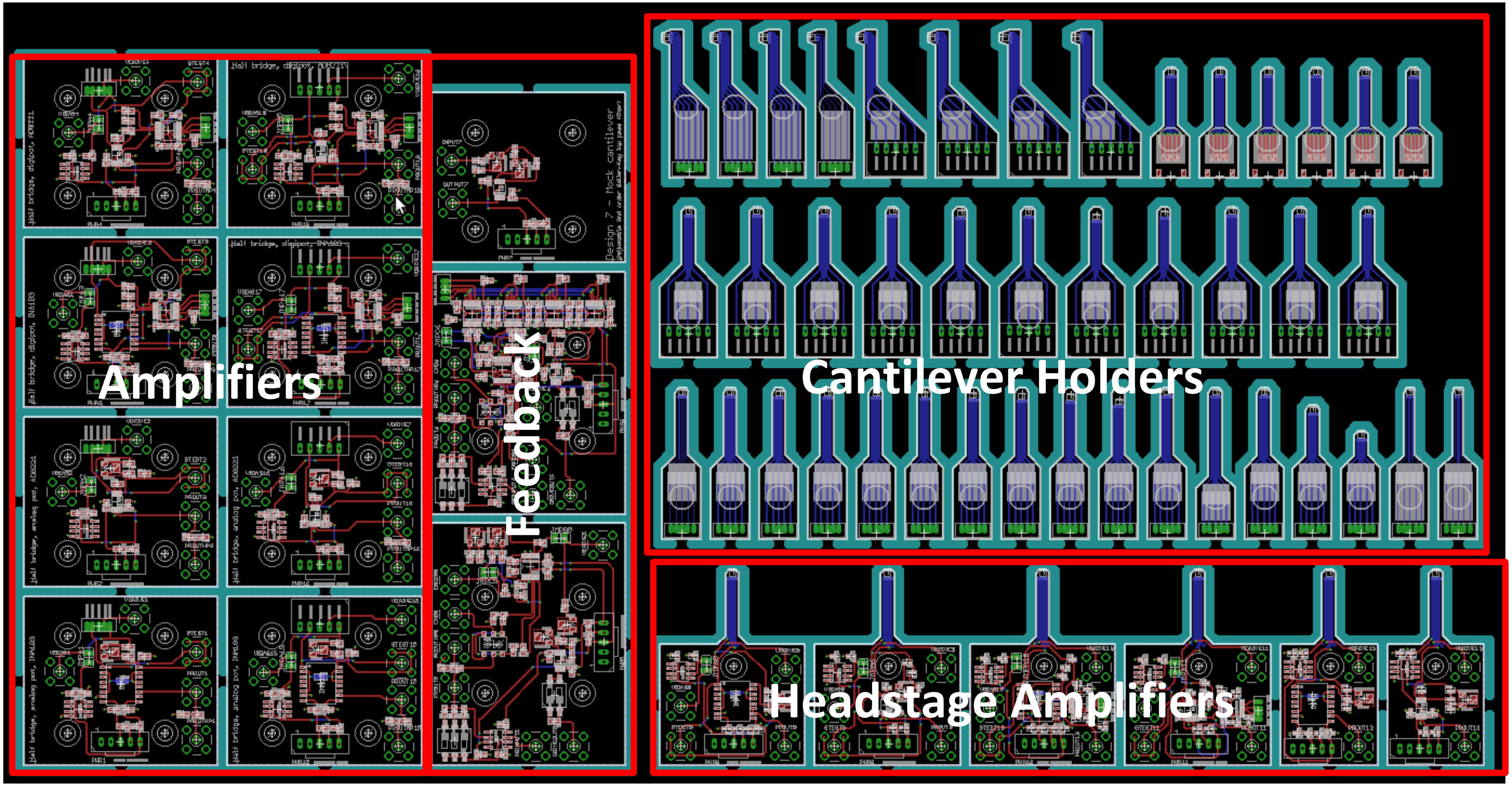
Feedback Modeling



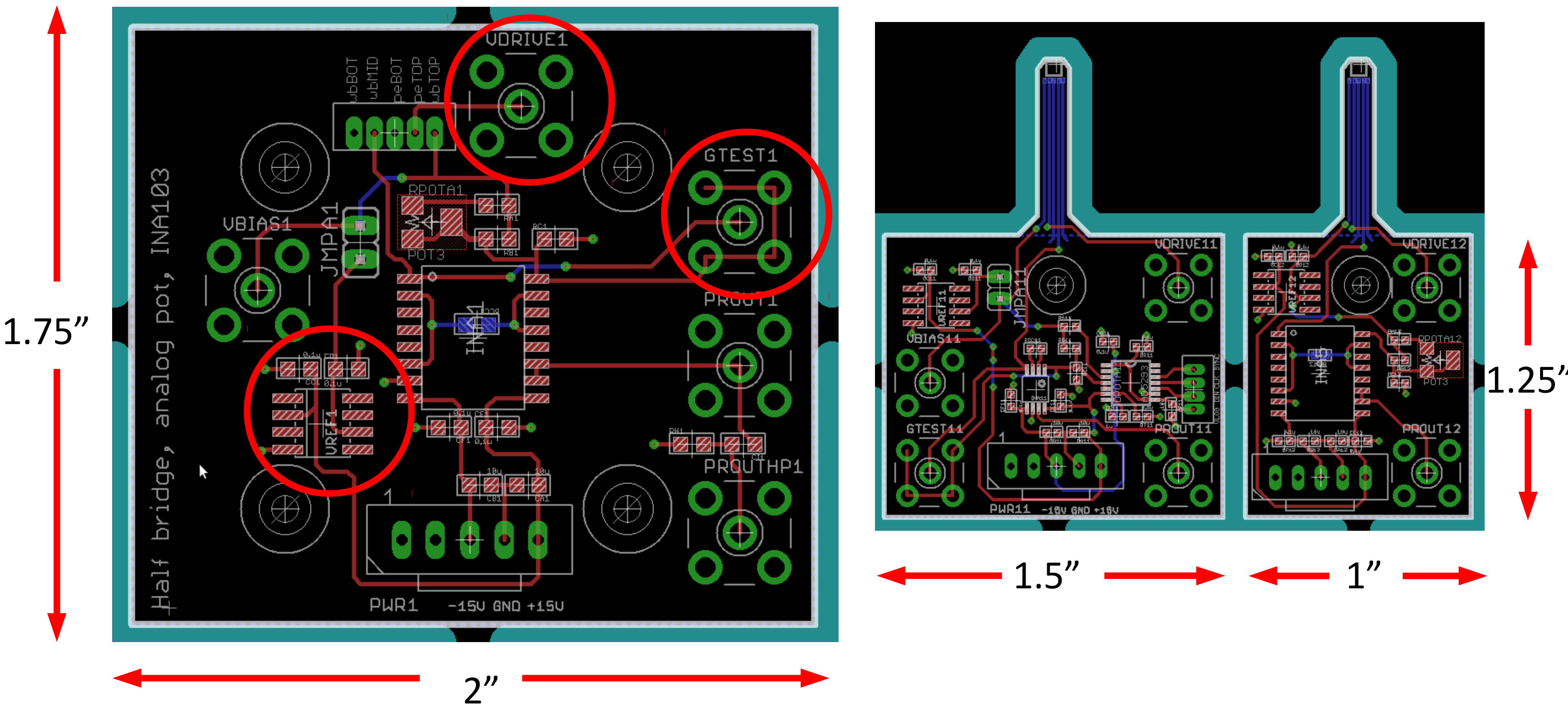
Feedback Modeling



PCB Layout


Amplifiers
Feedback
Cantilever Holders
Headstage Amplifiers

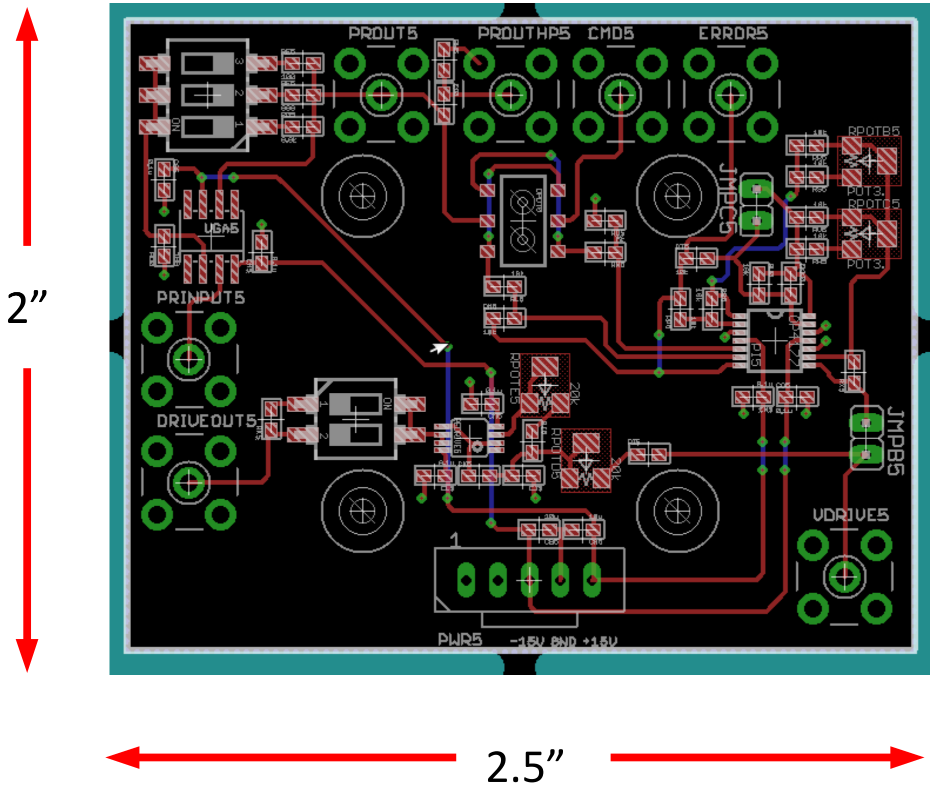
Circuits - Amplifiers

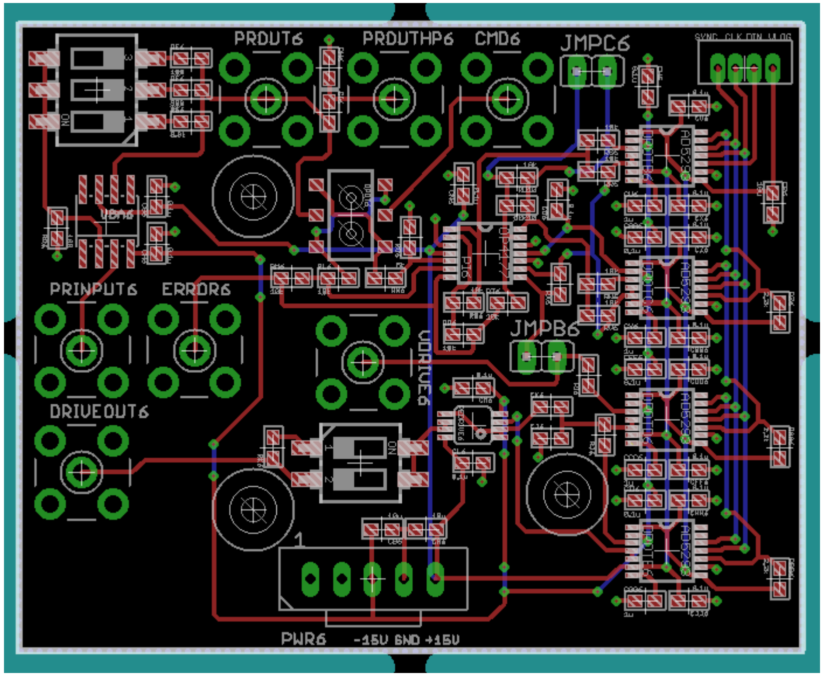


Circuits - Feedback

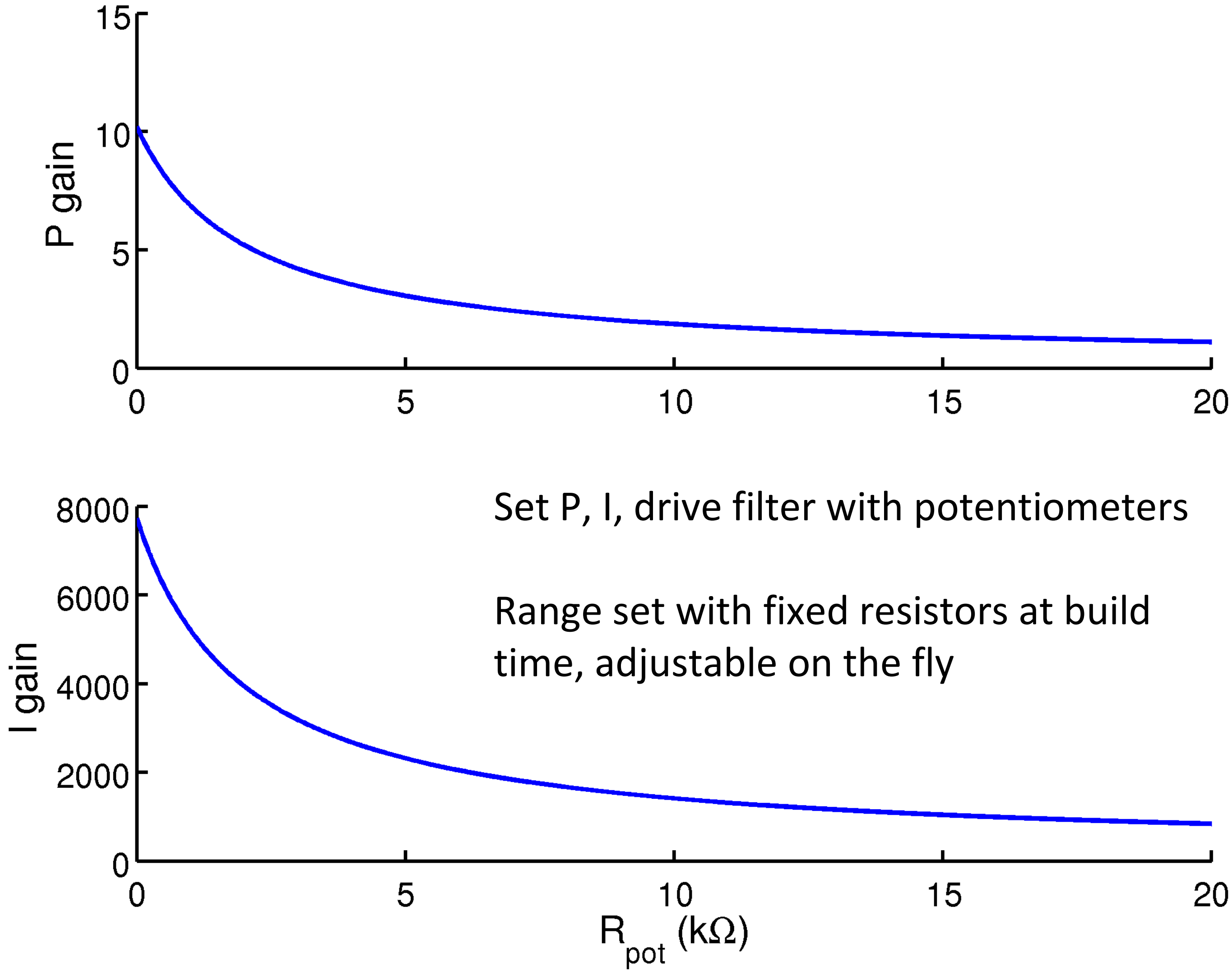
Analog Potentiometers

Digital Potentiometers





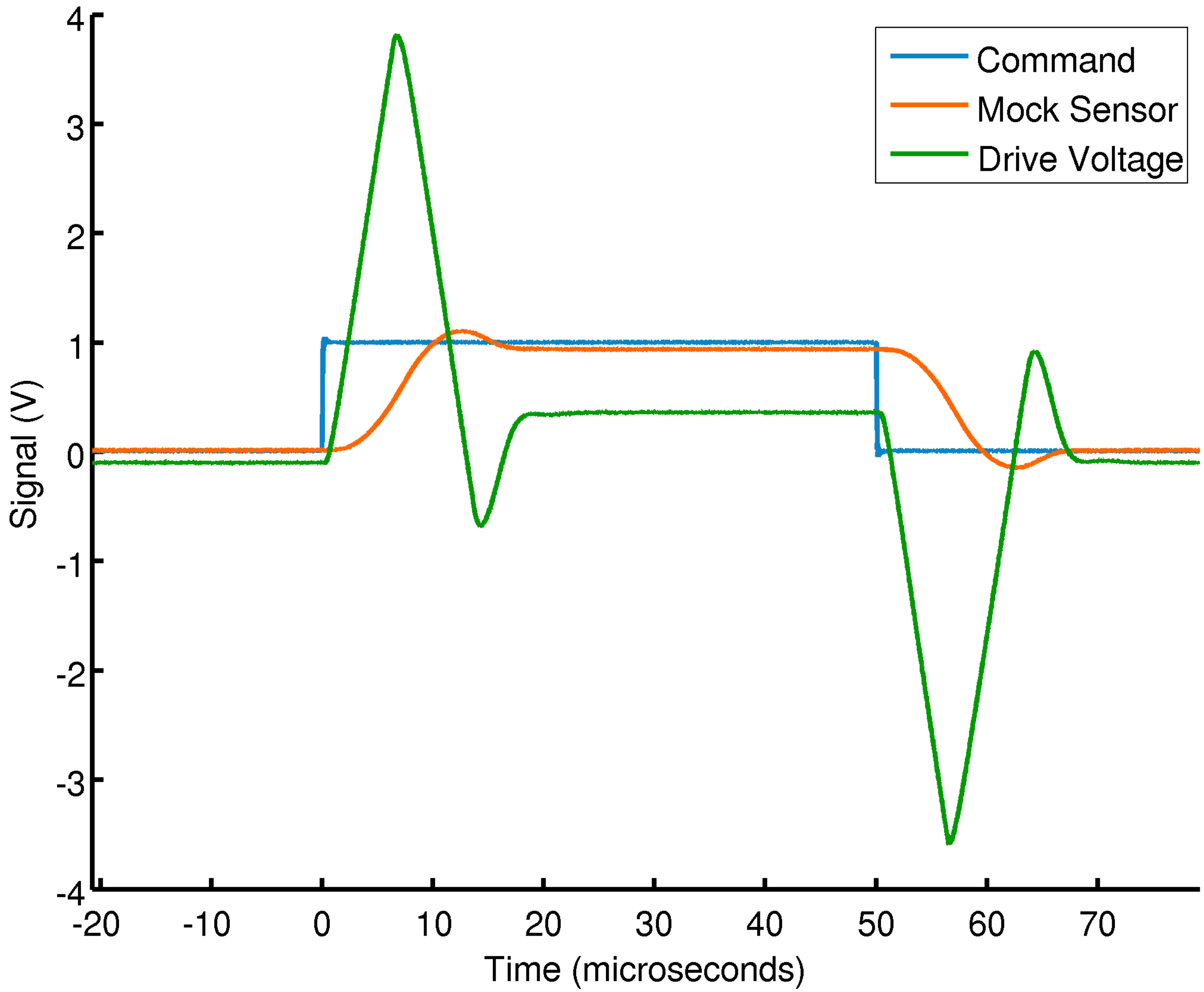
Circuit Design



Set P, I, drive filter with potentiometers

Range set with fixed resistors at build time, adjustable on the fly

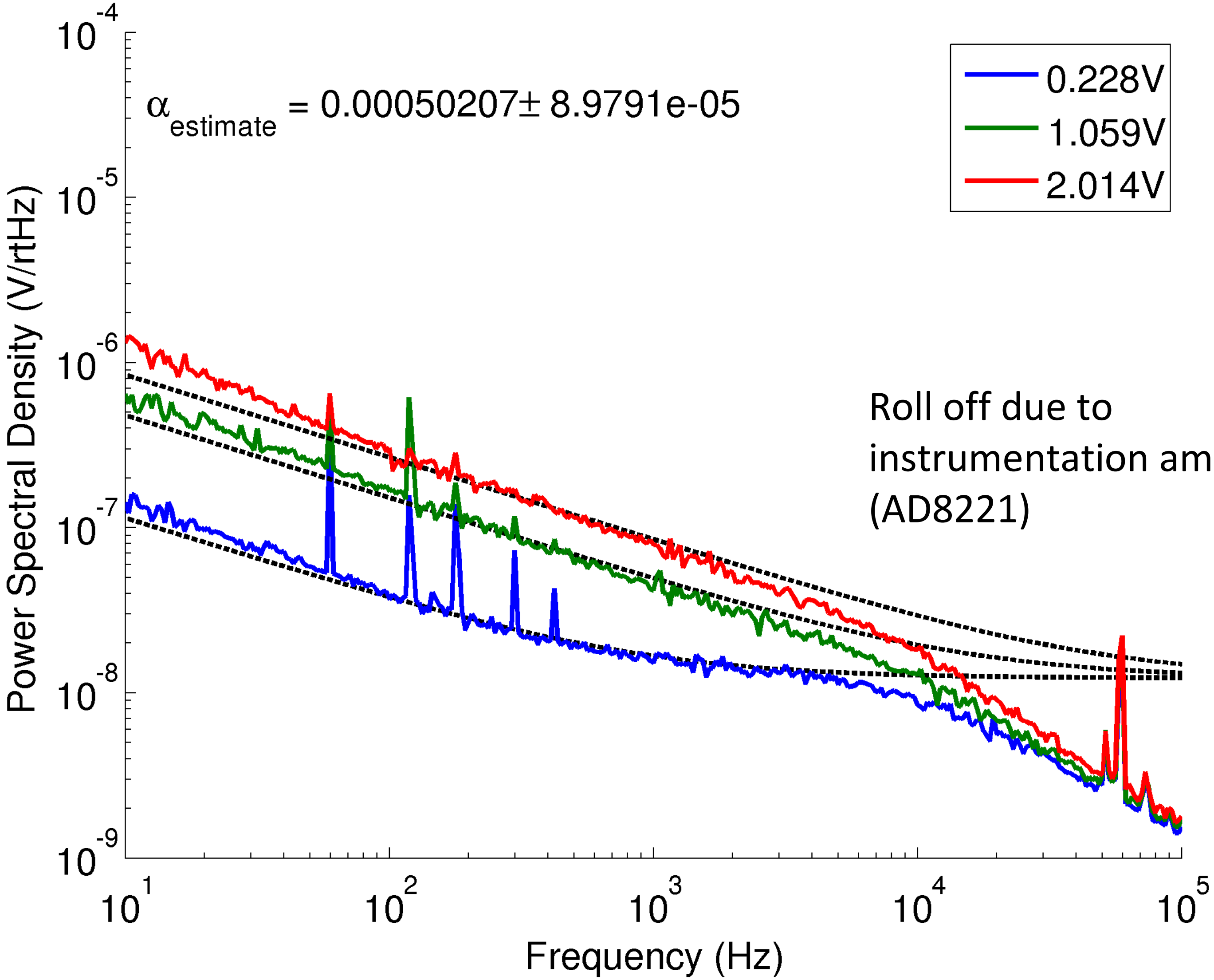
The circuit works



PR+PE Device Characterization

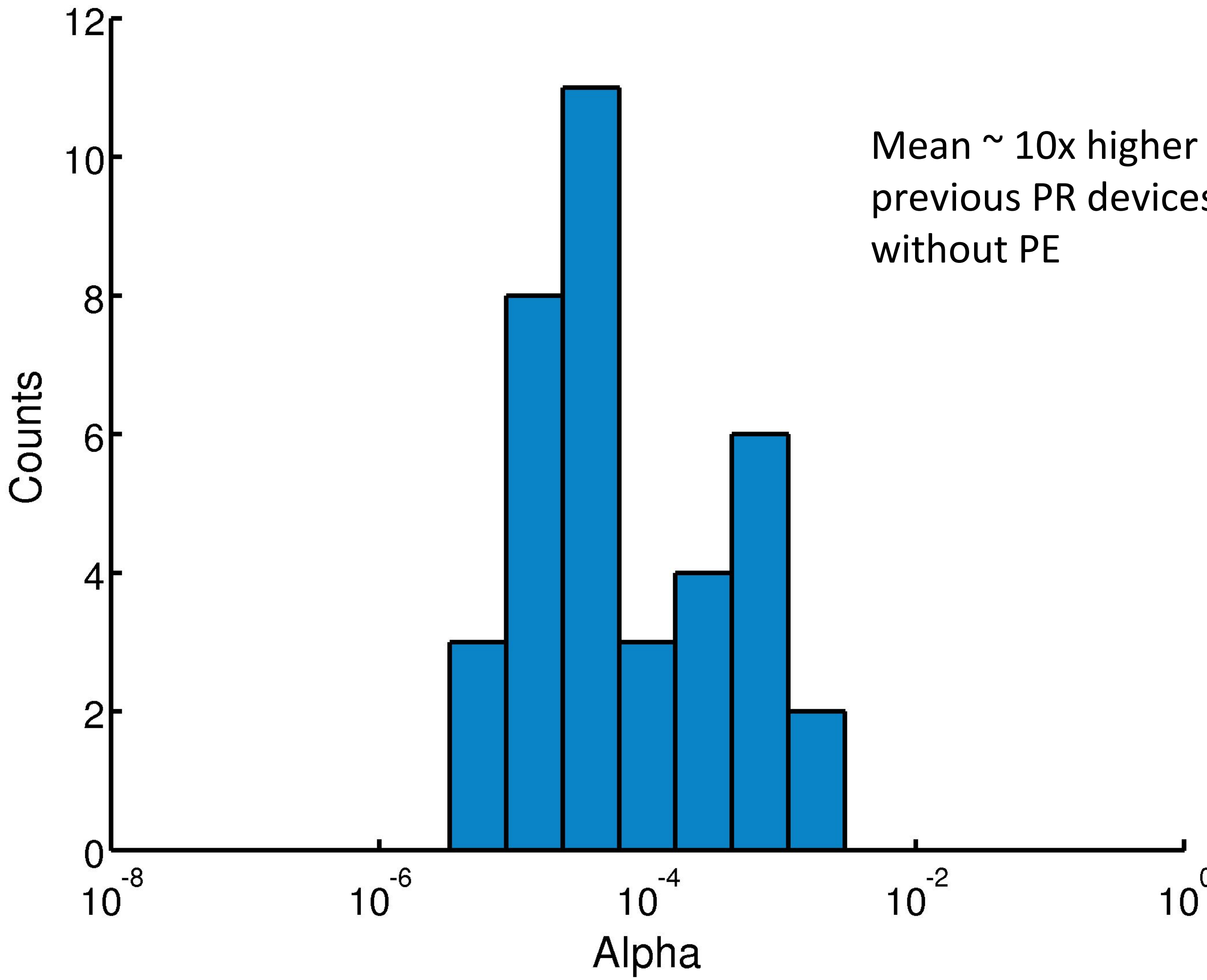
- **Noise spectrum**
- **Piezoresistor resistance**
- **Electrical cross-talk**
- Spring constant
- Force/displacement sensitivity
- Actuation distance

Noise spectra look good



Roll off due to instrumentation amplifier (AD8221)

1/f noise higher than expected

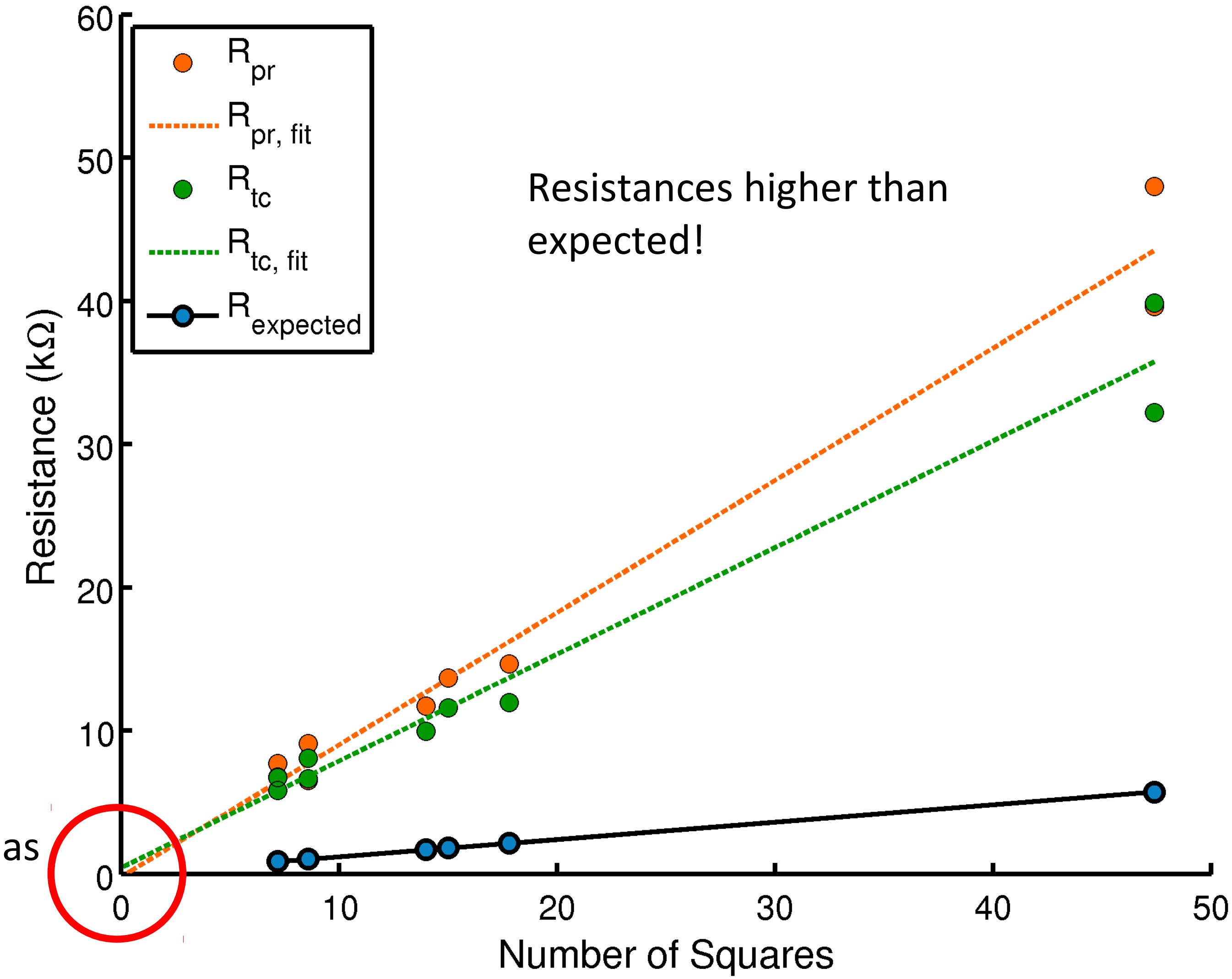


Mean ~ 10x higher than previous PR devices without PE

Two unknowns, one equation

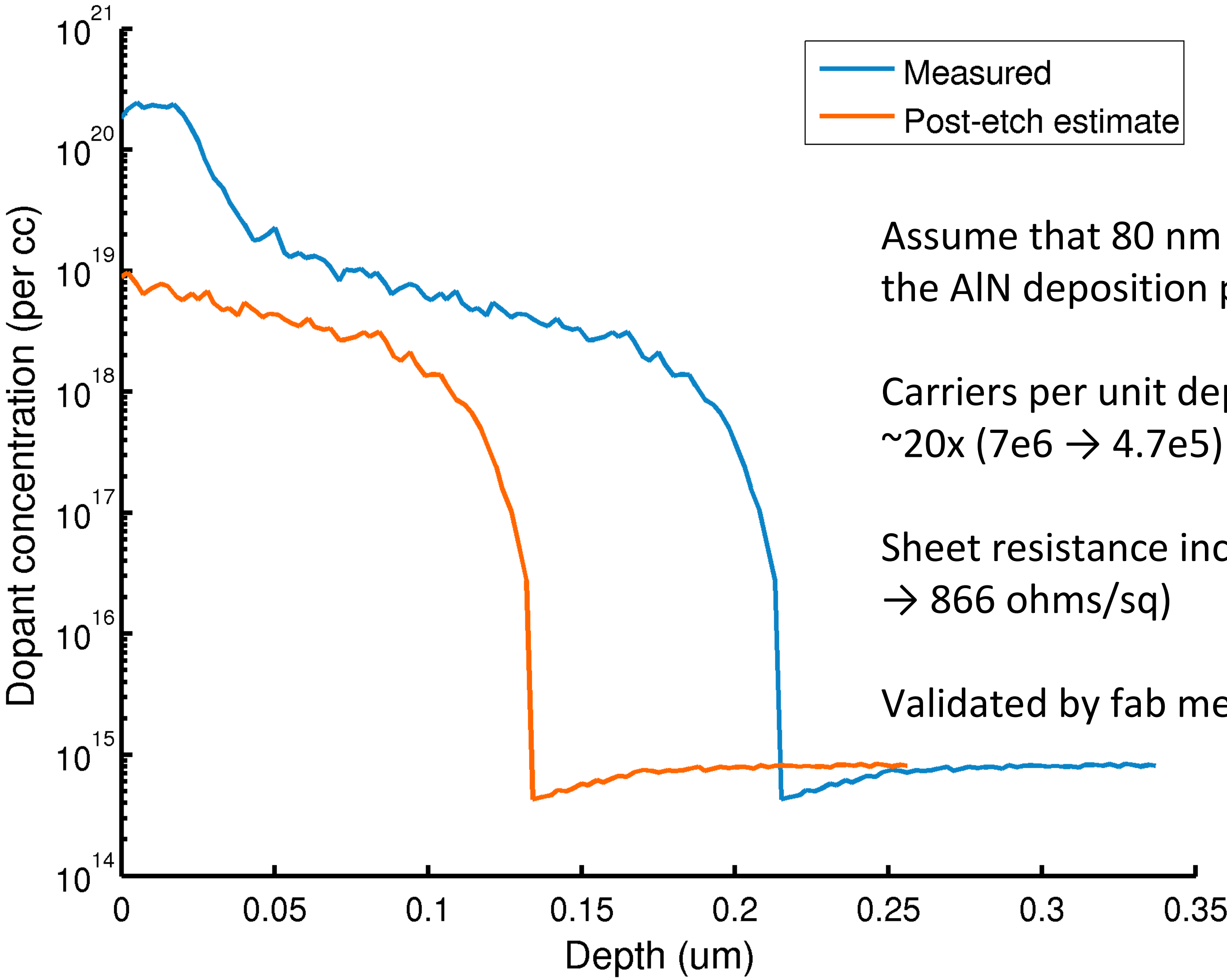
- 1/f noise depends on alpha and the number of carriers
- Alpha could be higher or the number of carriers could be smaller
- Need an additional parameter for fitting

Piezoresistor resistance



Contact vias are good!

Accidental etching



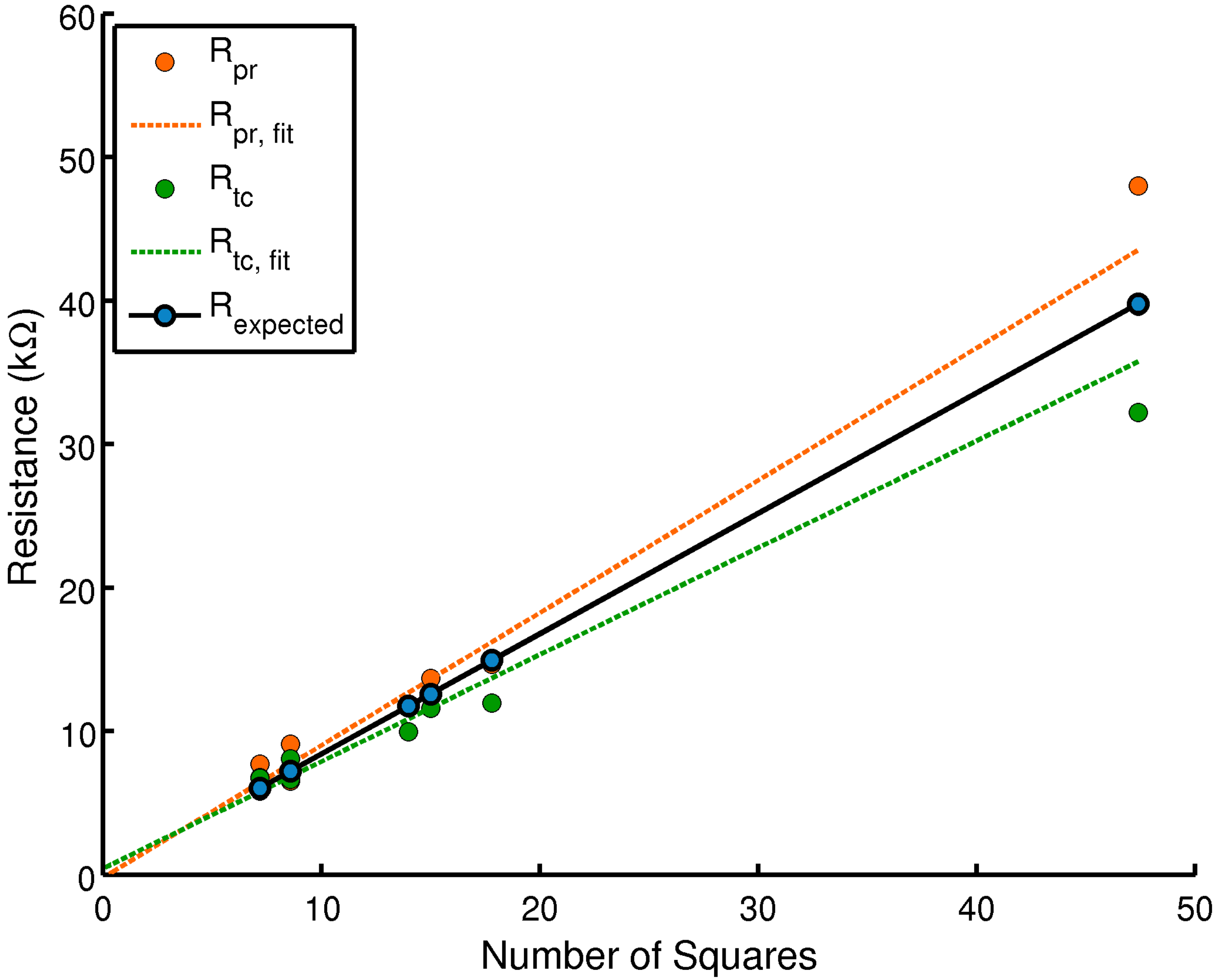
Assume that 80 nm of Si was etched in the AlN deposition preclean.

Carriers per unit depth decreases by ~20x (7e6 → 4.7e5)

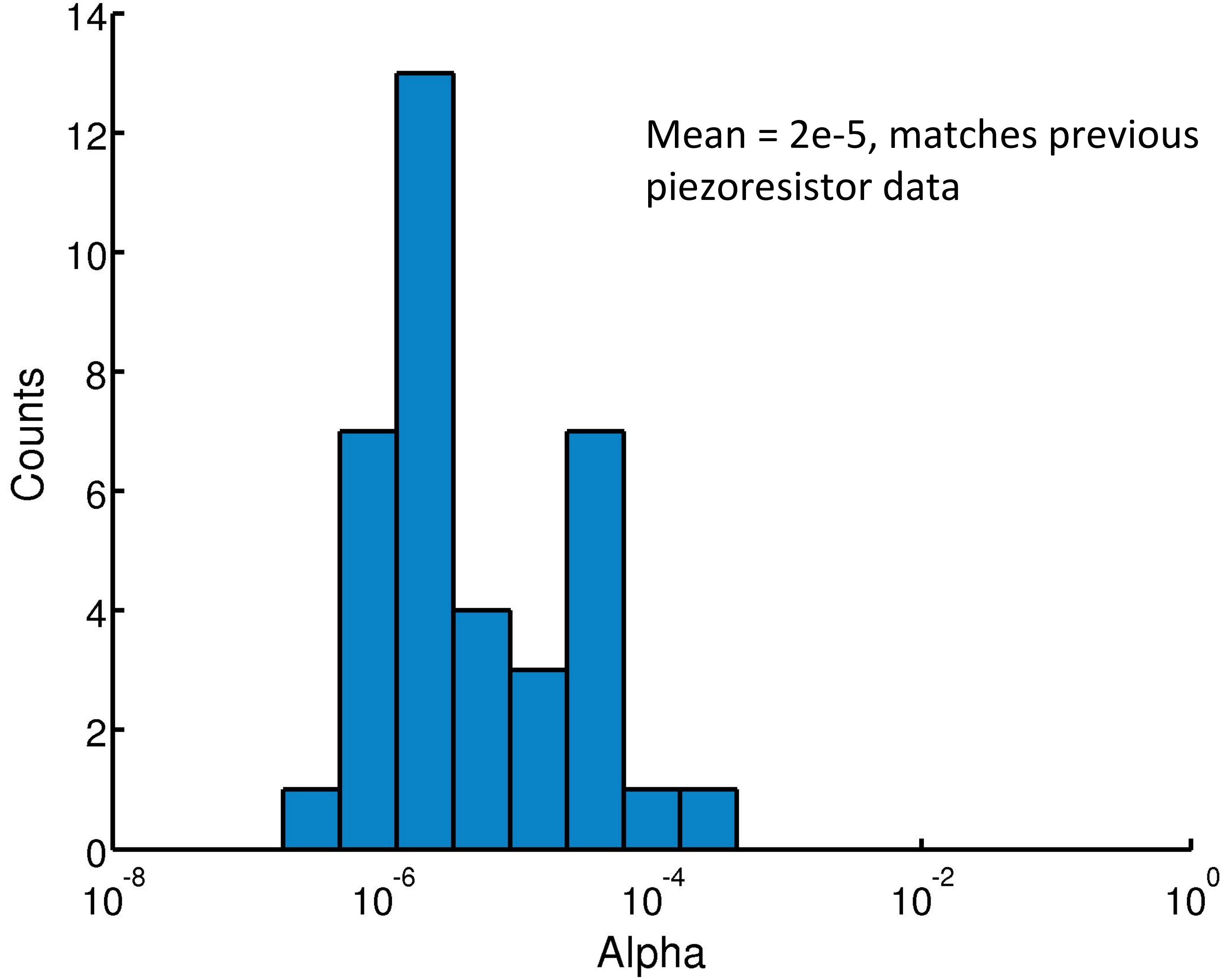
Sheet resistance increases by ~7x (120 → 866 ohms/sq)

Validated by fab measurements

Adjusted resistance model



Alpha adjustment

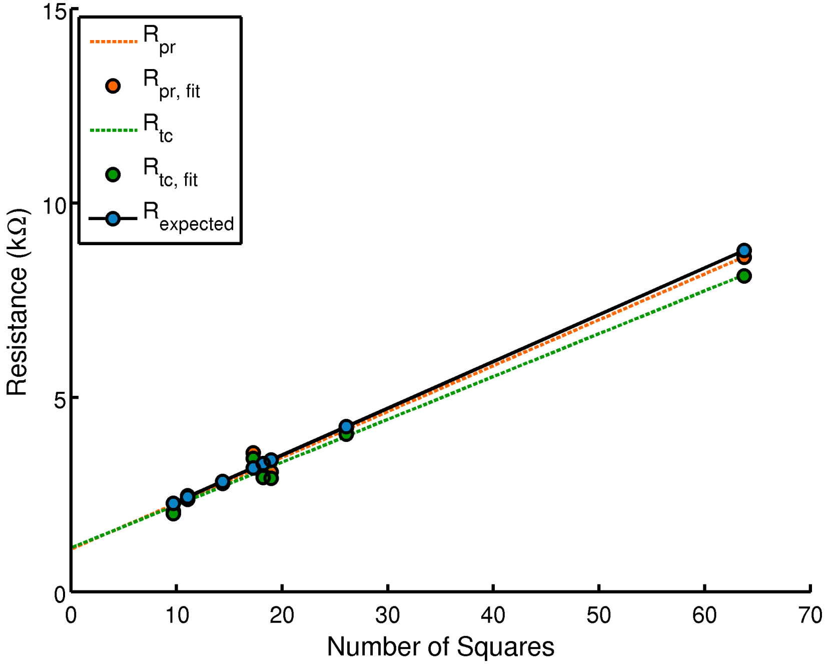


Mean = 2e-5, matches previous piezoresistor data

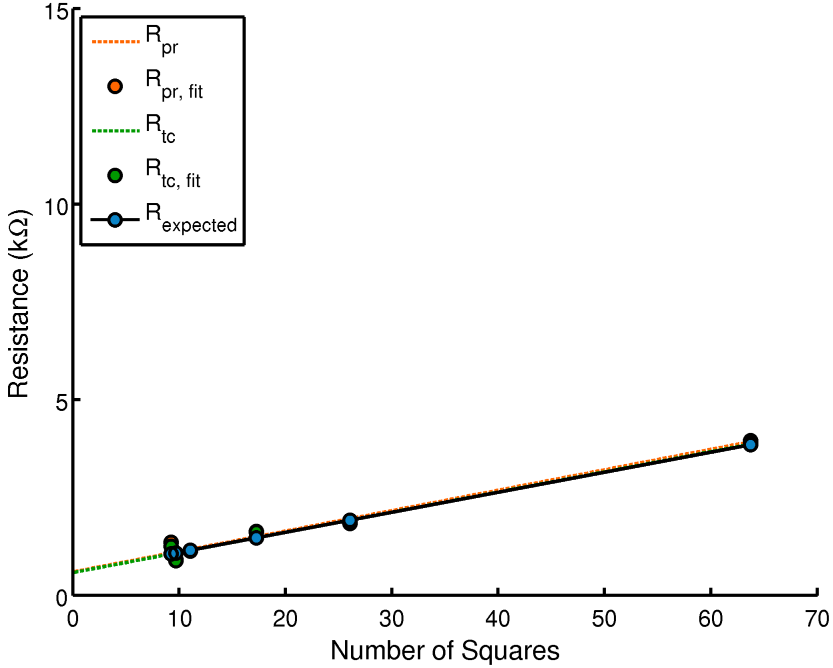
Overall impact?

- Noise ~10x higher
  - Johnson noise - 2.5x increase
  - 1/f noise – 4x increase
- Sensitivity ~ 4x higher
  - Beta* - 2x larger
  - Thickness – 33% less
- Minimum detectable force increased by 2.5x, good enough for most applications

Resistance Analysis of PR Devices



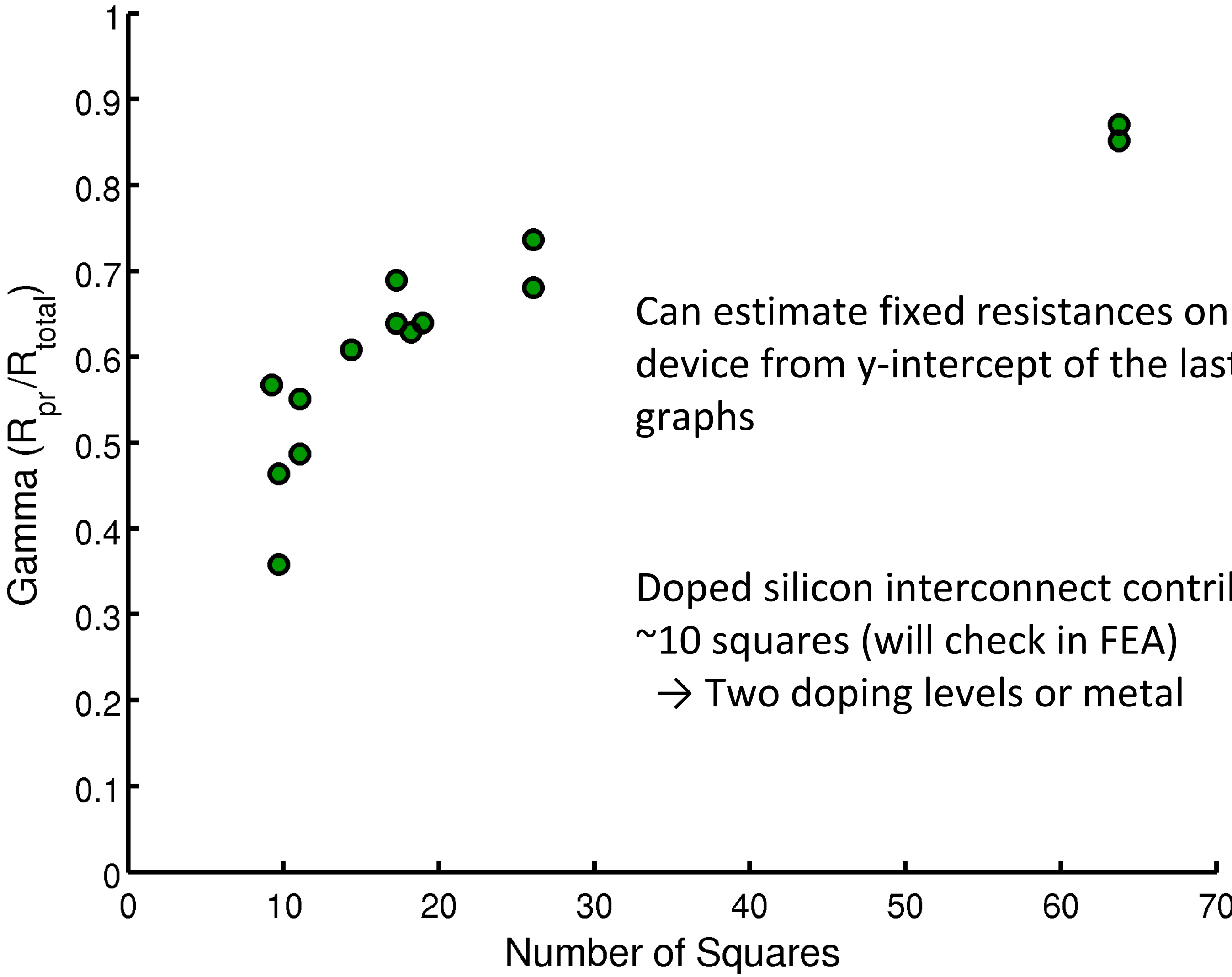
800C, 35 minutes



850C, 15 minutes

Assumed 100 nm undercut from litho/etch to improve fit (will measure)

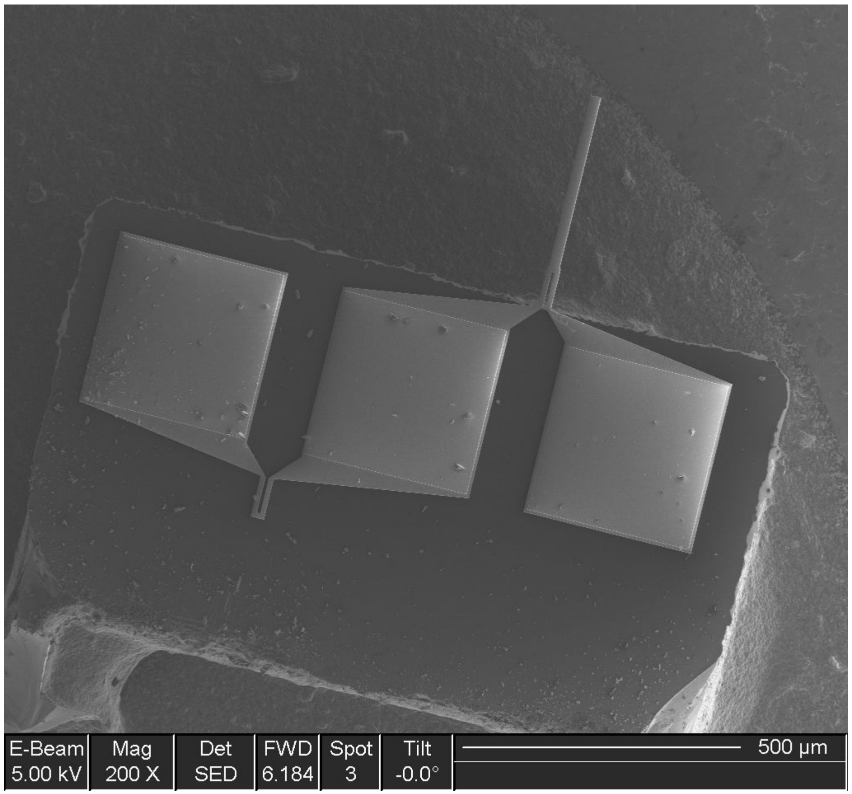
Resistance Analysis of PR Devices



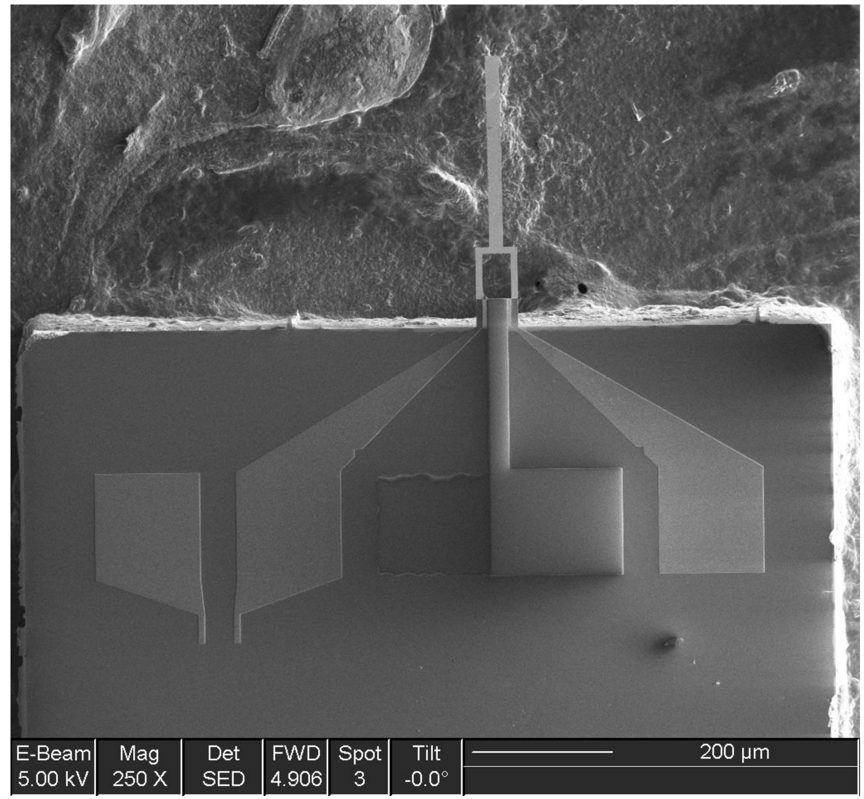
Can estimate fixed resistances on the device from y-intercept of the last graphs

Doped silicon interconnect contributes ~10 squares (will check in FEA)
→ Two doping levels or metal

PR interconnects



Doped Si interconnects

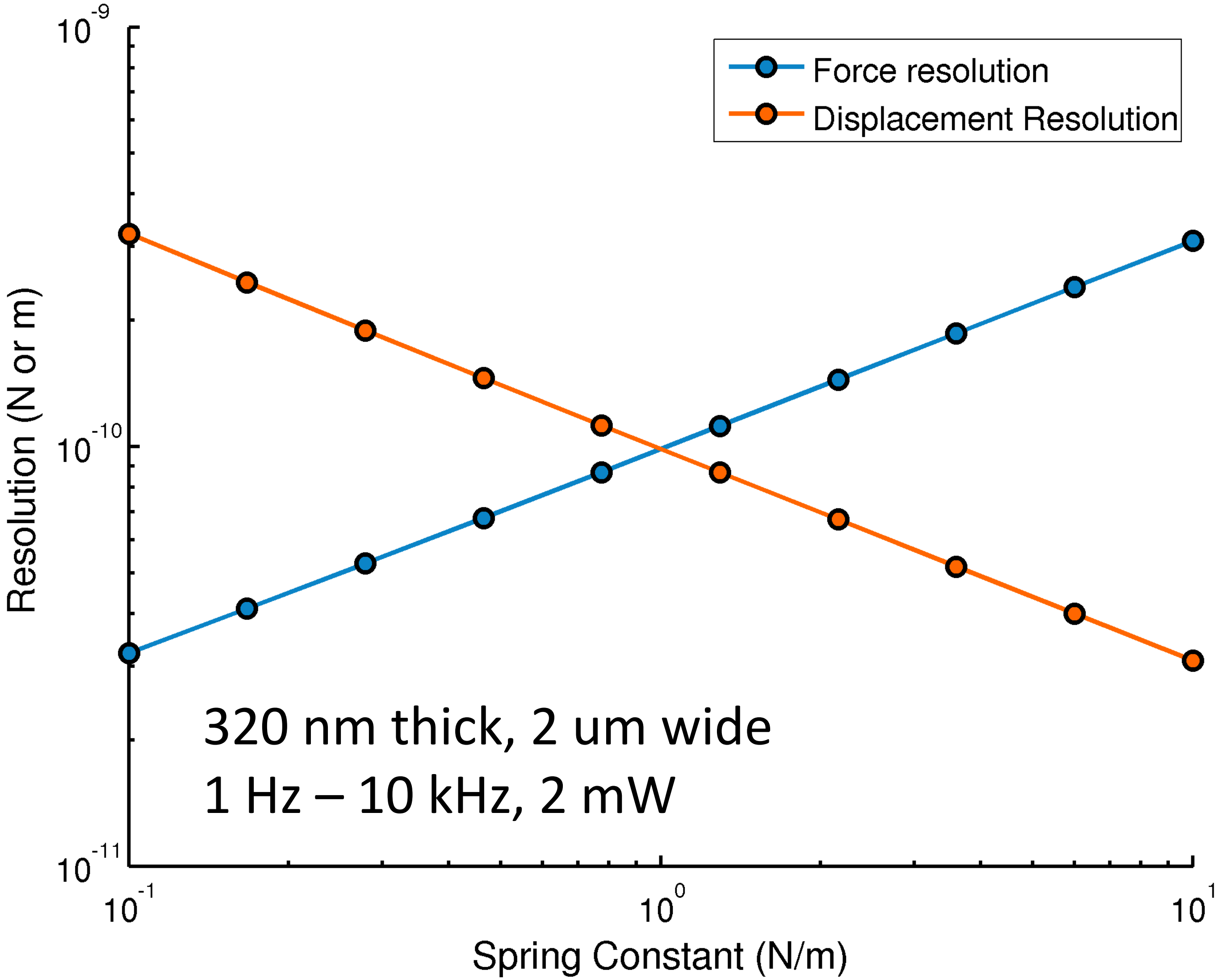


Al interconnects
w/ 10-30 um square via

Sensitivity

- Have had measurement issues
- Fixed PR output independent of wheatstone bridge bias voltage
- Devices optimized for high force sensitivity, low displacement sensitivity (i.e. long, soft levers)
- Piezoelectric shaker voltage couples to piezoresistor input (microvolts/nm)
- If displacement sensitivity isn't high enough, the PR signal is overwhelmed by the cross-talk signal

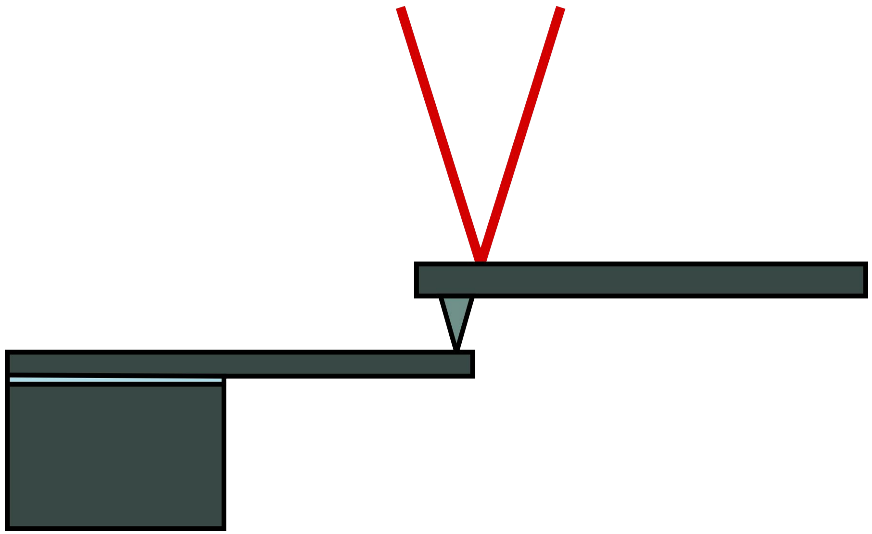
Force vs. Displacement Tradeoff



New Experiment Plan

- AFM solves cross-talk problem
- But can't bounce the laser off of my devices

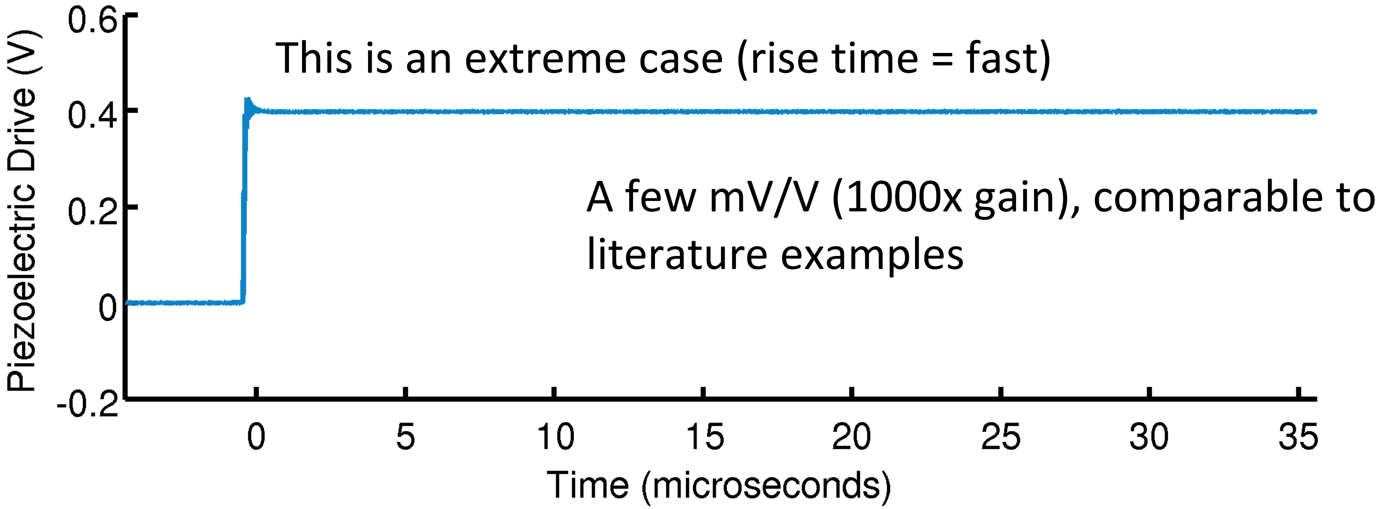
- Solution: mount the PR cantilever as a sample
- Can use for sensitivity, feedback

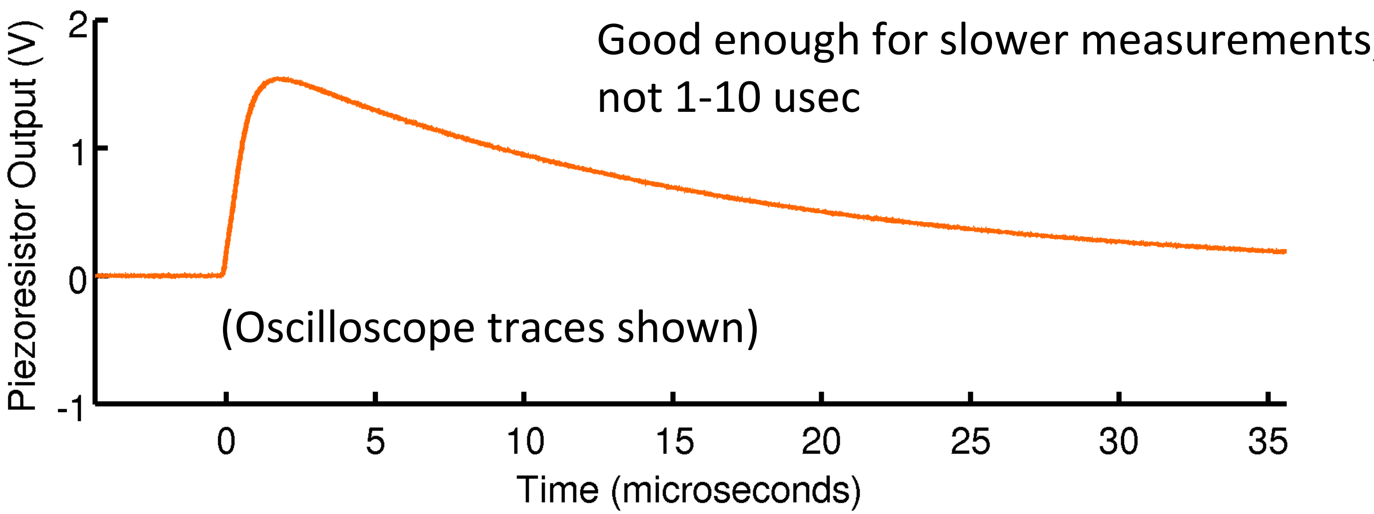


PE, PR Crosstalk

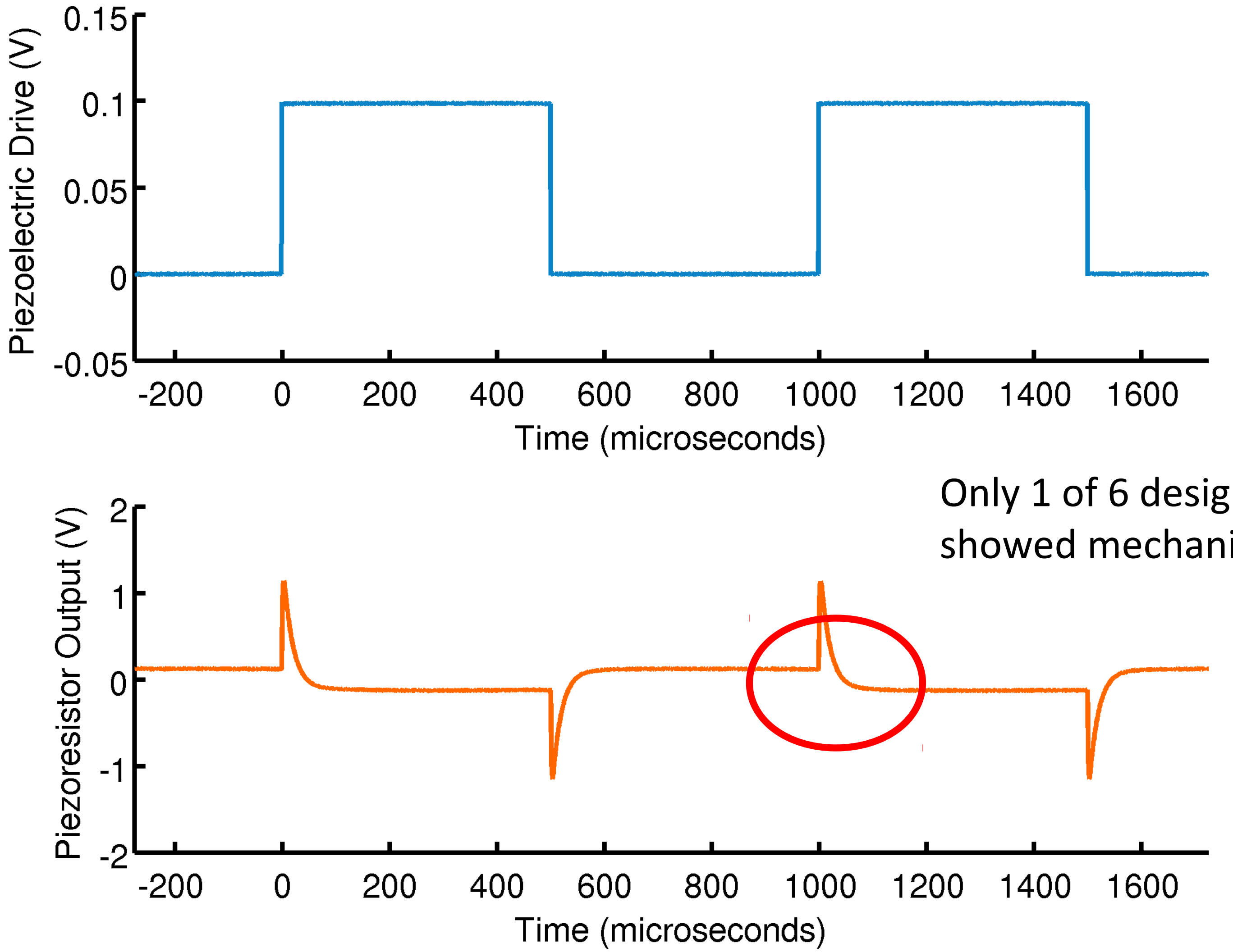
- Sensitivity and noise are great, but crosstalk could be the limiting factor
- Possible mechanisms
  - Capacitive: worse at higher frequencies, due to changing voltages in vicinity of each other
  - Mechanical: Piezoelectric bending changes piezoresistor resistance

There is capacitive crosstalk



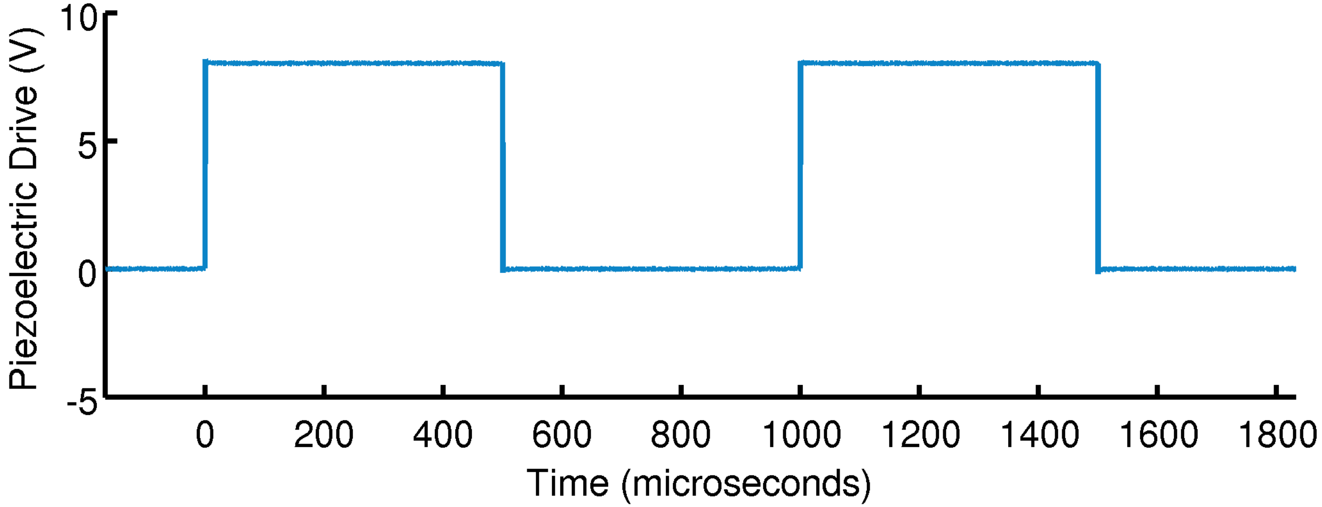


Some mechanical crosstalk

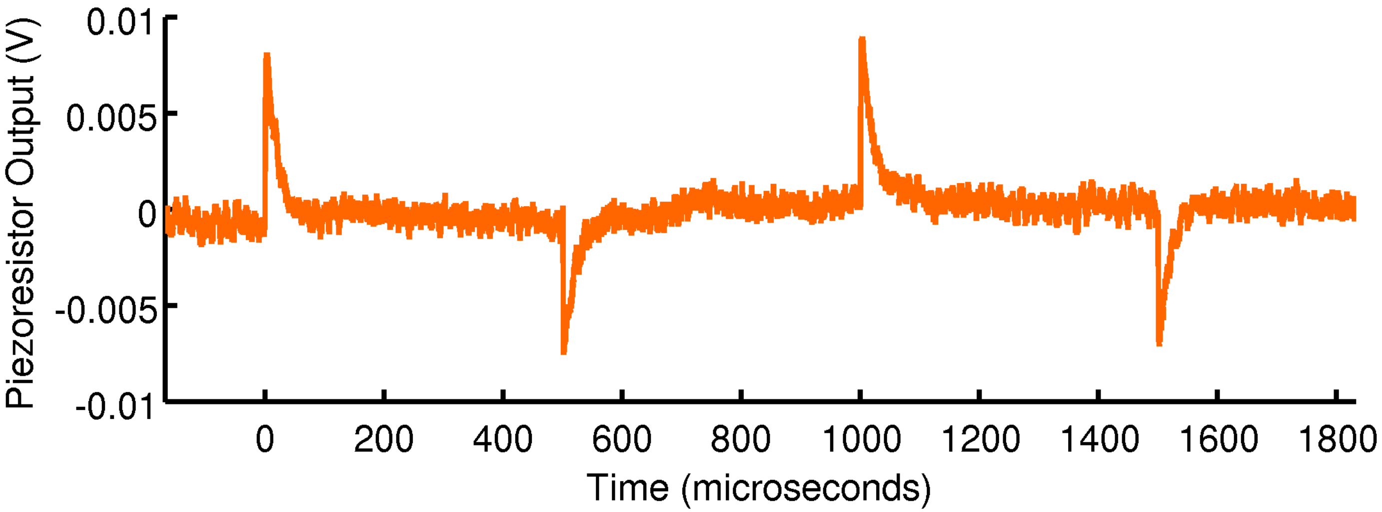


Only 1 of 6 designs tested
showed mechanical crosstalk

Minimal crosstalk from PCB

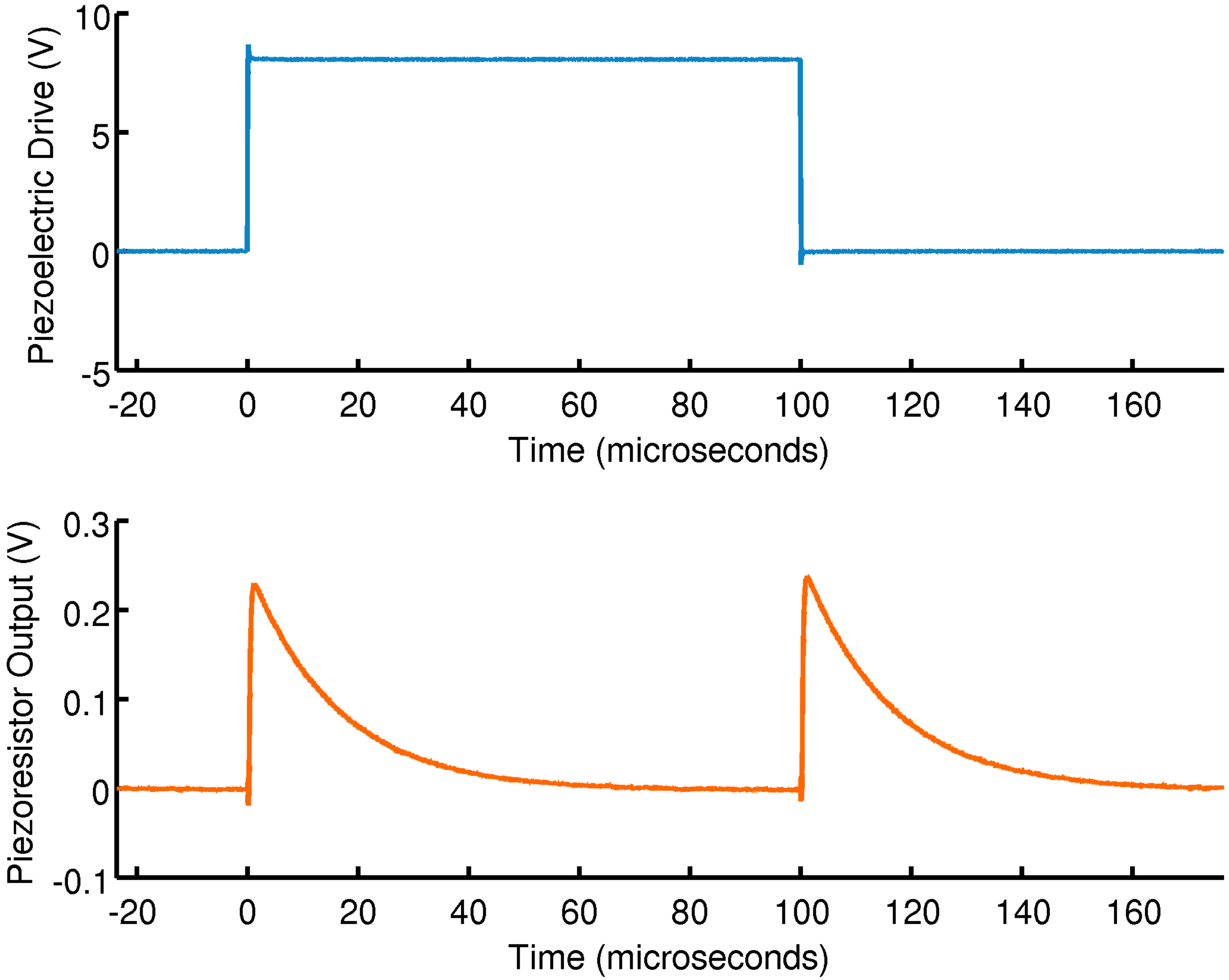


Connected discrete resistors and capacitors in place of the cantilever



Also no crosstalk from the cable (shielded)

Some crosstalk from cantilever PCB



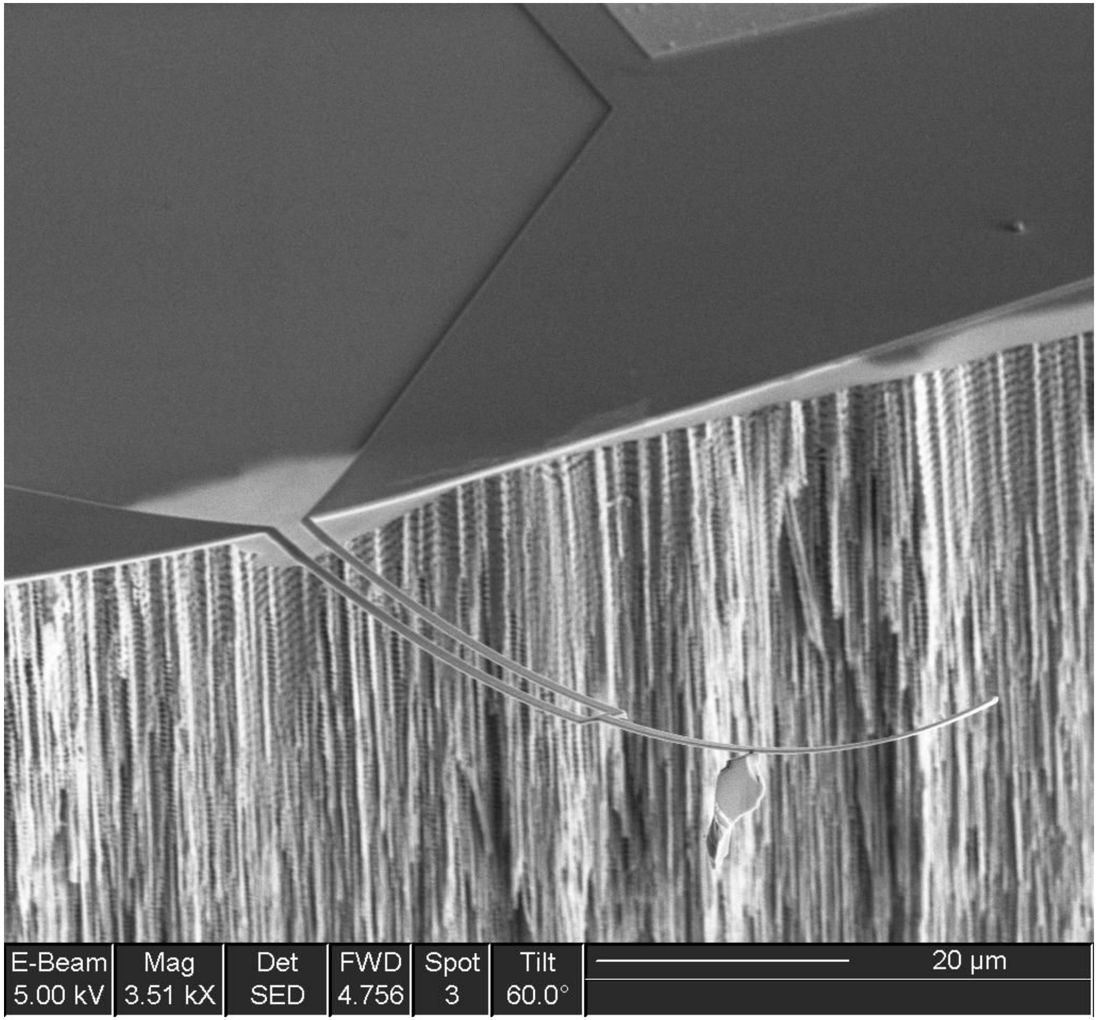
Connected cantilever PCB, shorted the bondpads by wirebonding

Crosstalk – What next?

- Modeling required
- Affects highest speed measurements, not bad enough to stop system development
- Slower measurements (msec) fine
- Possible solution: compensation on silicon die by placing piezoelectric next to temperature compensation PR

Bending Stress

Why?



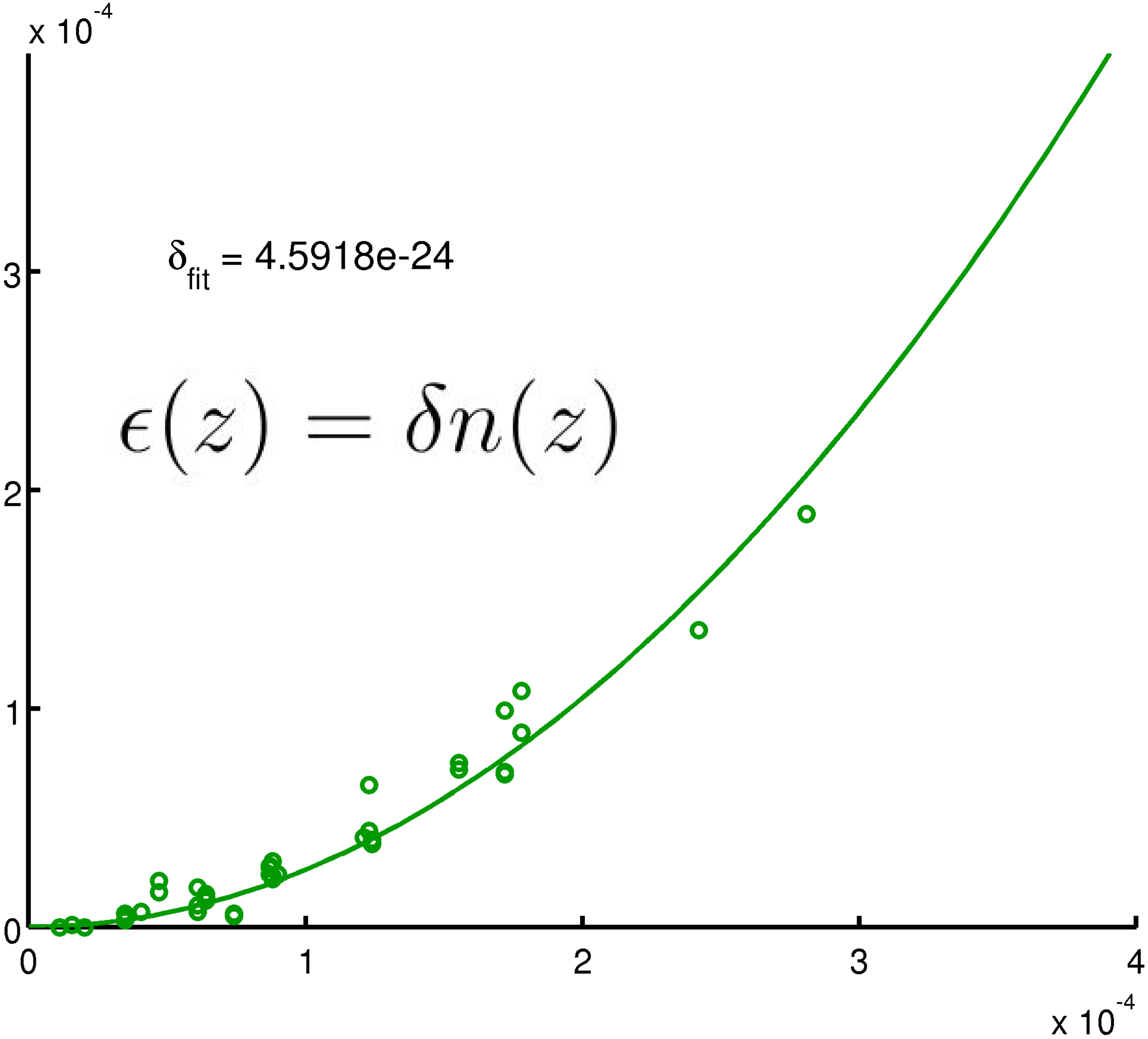
How Big is an Atom?

Atomic radii (pm)

Group (vertical) / Period (horizontal)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	H 25																	He
2	Li 145	Be 105											B 85	C 70	N 65	O 60	F 50	Ne
3	Na 180	Mg 150											Al 125	Si 110	P 100	S 100	Cl 100	Ar
4	K 220	Ca 180	Sc 160	Ti 140	V 135	Cr 140	Mn 140	Fe 140	Co 135	Ni 135	Cu 135	Zn 135	Ga 130	Ge 125	As 115	Se 115	Br 115	Kr
5	Rb 235	Sr 200	Y 180	Zr 155	Nb 145	Mo 145	Tc 135	Ru 130	Rh 135	Pd 140	Ag 160	Cd 155	In 155	Sn 145	Sb 145	Te 140	I 140	Xe
6	Cs 260	Ba 215	*	Hf 155	Ta 145	W 135	Re 135	Os 130	Ir 135	Pt 135	Au 135	Hg 150	Tl 190	Pb 180	Bi 160	Po 190	At	Rn
7	Fr	Ra 215	**	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Uub	Uut	Uuq	Uup	Uuh	Uus	Uuo
Lanthanides	*	La 195	Ce 185	Pr 185	Nd 185	Pm 185	Sm 185	Eu 185	Gd 180	Tb 175	Dy 175	Ho 175	Er 175	Tm 175	Yb 175	Lu 175		
Actinides	**	Ac 195	Th 180	Pa 180	U 175	Np 175	Pu 175	Am 175	Cm	Bk	Cf	Es	Fm	Md	No	Lr		

From Wikipedia: http://en.wikipedia.org/wiki/Atomic_radius

Cantilever Tip Deflection

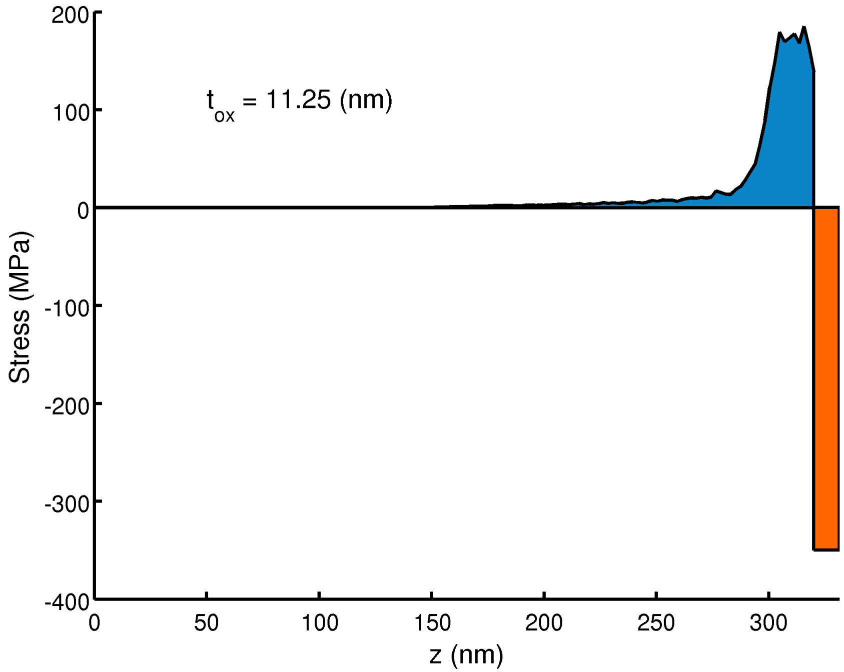


Compensation Strategy

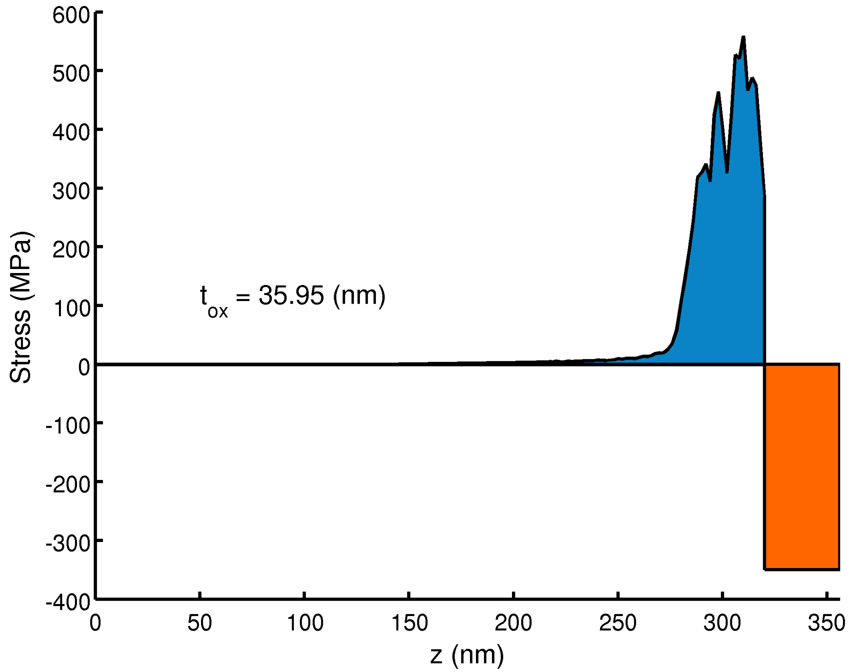
- Solution for tensile stress at the top surface
  - Tensile at the bottom
  - Compressive at the top
- SiO_2 is ideal
  - E = 80 GPa
  - Stress = 350 MPa
- But how?
  - Thermal: Consumes Si, thermal budget (more diffusion)
  - LTO: Poor uniformity, time to deposit thin layers
  - PSG: Thickness control, unknown parameters
- How much oxide thickness?

Compensation Oxide

800C, 35 minutes



850C, 15 minutes

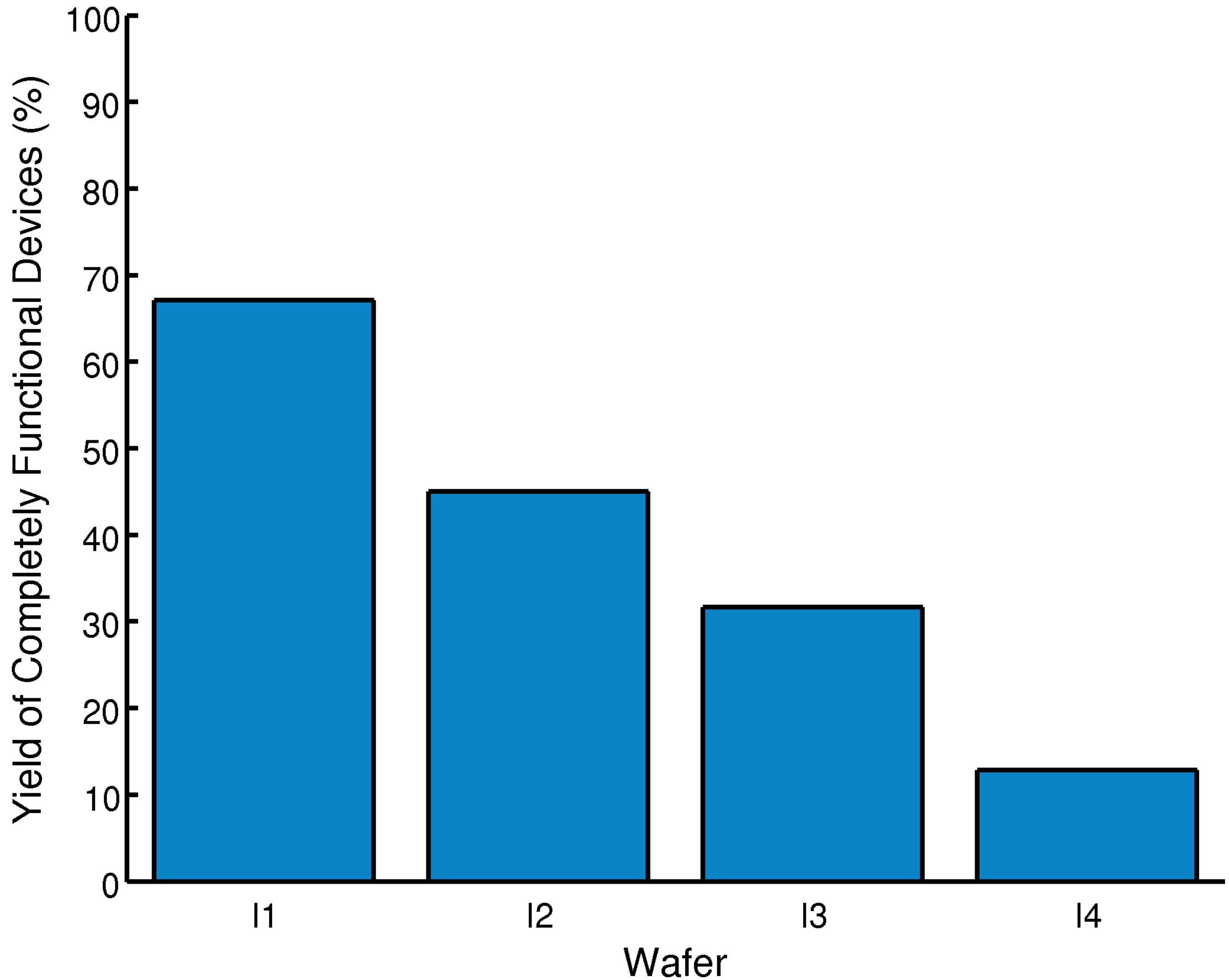


$$\sum M = \sum_i \int (z - \bar{z})\sigma_i dA$$

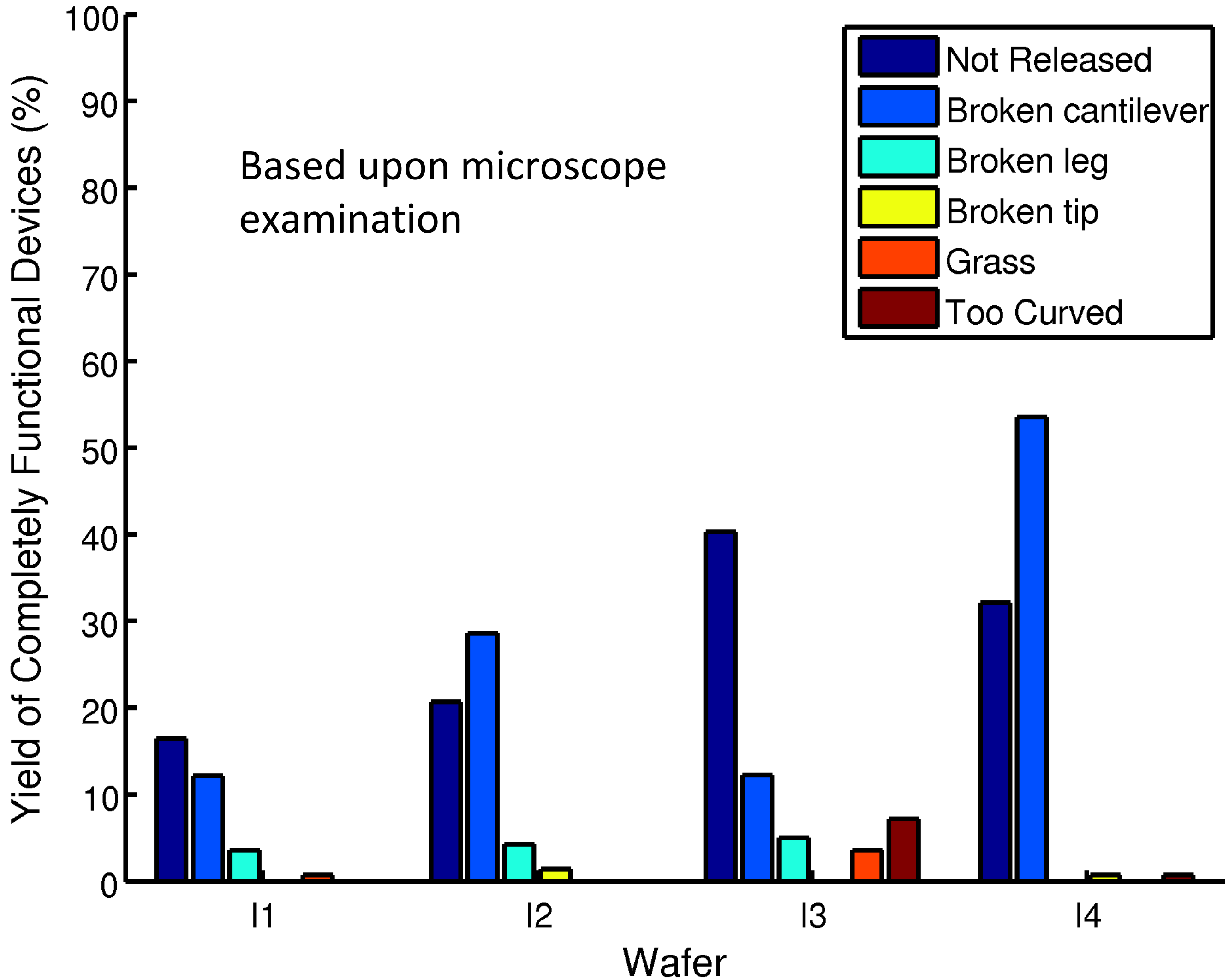
$$\boxed{t_{oxide}^2\left(\frac{\sigma_{oxide}}{2}\right) + t_{oxide}\left(\frac{t_{si}\sigma_{oxide}}{2}\right) + \int_0^{t_{si}} (z - \frac{t_{si}}{2})\sigma_{si}(z)dz = 0,}$$

$$0 = w_{si}\int_0^{t_{si}} (z - \bar{z})\sigma_{si}(z)dz + w_{oxide}\int_{t_{si}}^{t_{si}+t_{oxide}} (z - \bar{z})\sigma_{oxide}dz$$

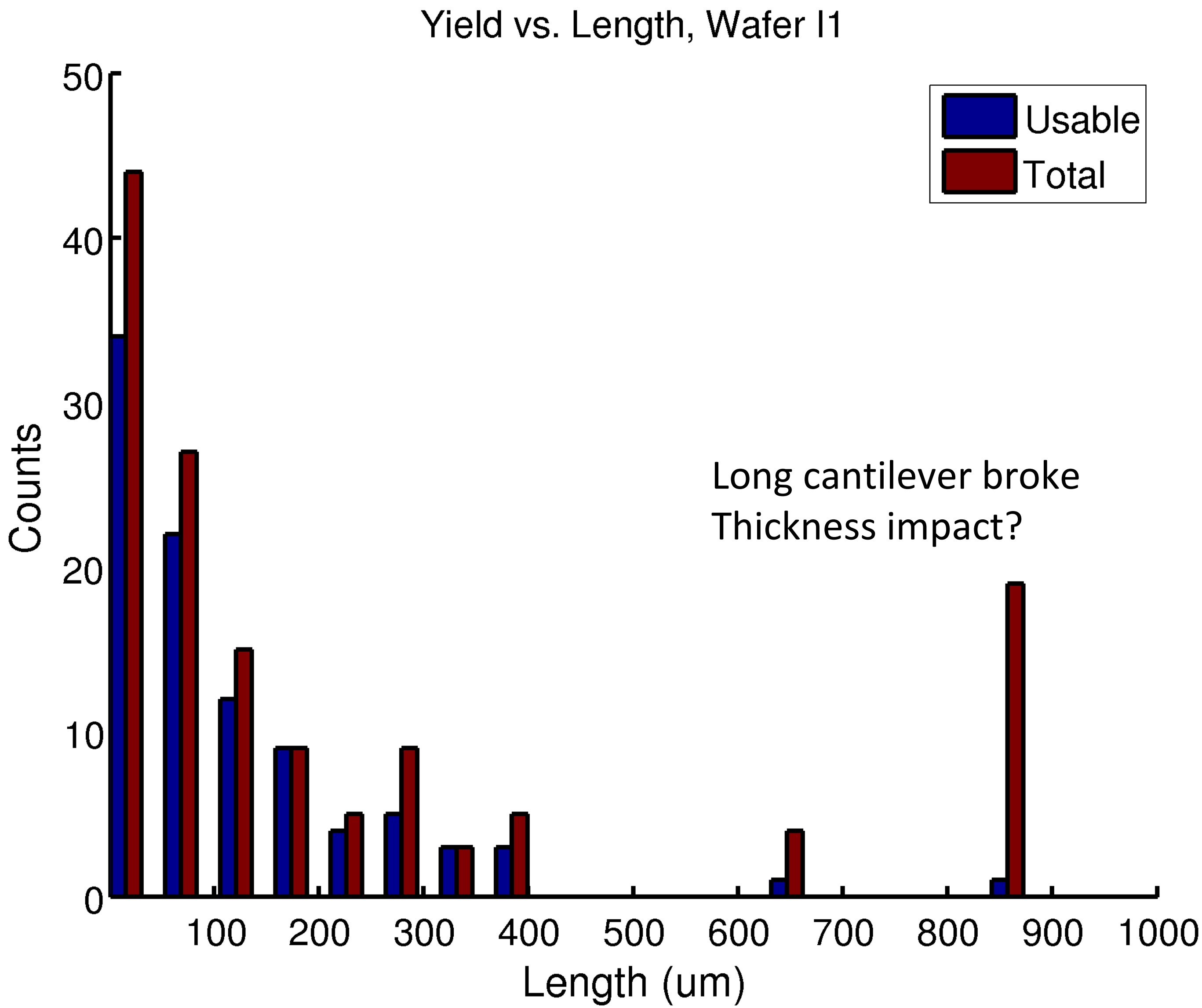
Postmortem on PR Fab



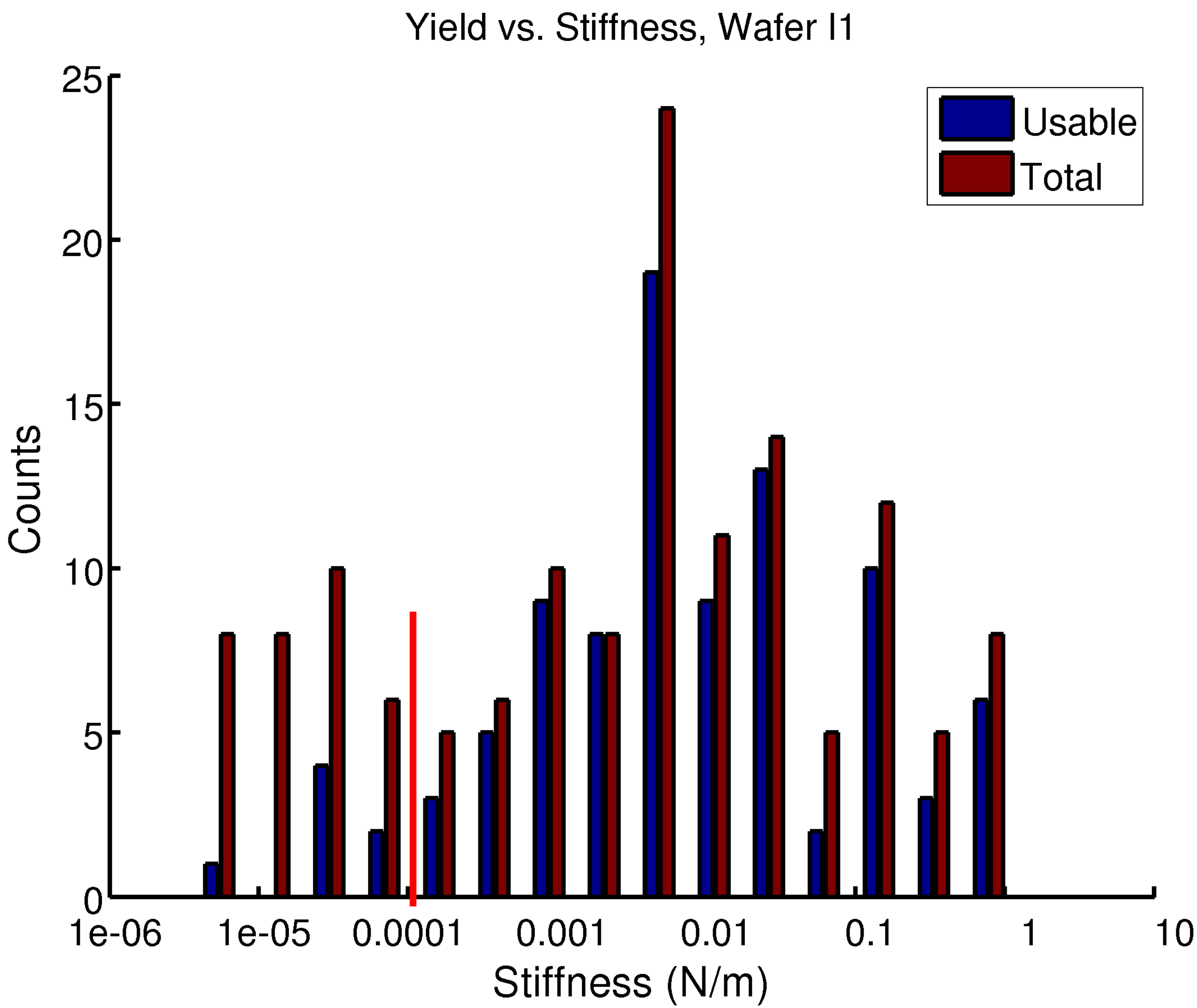
Failure types



Which designs broke?



Which designs broke?



Conclusions

- Piezoresistors are noisier, higher resistance than expected, but minimal impact on performance
- There is electrical crosstalk on the microsecond scale
- Devices usable for system testing and some measurements
- Usual sensitivity calibration method doesn't work for (some) devices, will start doing some characterization on the AFM

What's Next?

- Sensitivity, feedback testing on AFM
- System prep for bio experiments
- Fab 2.0