Research Update

Joey Doll

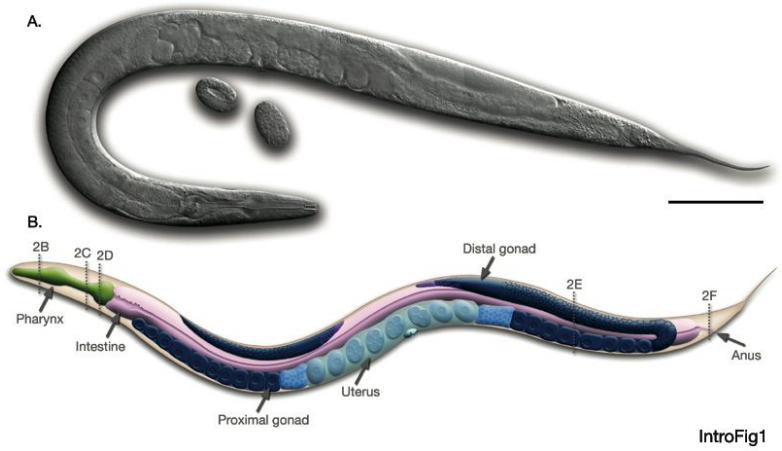
Worm Touch Meeting

6/17/2009

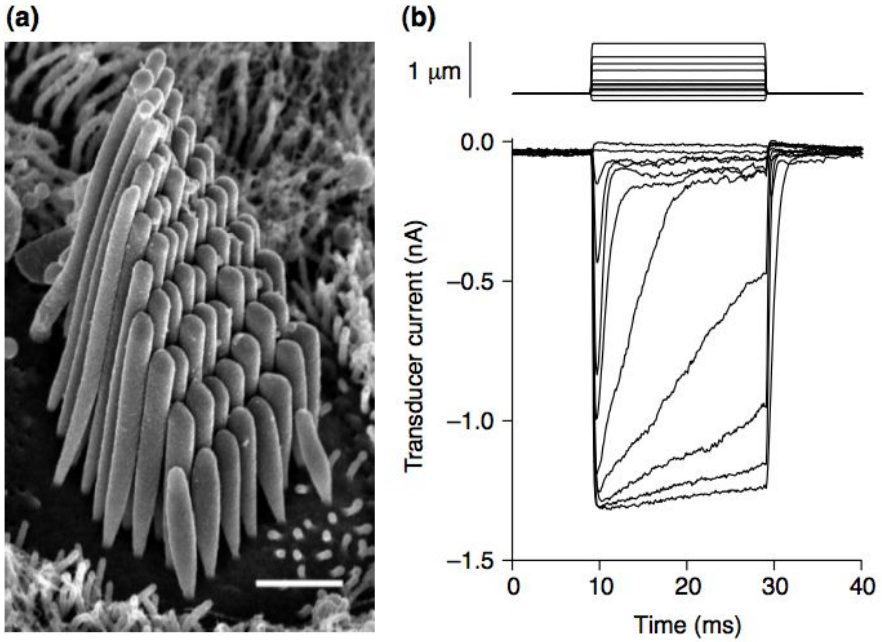
Overview

- Motivation / Device Overview
- What I've Been Up To
- Current Status

Motivation



Worm TRNs



Turtle hair cell

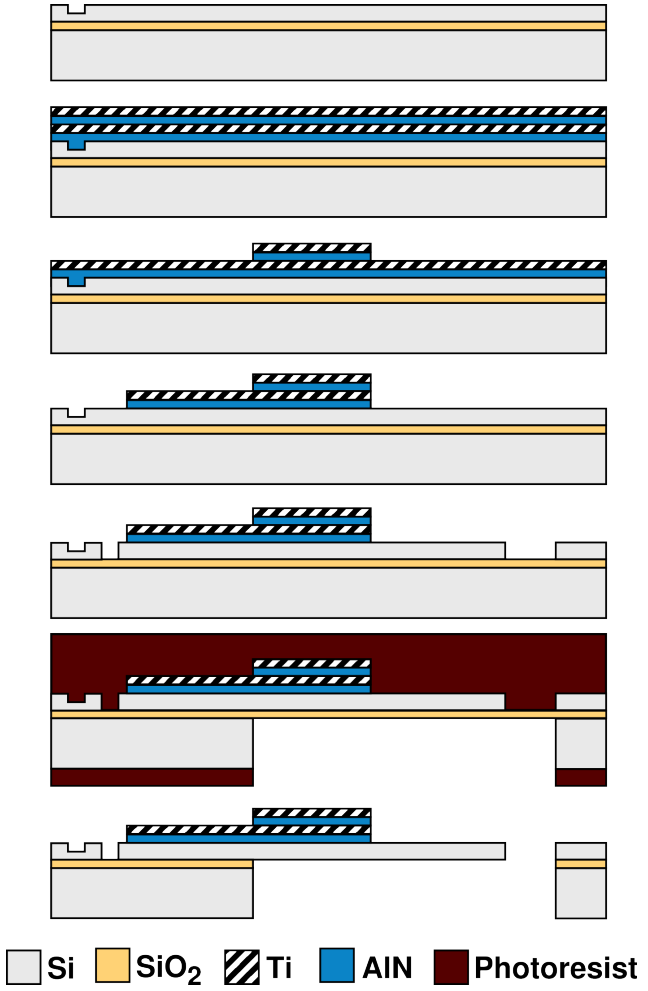
Clues to the cochlear amplifier from the turtle ear, Fettiplace, Ricci and Hackney, 2001

Performance Goals

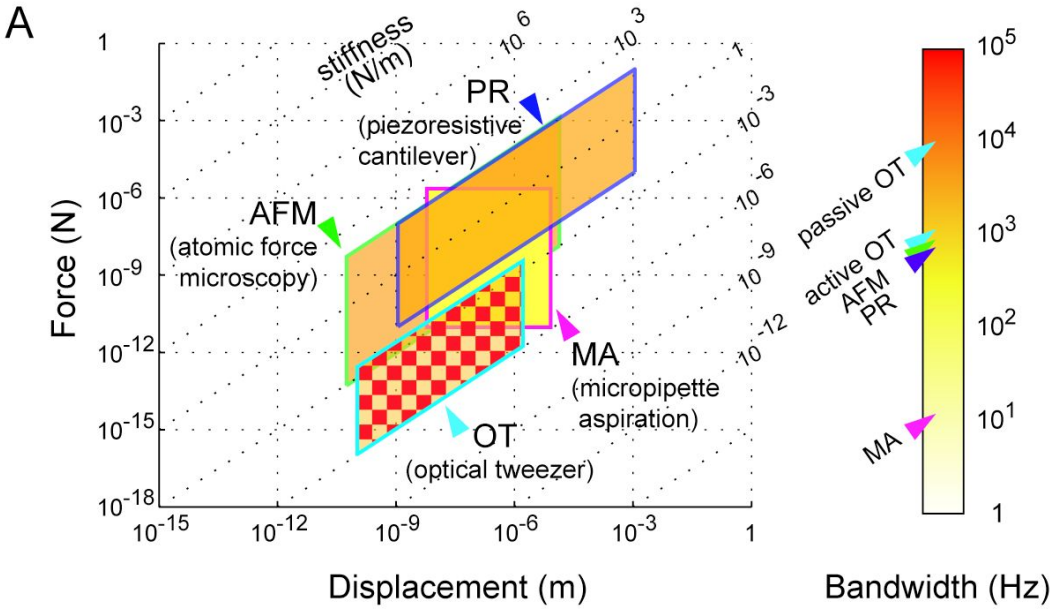
- 100 pN force resolution in 1 Hz – 50 kHz bandwidth
- 10 microsecond rise time, 500nm tip displacement
- Closed loop force control
- Operation in fluid
- (Aiming for the mammalian hair cell)

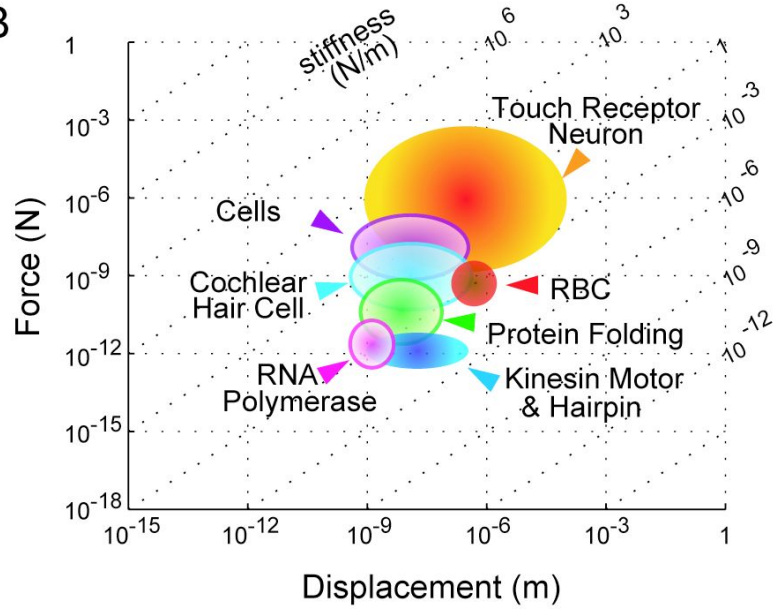
Why MEMS?

- Small → high frequency, low stiffness
- Batch fabrication
- All electronic (no optics required)
- Can design devices over a range of size, stiffness (lithographic process)
- Easy manipulation of probe position



Force Sensing Techniques





Park et al, PNAS 2007

Piezoresistivity in Silicon

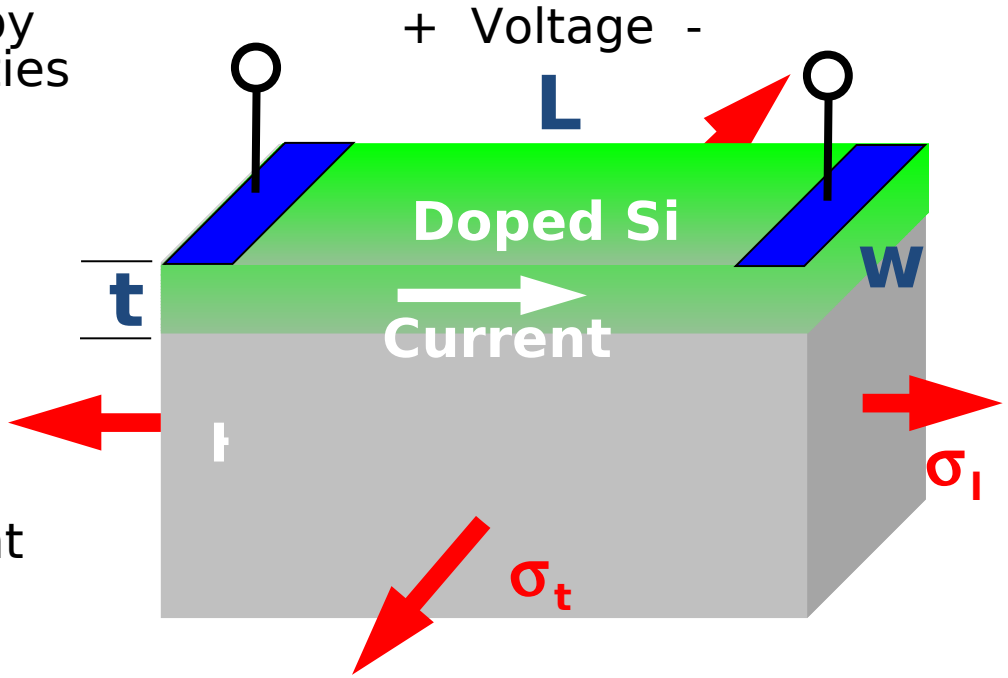
- Resistor elements fabricated by selectively introducing impurities (doping)
- Resistance of a doped silicon region is given by

$$R = \rho \frac{L}{wt}$$

- In piezoresistive materials like doped Si, ρ is stress-dependent

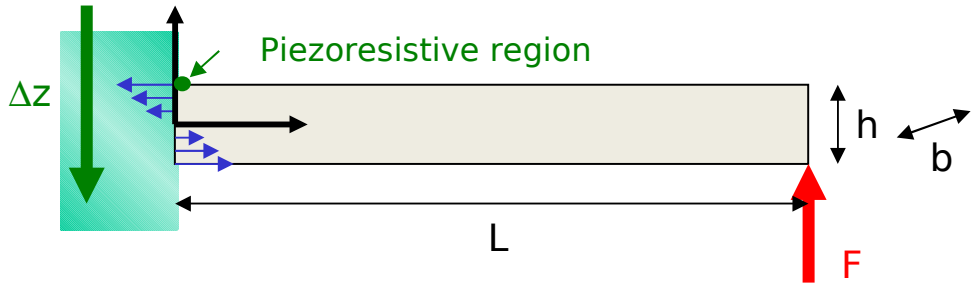
$$\frac{\Delta\rho}{\rho} = \pi_l \sigma_l + \pi_t \sigma_t$$

- Where π_l is the **longitudinal** piezoresistive coefficient
- And π_t is the **transverse** piezoresistive coefficient



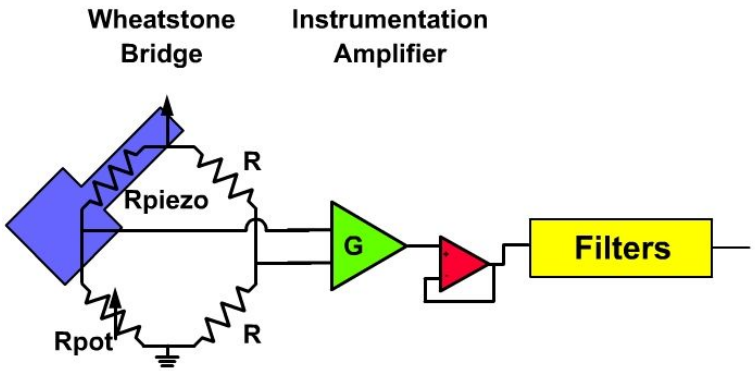
The simplest case: piezoresistors patterned so current flows in the direction of the uniaxial stress - only longitudinal components need to be considered.

Piezoresistive Force Sensing

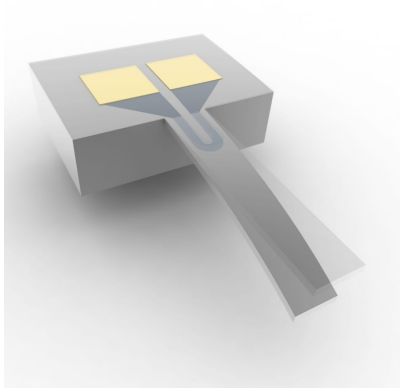


$$F = k\Delta z \qquad (k = \frac{3EI}{L^3} = \frac{Ebh^3}{4L^3})$$

$$V_{out} \cong G\frac{V_B \Delta R}{4R} \cong G\frac{3V_B \pi_L L}{2bh^2}F = GSF \qquad (S = \frac{3V_B \pi_L L}{2bh^2})$$



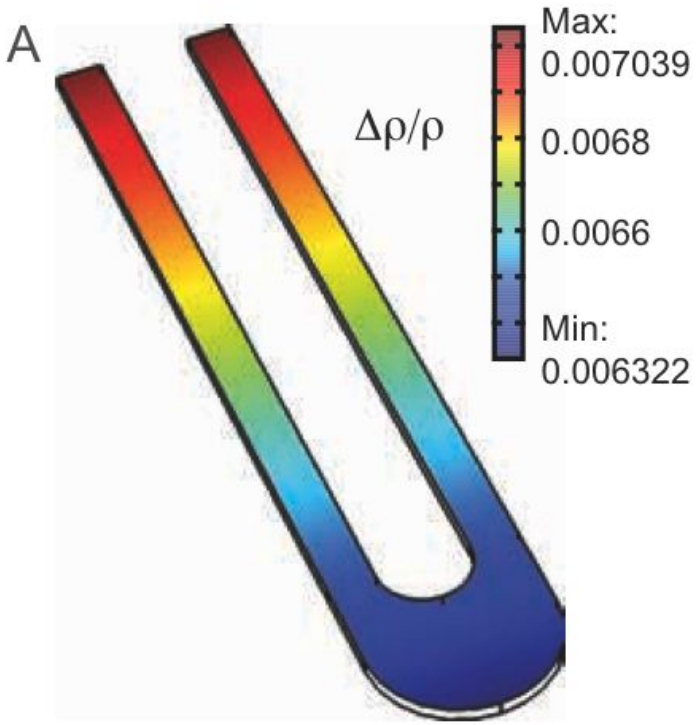
$$\frac{\Delta R}{R} \cong \pi_L \sigma \cong \frac{6\pi_L L}{bh^2}F$$



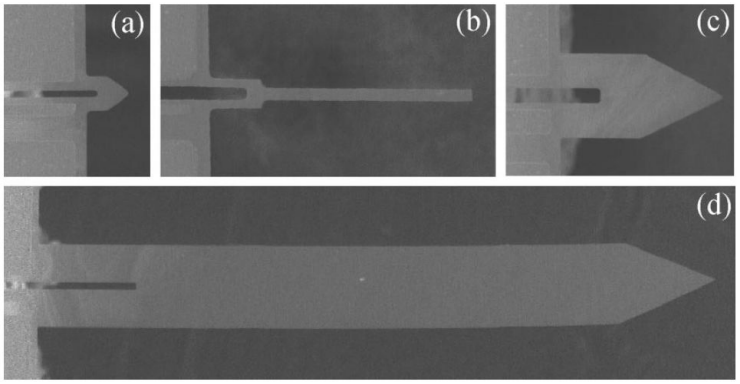
Slide modified from Sung-Jin Park, 2007

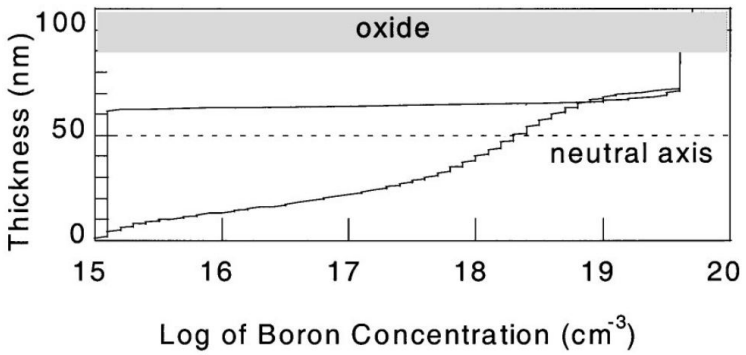
Piezoresistor Design

- Choices
  - Cantilever dimensions
  - Piezoresistor dimensions and process parameters
  - Dopant concentration
  - Bias voltage
- Given constraints
  - Frequency range
  - Measurement bandwidth

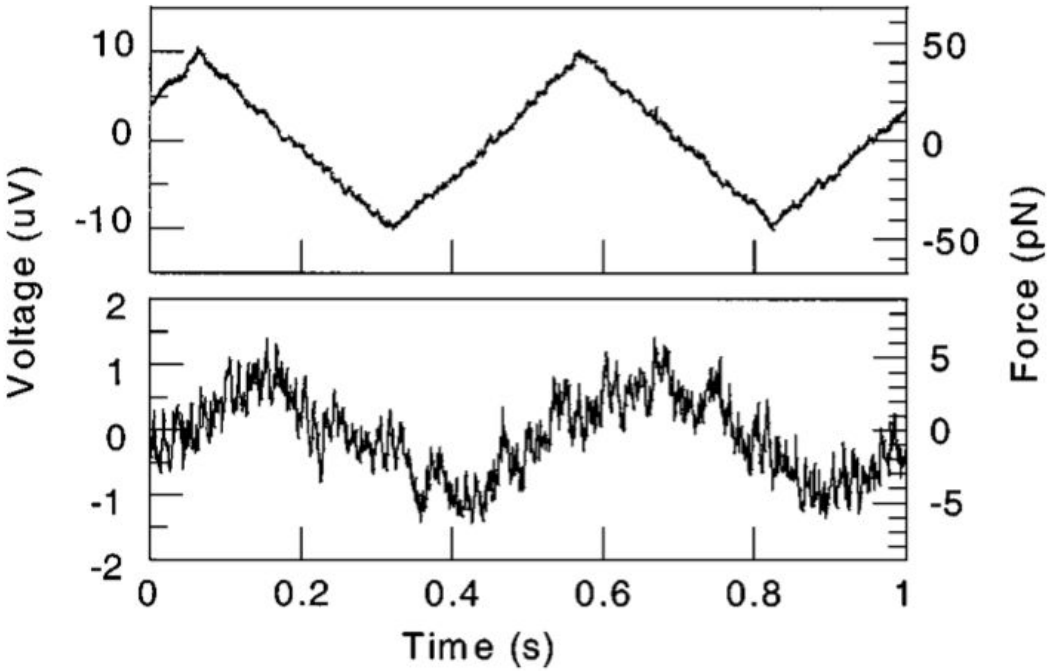


Example Device



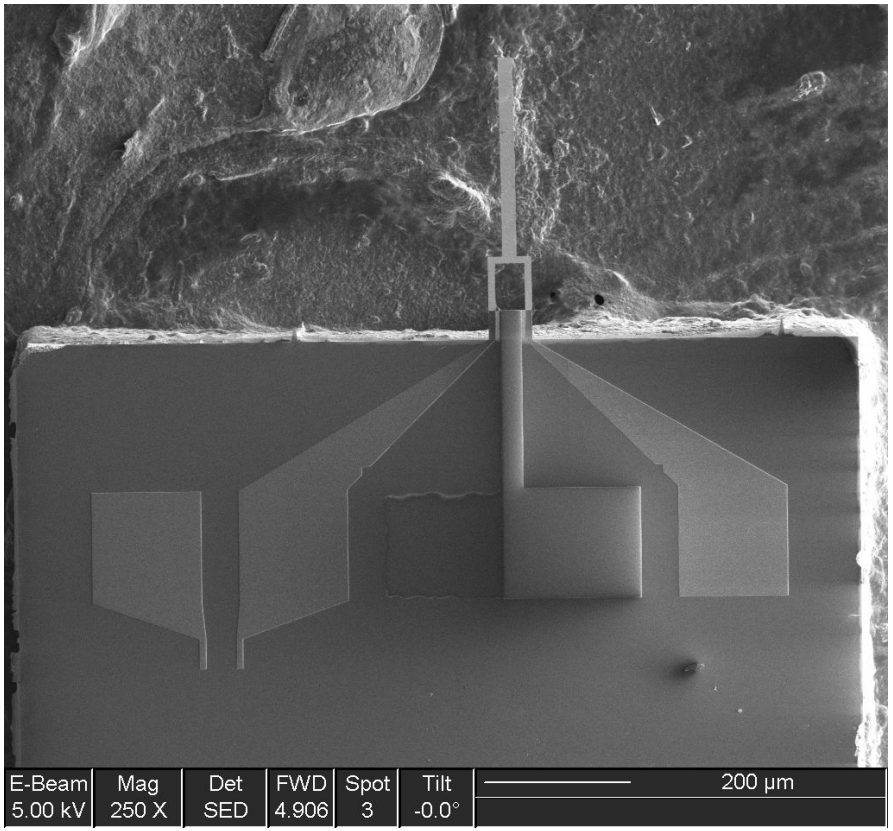


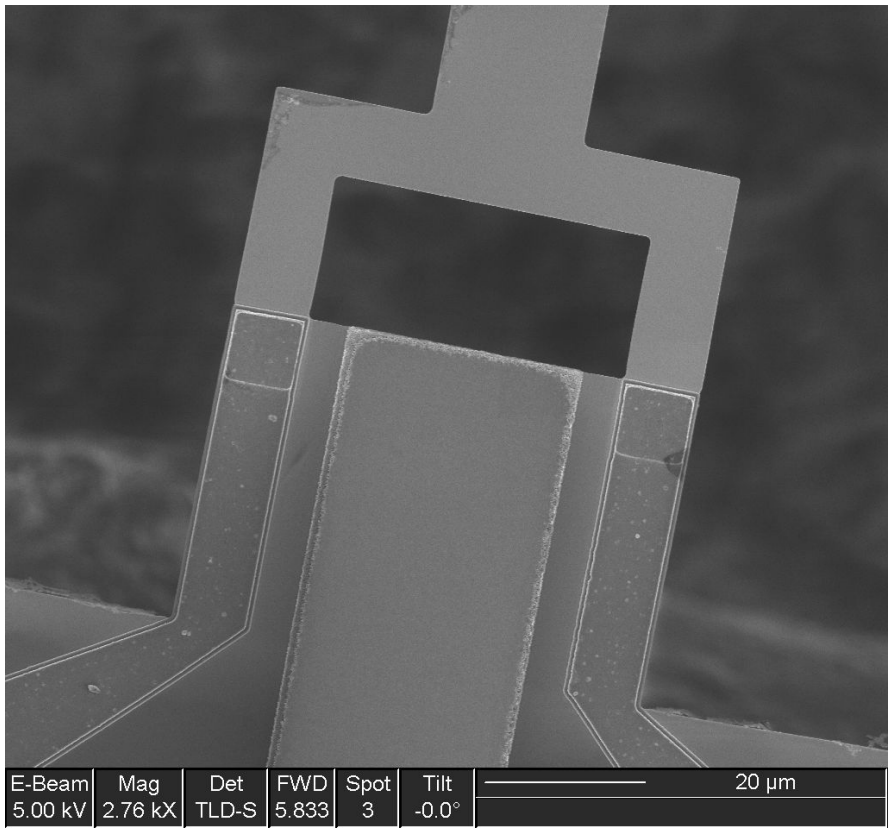
- 89 nm thick
- 500 fN resolution from 10Hz to 1kHz



High-sensitivity piezoresistive cantilevers under 1000A thick, Harley and Kenny, APL (1999)

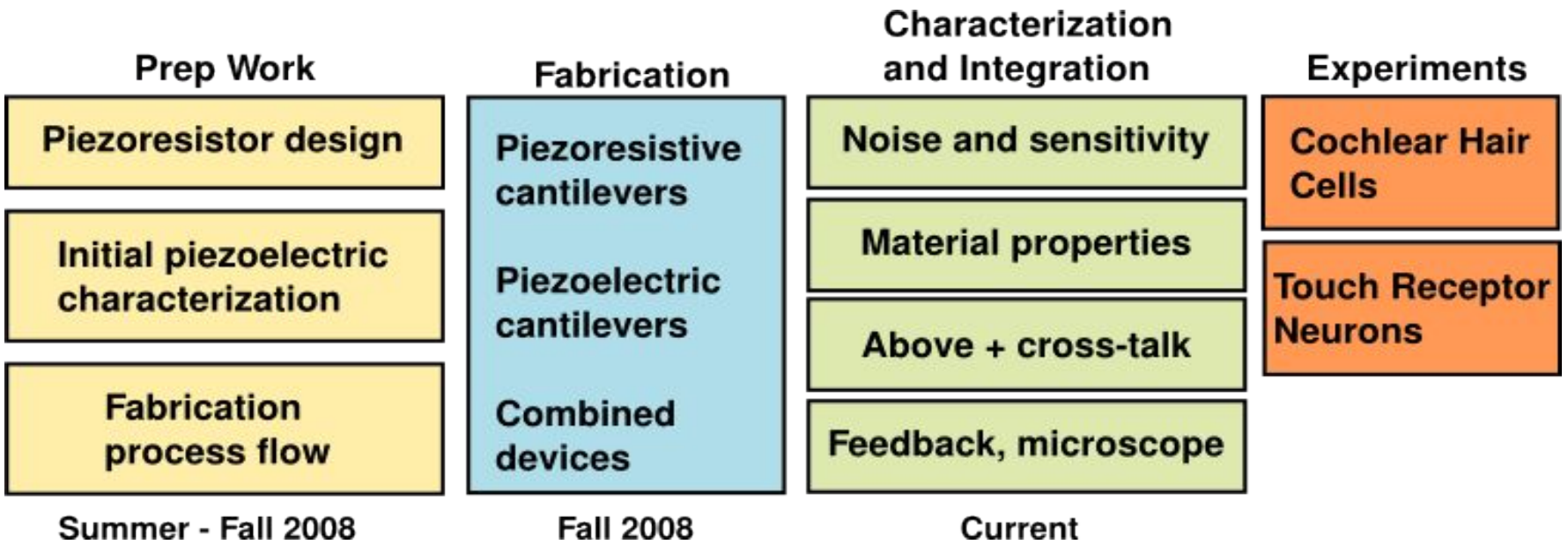
The Device



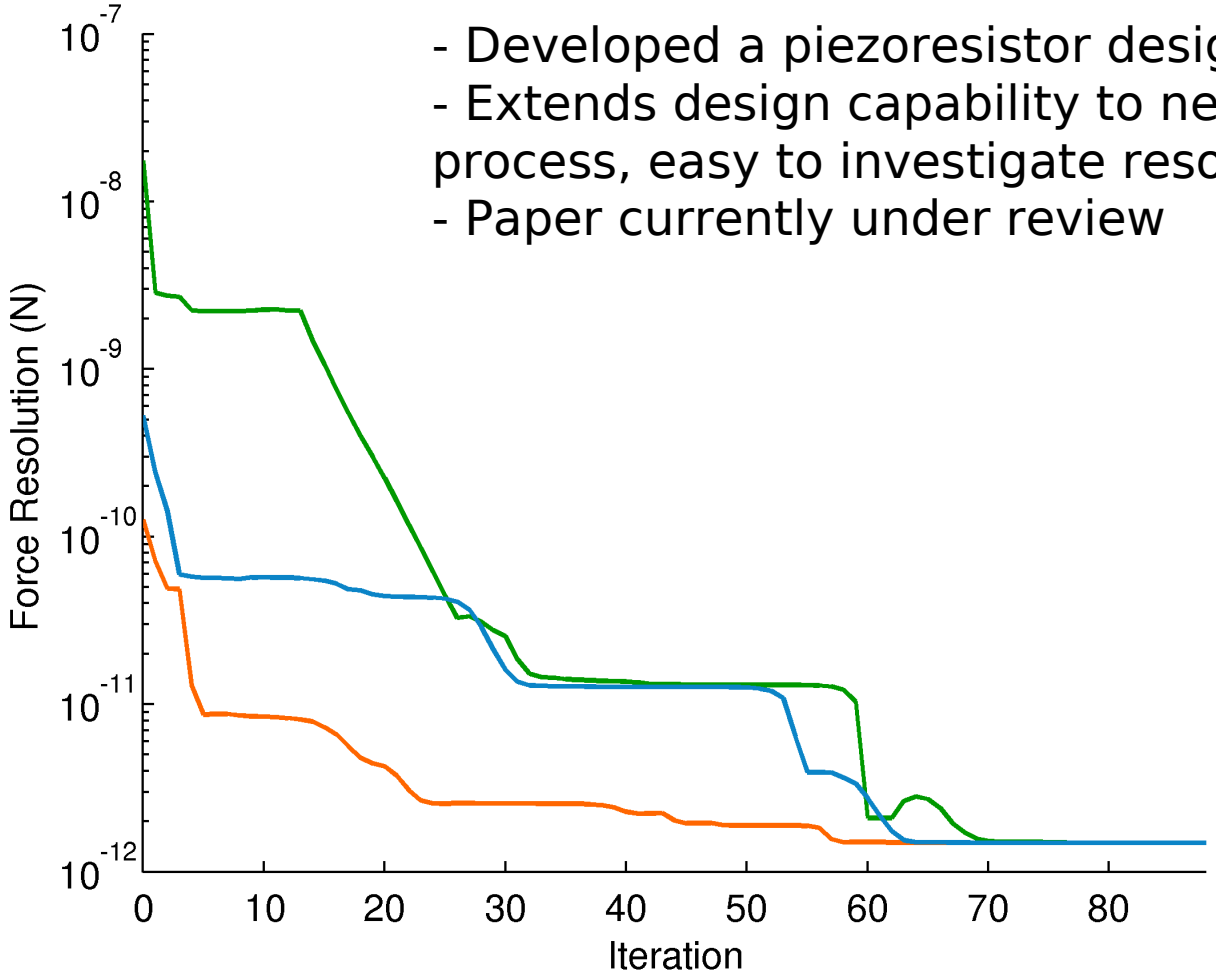


Piezoresistive force detection
Piezoelectric actuation

The Plan


Prep Work
Piezoresistor design
Initial piezoelectric characterization
Fabrication process flow
Summer - Fall 2008
Fabrication
Piezoresistive cantilevers
Piezoelectric cantilevers
Combined devices
Fall 2008
Characterization and Integration
Noise and sensitivity
Material properties
Above + cross-talk
Feedback, microscope
Current
Experiments
Cochlear Hair Cells
Touch Receptor Neurons

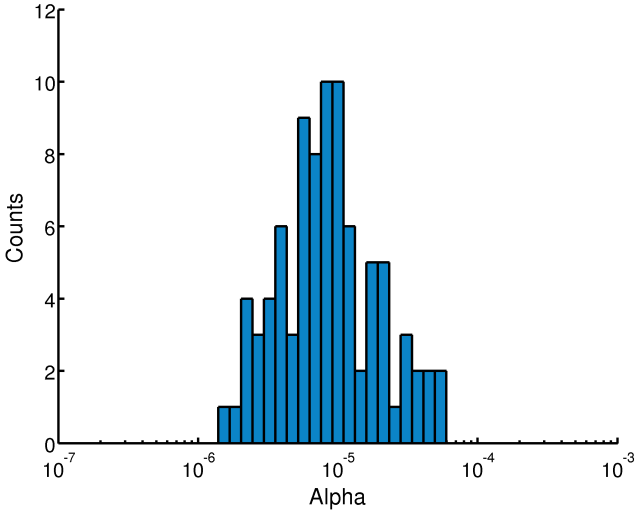
Piezoresistor Design

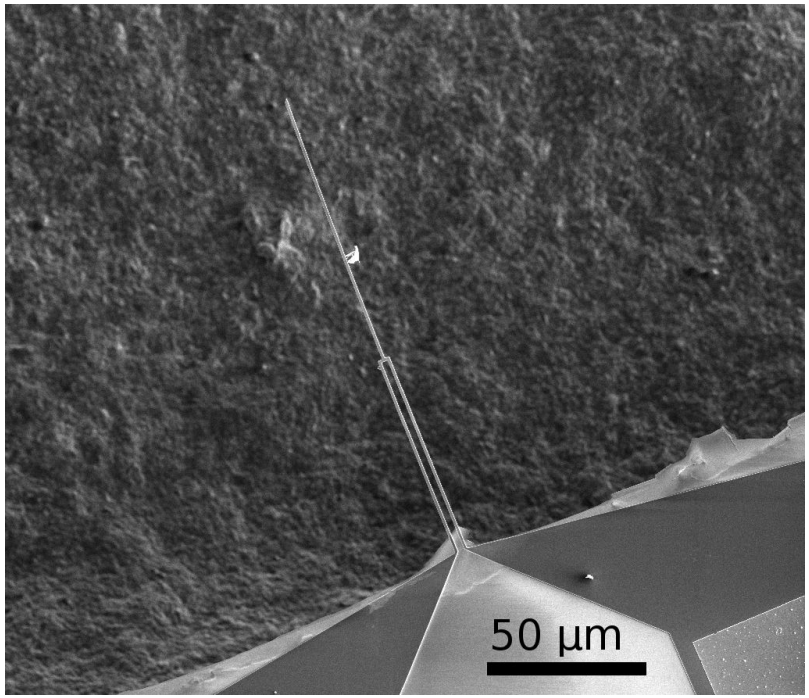


- Developed a piezoresistor design tool
- Extends design capability to new fabrication process, easy to investigate resolution limits
- Paper currently under review

Piezoresistive Cantilevers

- Fabricated force sensors (no built-in actuation) using the design tool
- Performance is mostly there, still need to do some additional measurements
- Small (high freq) cantilevers not so good, need to do additional experiments / update model.

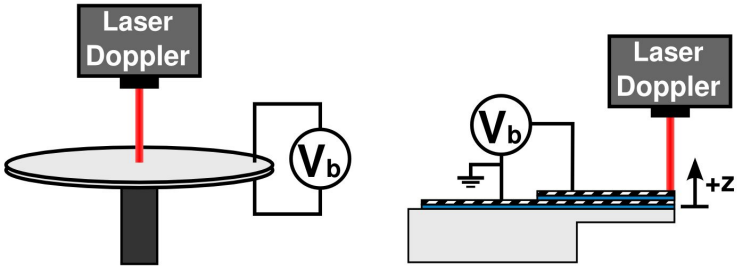




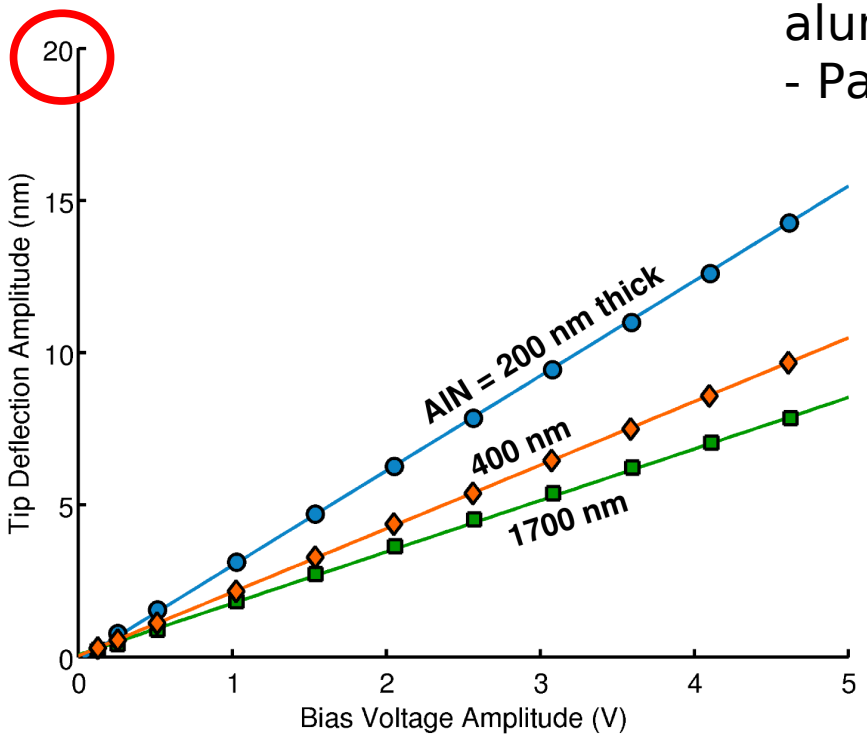
Design #	t (nm)	w (µm)	l (µm)	l_{pr} (µm)	w_{pr} (µm)	f_0 (kHz)
1	320	6	123	34	3	25.5
2	320	10	88	24	5	49.8
3	320	2	47	25	1	174.7
4	320	2	35	6	1	315

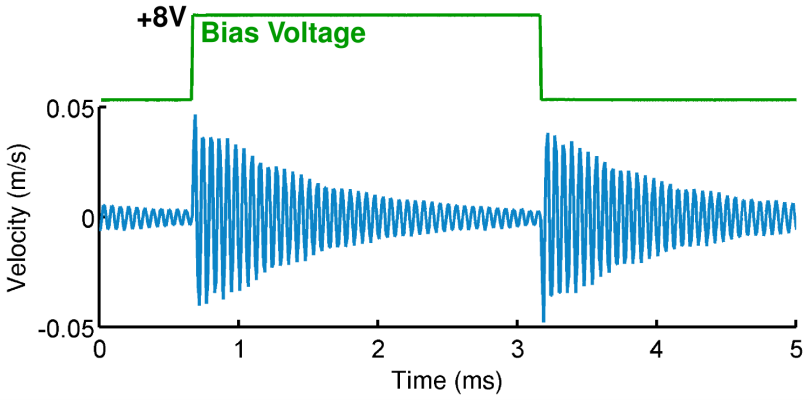
Design #	f_0 (kHz)	f_{max} (kHz)	R (kΩ)	F_{min} Theory (pN)	F_{min} Exp. (pN)
1	22	5	4.2	7.8	5.2
2	66.4	10	2.5	17.1	51.7
3	187.3	50	8.4	28.8	298
4	419.5	100	3.5	35.9	678

Piezoelectric Actuation

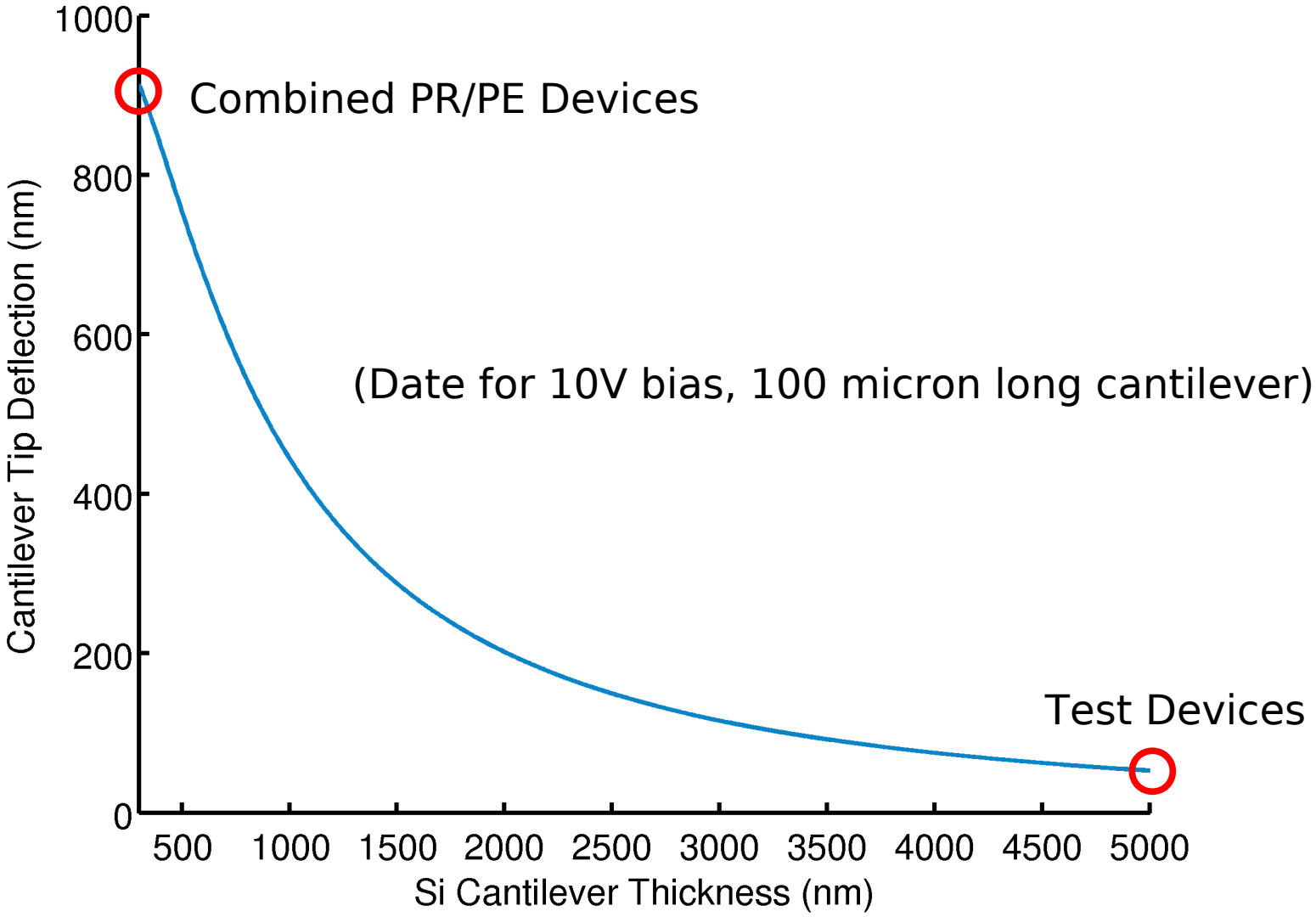


- Piezoelectrics are tricky to fabricate in MEMS processes (e.g. contamination)
- Needed a 'clean' process
- Developed/characterized a process for aluminum nitride (AlN) on Ti
- Paper almost ready to submit





Piezoelectric Actuation



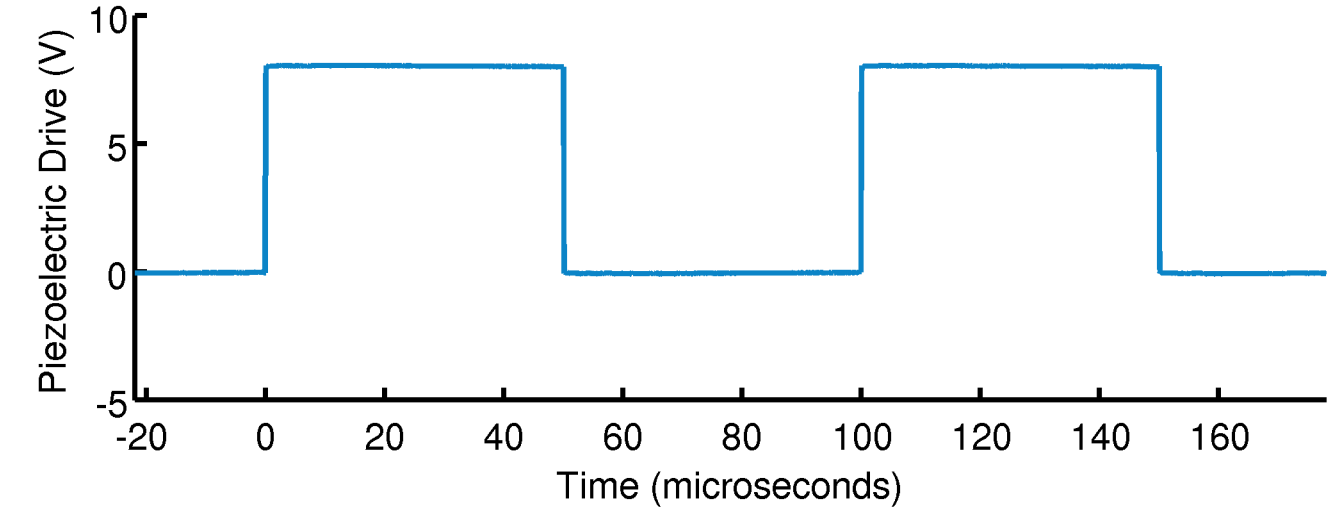
Summary So Far

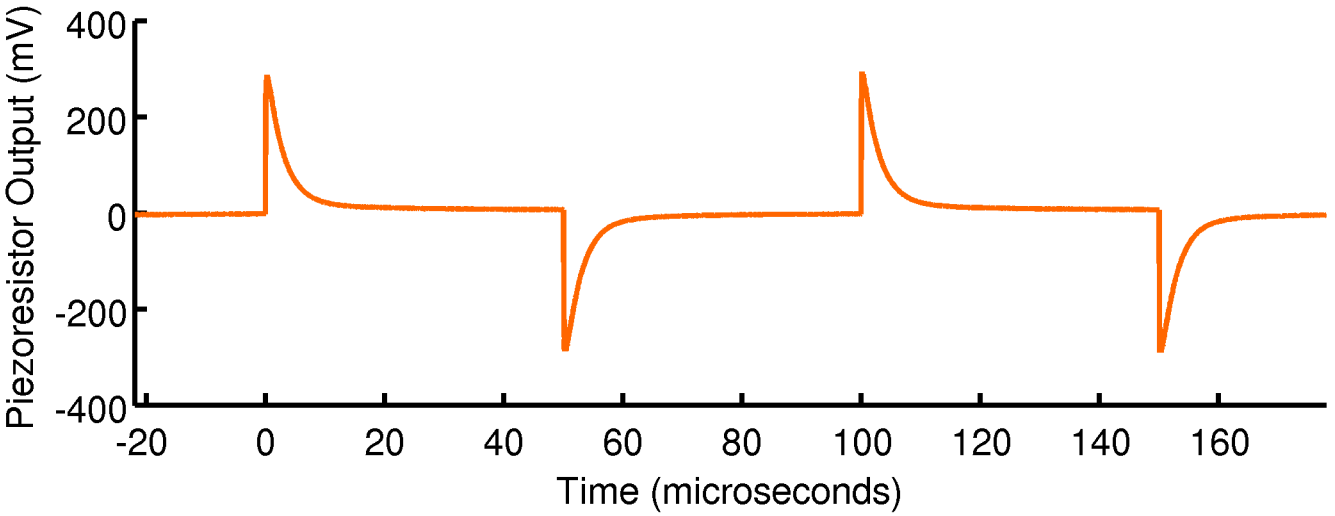
Pieces work well separately

- Piezoresistor
- Piezoelectric

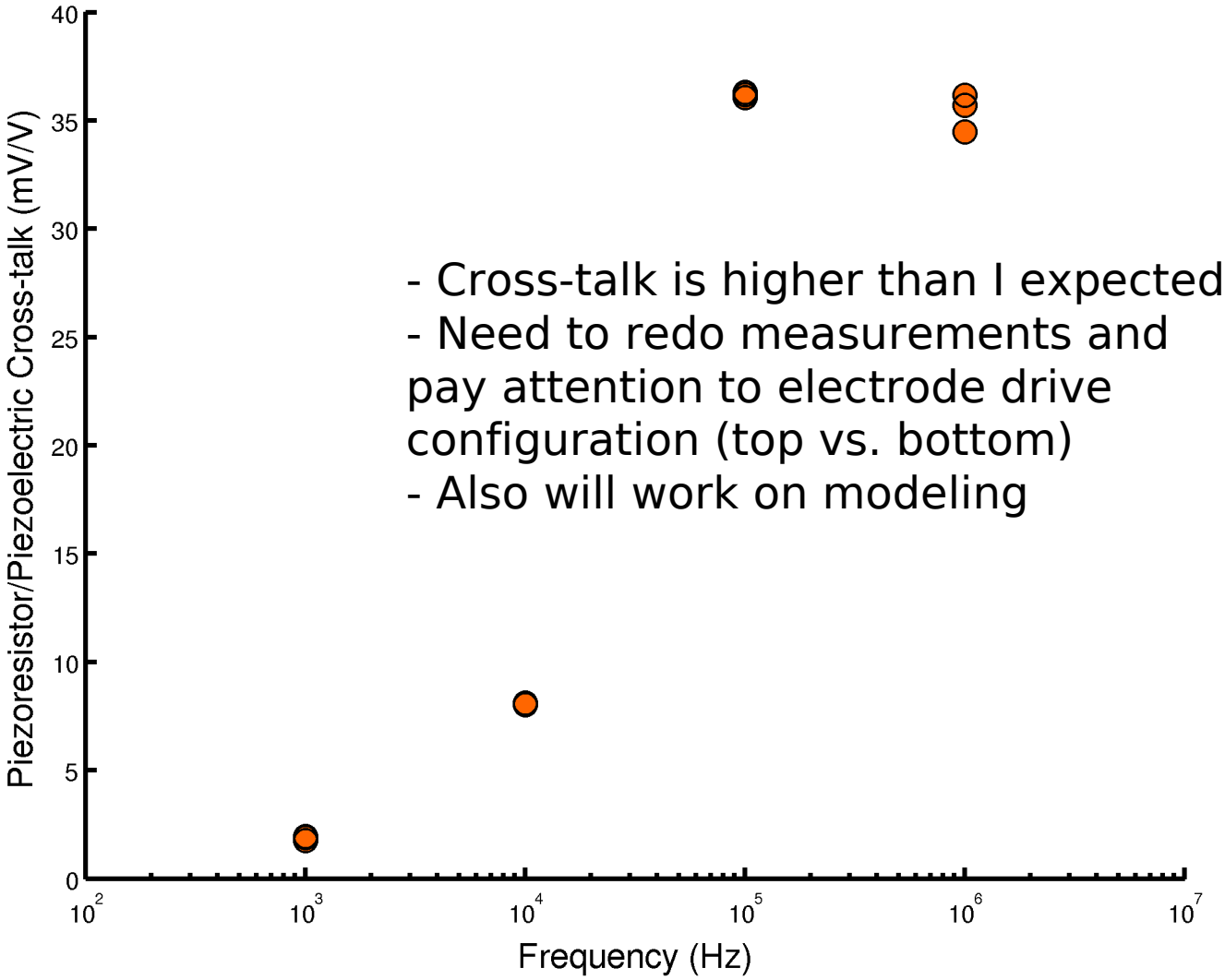
- What about together?
- Potential problems
  - Cross-talk
  - Fabrication incompatibilities
  - Feedback circuitry

PE – PE Cross-Talk





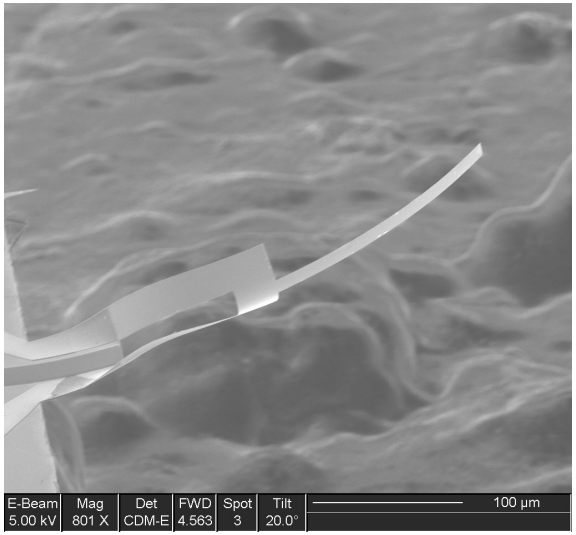
PE – PE Cross-Talk

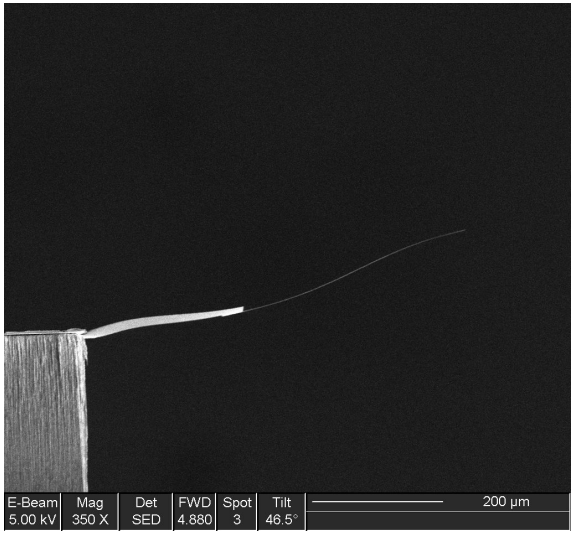


- Cross-talk is higher than I expected
- Need to redo measurements and pay attention to electrode drive configuration (top vs. bottom)
- Also will work on modeling

Process Compatibility

- Everything worked surprisingly well
- Some potential problems
  - Instrinsic stress
  - **Piezoresistor etching**
- Will have answer in next couple of weeks
- Worst case, another fab run is required → 2-3 months
  - Other improvements could be made



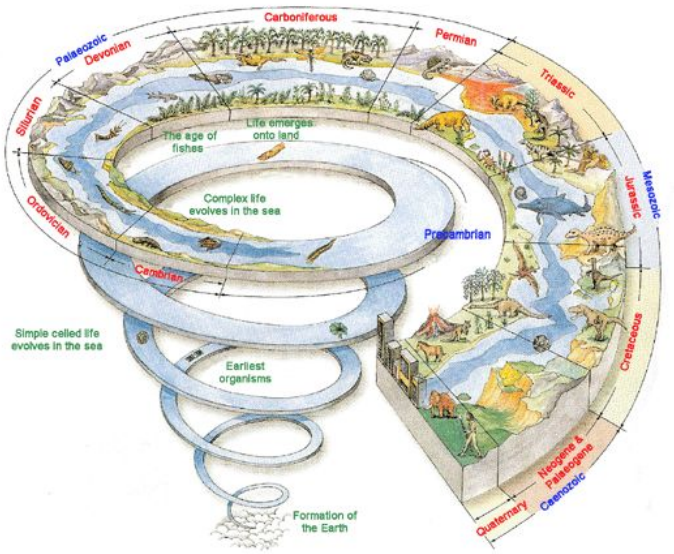


Things Left To Do

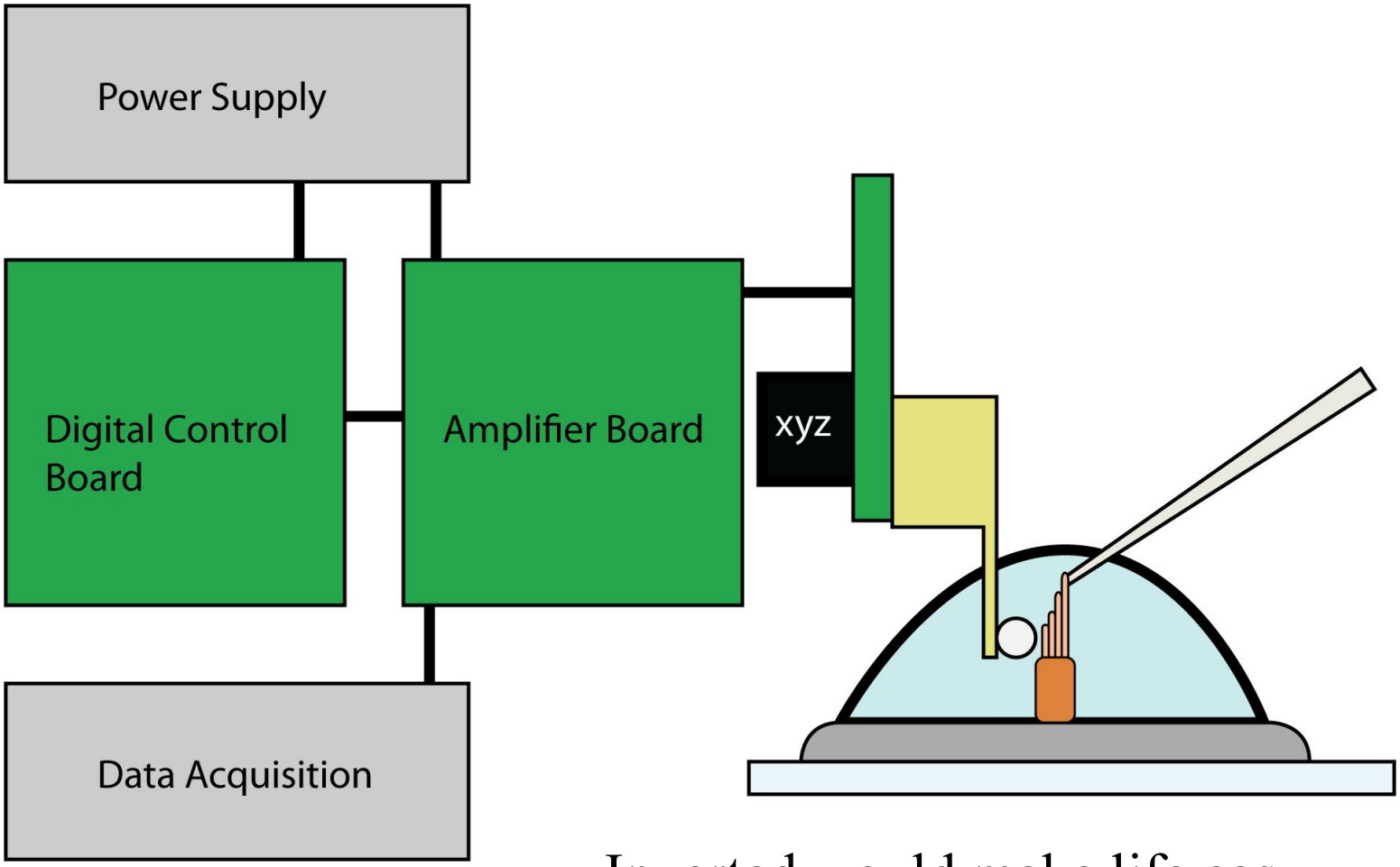
- Layout printed circuit boards
  - Head stage amplifier
  - Feedback force control
- Test feedback operation in air
- Validate underwater operation using parylene passivation
- More investigation into cross-talk and model the experimental results

Timeline

- **Jan-May:** Device characterization
- **June-August:** System integration



Experimental Setup



Inverted would make life easy.
Upright might be workable.

Things to Measure