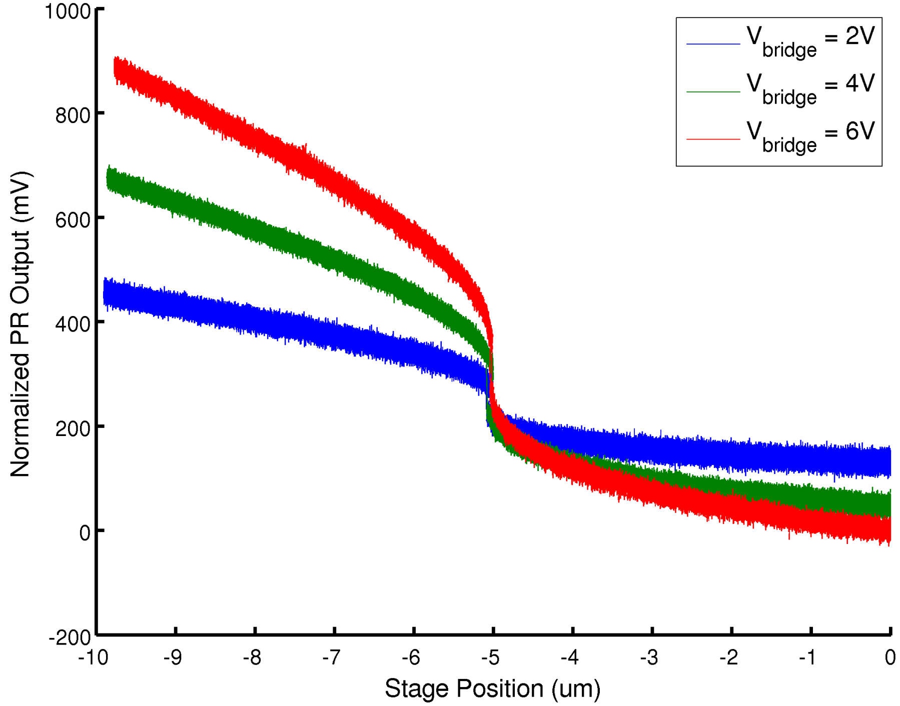

Integrated PR+PE Cantilevers Status Update

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Dec. 26, 2009

Intro

- These slides describe my most recent characterization results for PR+PE devices
- They're intentionally a bit wordy because I'm not presenting them in person, so try to bear with them

One Slide Synopsis

- I've established that most of the wafers (2 of 3) and designs (4 of 6) are not useful for experiments
  - Due to low resonant frequencies, PR sensitivity issues related to curvature
- I need to make some additional measurements on the last two design (PR sensitivity, stiffness) to see if they will work. I will send around additional slides in mid-January.
- Another fabrication run will definitely be necessary and will take about 4 months (1 to plan, 2 to fab, 1 to test)

Measurements/Models

- Current vs. voltage (I-V) of the PR sensor
- Electrical noise of the PR sensor
- Displacement sensitivity of the PR sensor
- Resonant frequency of the cantilever
- Tip deflection from the PE actuator
- Cross-talk from actuator input to sensor output
- Mechanical finite element analysis (FEA) model

Fabricated Wafers

Wafer	PR Doping Amount	Metal Line Insulation	Cantilever Curvature
D1	Low	Thin	High
D2	Low	Thick	Low
D4	High	Thick	High

- Three wafers survived the fabrication process (D1, D2 and D4)
- Higher doping means lower PR resistance
- Thicker line insulation means less cross-talk
- Cantilever curvature is undesirable bending of the cantilever and should be high when doping is high. If not, it suggests that some of the dopants are missing.

Design Summary

Design	Cantilever Length (um)	PR Width (um)	Tip Width (um)	Approx. k (pN/nm)	Approx. f0 (kHz)
1	840	10	20	.017	0.5
2	425	10	20	.16	1.9
3	212	10	20	2.3	10.6
4	101	10	20	39.6	78.3
5	660	30	20	.042	0.5
6	341	30	20	.41	2.1

* PE actuator strip is 40um long, so the effective free moving cantilever length that determines the spring constant and resonant frequency is ~= length - 40

Resonant Frequencies

- Designs #4 and maybe #3 are probably the only ones useful for measurements
- Overall, the frequencies are lower than intended during mask design
  - Silicon thickness changed from 1um to 250nm during the fabrication run (4x reduction in f0)
  - I hadn't updated my design spreadsheets and didn't realize they were this low until recently

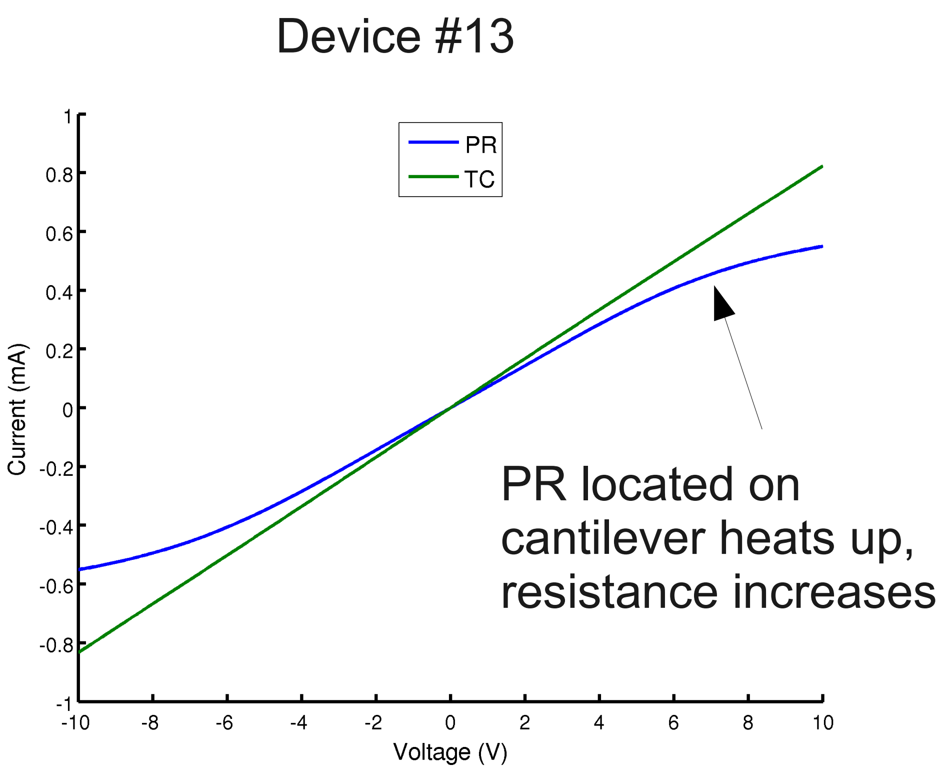
Tested Devices

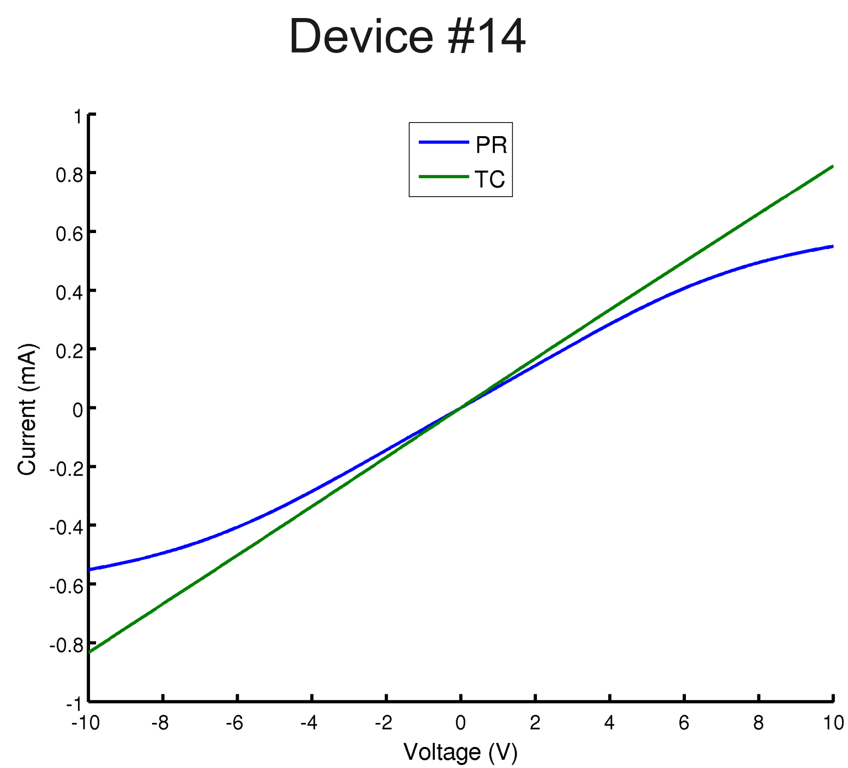
- Finished complete testing for 2 devices so far
  - Started with about 30 devices in latest round, but broke some during device prep, testing, and most due to mismatched PR resistors (more in I-V discussion)
- Devices
  - Device #13 (wafer D1, design #2, ~400um long)
  - Device #14 (wafer D1, design #3, ~200um long)

I-V Measurements

- Idea: Apply a test voltage across a resistor and measure the current that flows. Sweep the test voltage to determine how the resistor behaves across a voltage range.
  - We have a specialized tool in the lab for doing this
- Previously I've been relying on multimeter measurements, which only allow a single, very small test voltage. So I didn't have the complete picture of my resistor behavior.

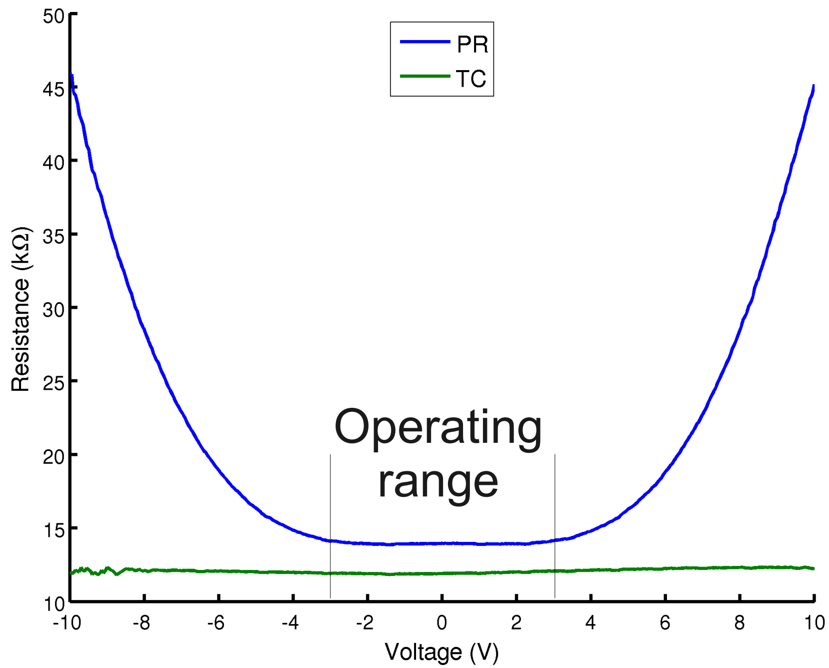
Good I-V Curves



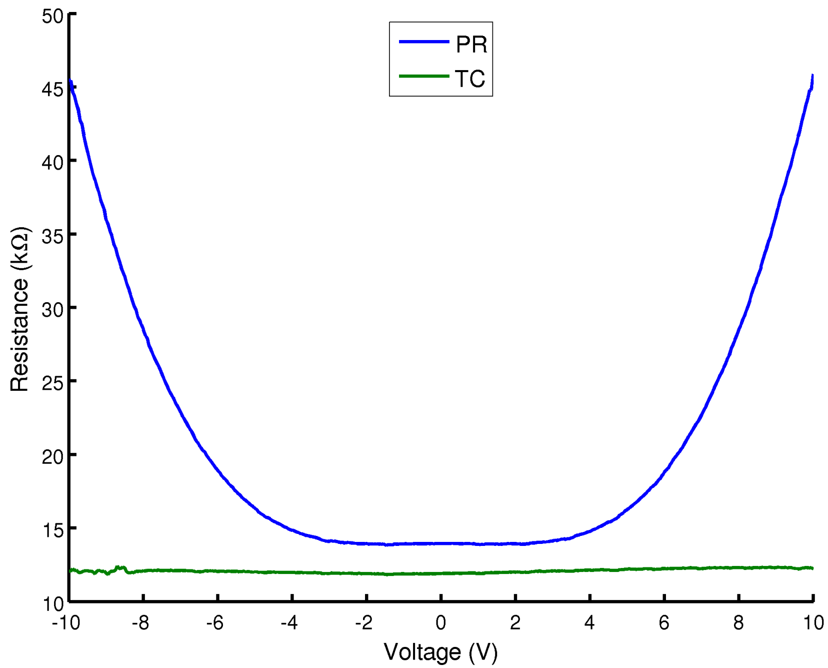


Good I-V Curves

Device #13

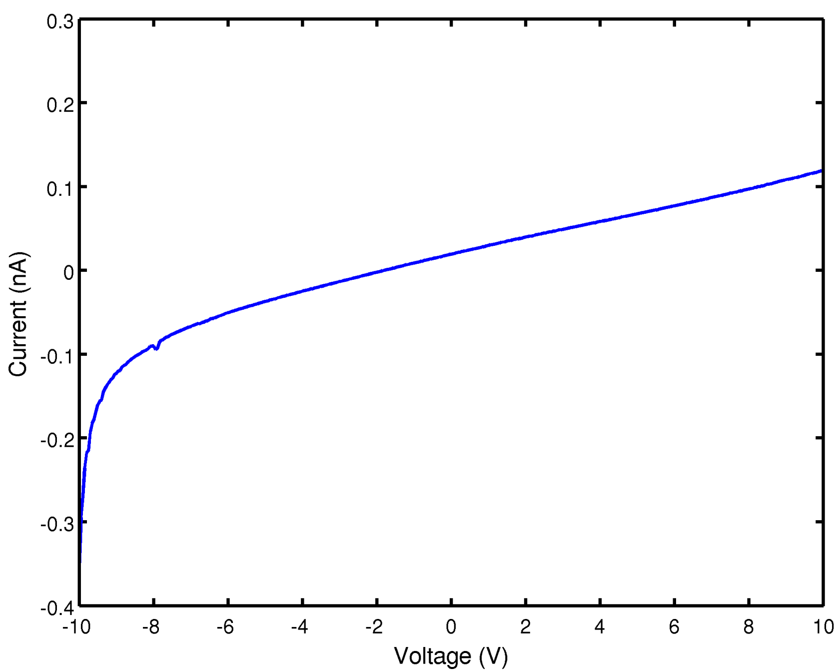


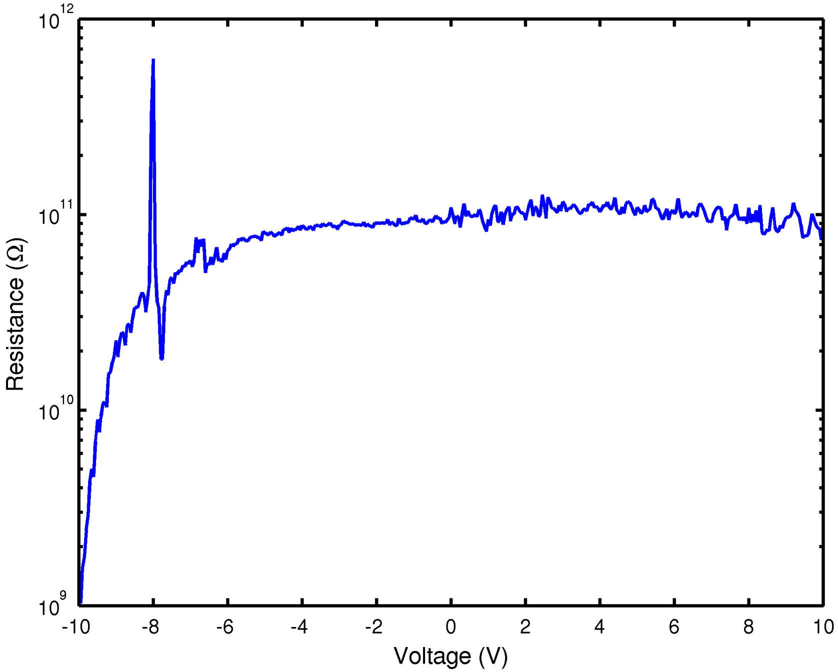
Device #14



Resistance is independent of voltage for typical voltages
(> 3V across each resistor, 6V bridge bias)

Good I-V (Piezoelectric)





The piezoelectric films are either hit (resistances in the Mohm to Gohm range) or miss (resistance of about 200 ohms due to accidental shorting while wirebonding). After some early yield problems, wirebonding is reliable now and yield is probably ~80%.

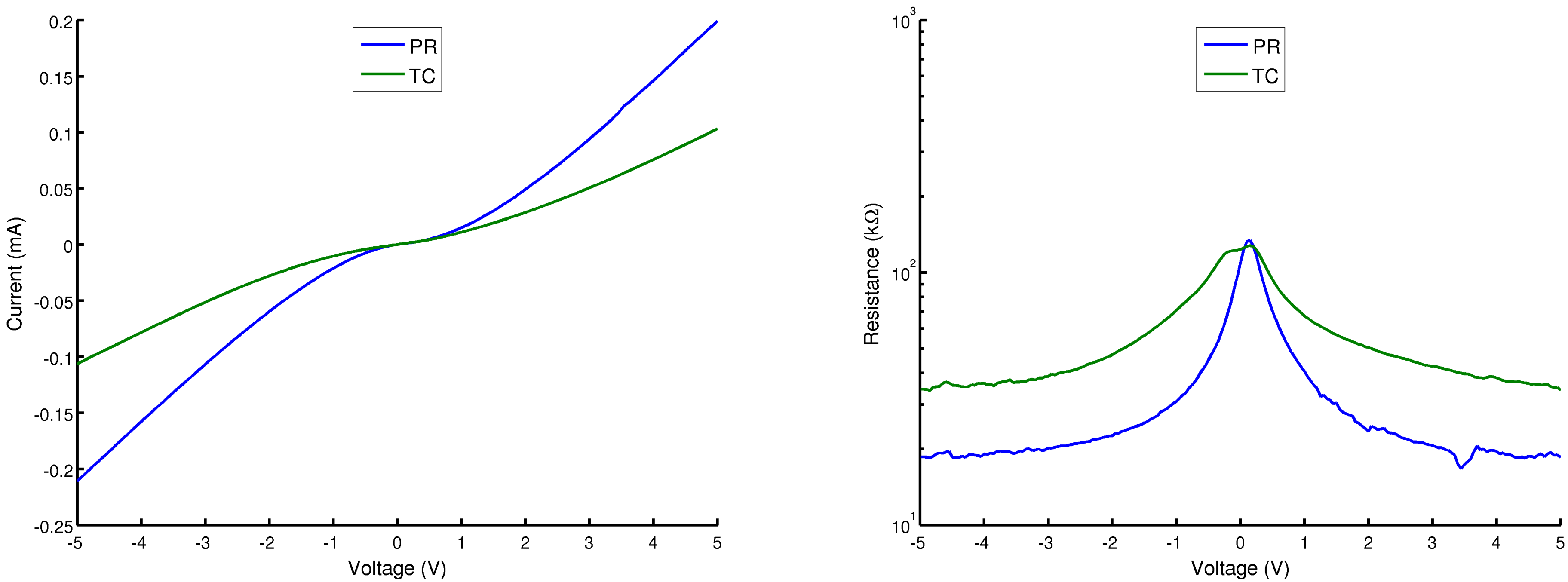
Bad I-V Curves

- Most of the devices from wafer D1 displayed good I-V curves (linear near zero bias voltage, resistance independent of voltage)
  - Due to high silicon dopant concentration allowing electrons to tunnel directly between the aluminum and silicon (ohmic contacts)
- Devices from wafers D2 and D4 are less reliable so far. Here are a few example curves...

Bad I-V Curve Examples

Structure = 2 metal-semiconductor junctions (electrons go from M → S and S → M)

Device #2 (wafer D2)

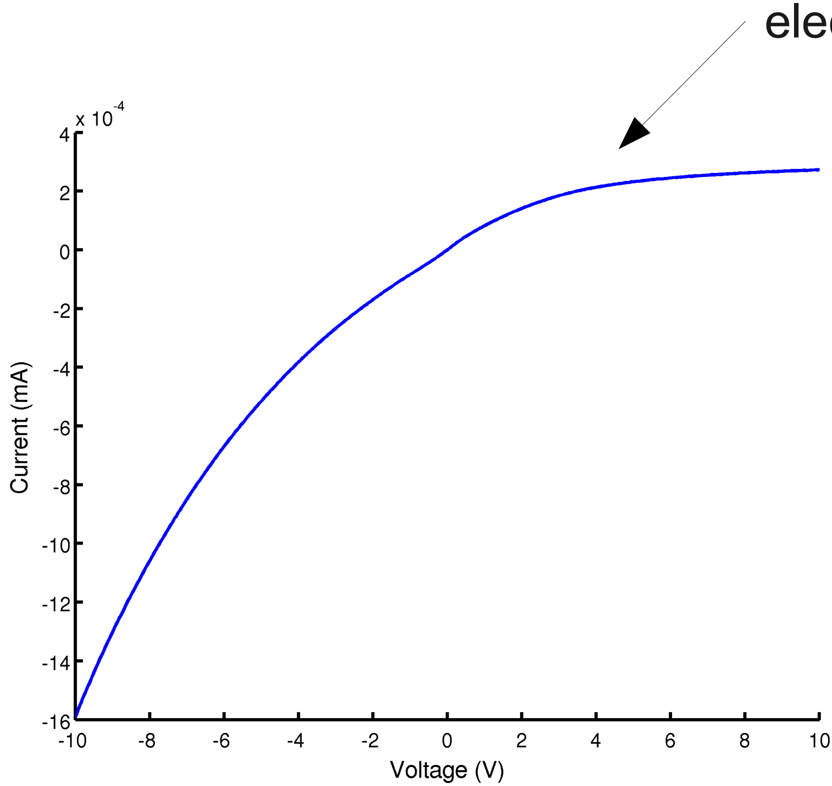


Three problems:

- Exponential I-V near zero bias → large parasitic contact resistances reduce deltaR/R
- Ratio of resistances varies with voltage → hard to balance the Wheatstone bridge
- Resistances don't match at high bias → low Wheatstone bridge sensitivity even at high bias

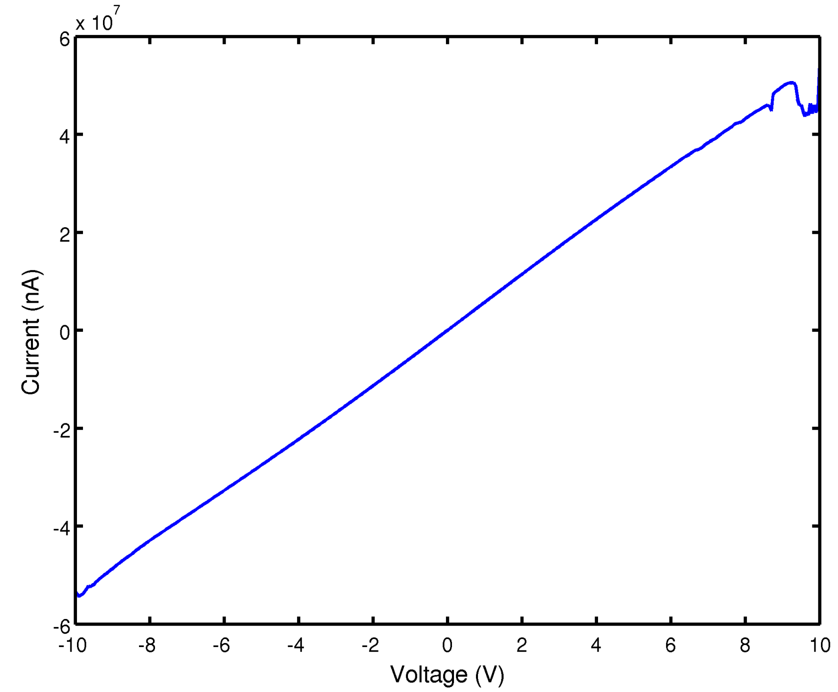
Bad I-V Curve Examples

Worse than the last slide, when this contact would eventually short out at large positive bias because electrons were eventually able to tunnel



Rectifying contact (Schottky diode)
- Electrons can only go from the semiconductor to the metal, not from the metal to the semiconductor

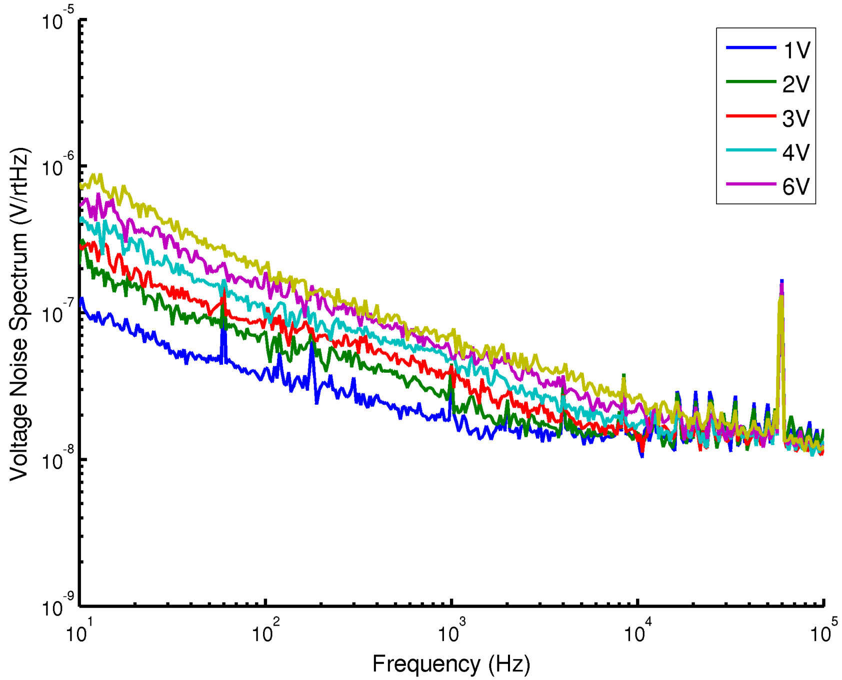
A bad (shorted) piezoelectric (200 ohm)

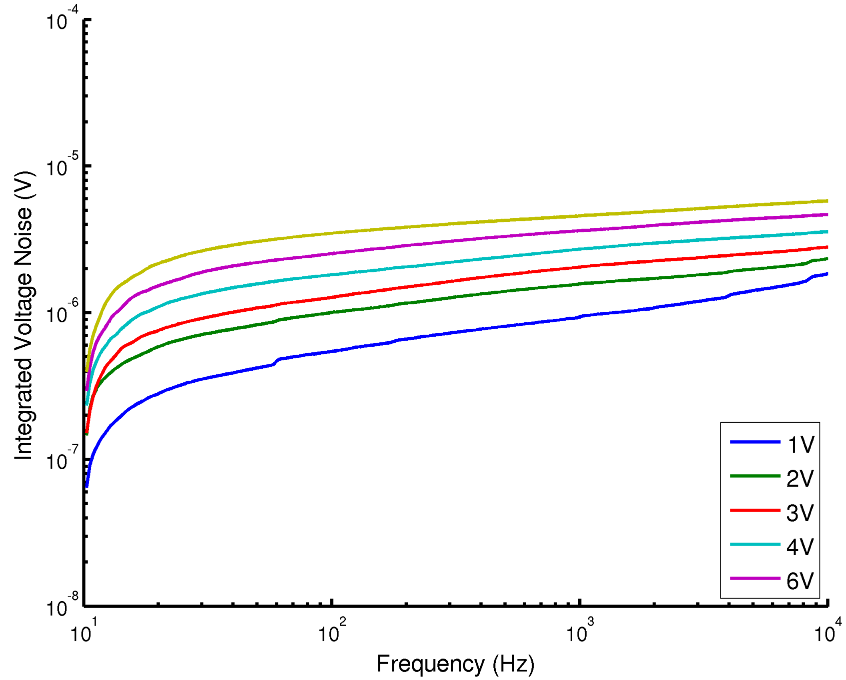


Summary I-V Curves

- All bad I-V curves are due to low dopant concentration underneath the Al contacts
  - Reached the same conclusion in my last presentation due to circumstantial evidence (higher noise, higher resistance) but this is direct evidence now
- Most of the devices from wafers D2 and D4 have bad I-V curves. Most of the devices from D1 have good I-V curves.
- **Summary:** About 30% of the current devices are good and I can focus my efforts on them. In the future, will measure an I-V curve first before any further device testing. All of my PR only devices have ohmic contacts (good I-V curves) and I have a good idea of where the problem is in the PR+PE process, so this can be fixed in fab v2.

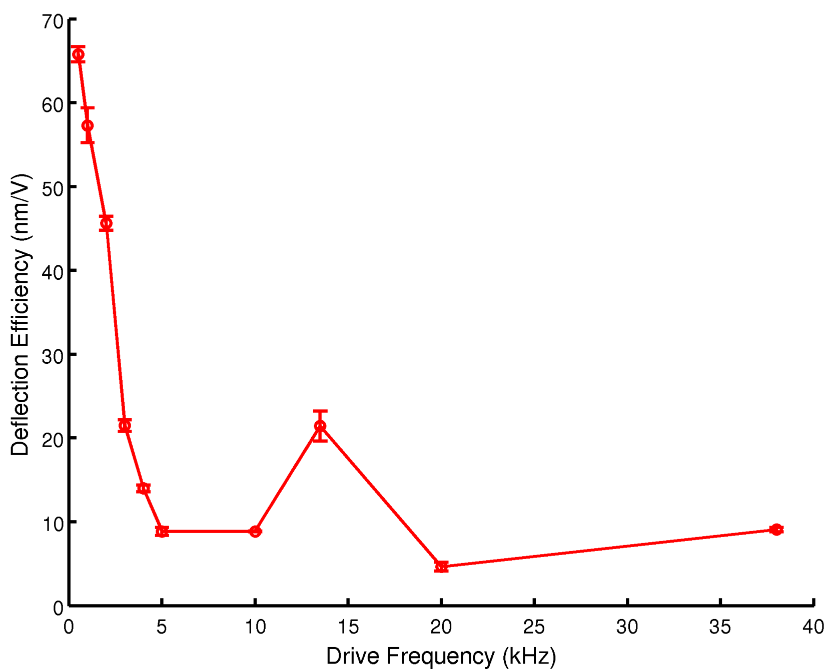
Noise

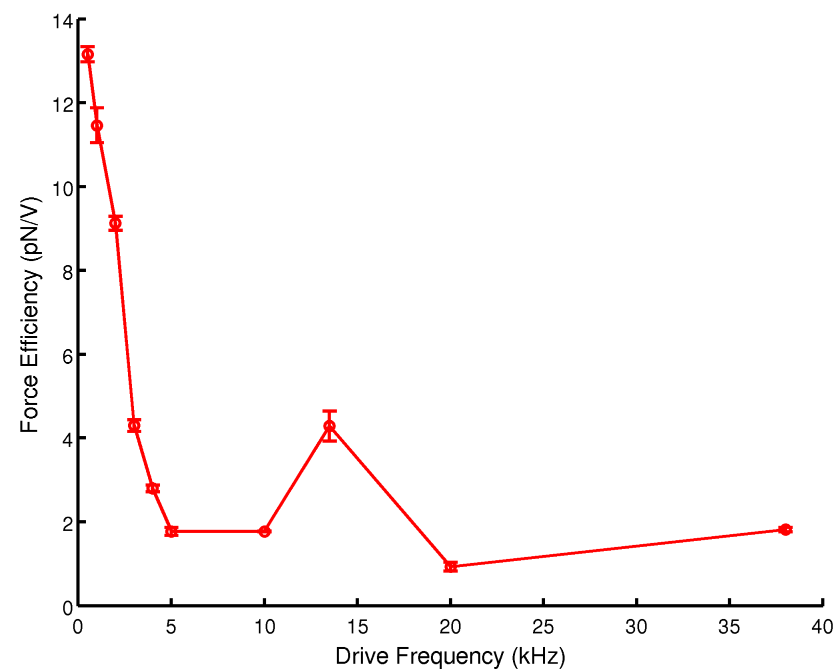




Device #14 – Noise is about expected. Cantilever covered with metal box for measurements.

PE Actuation





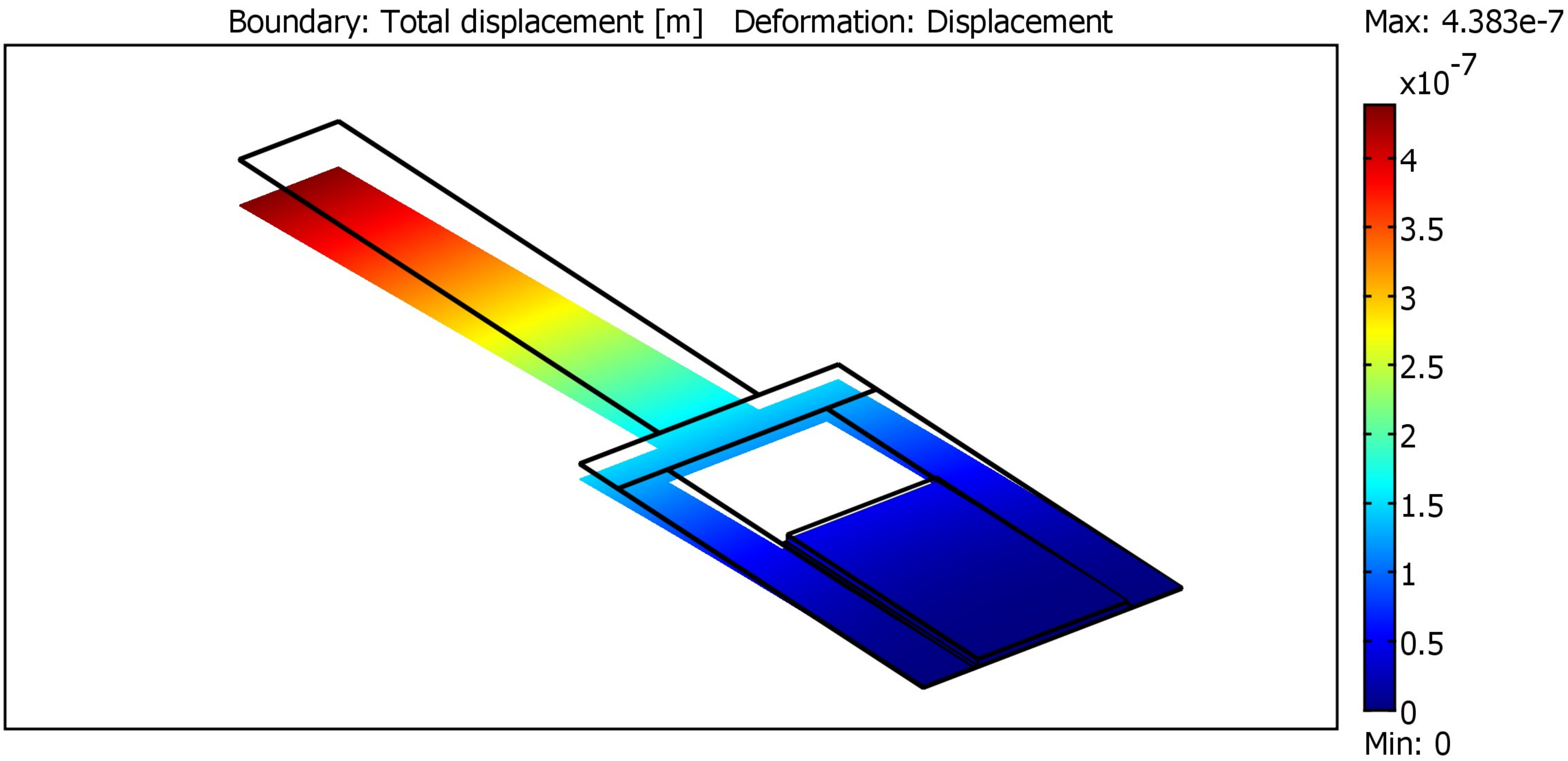
Tip deflection and force (estimated from nominal k) for device #12 (design #2). The piezoelectric film can support voltages up to about 10V (over a 250nm electrode gap), although cross-talk increases with drive, so tip deflections up to 750 nm possible.

PE Actuation Scaling

$$
\begin{aligned}
x_{tip} &\propto L \\
k &\propto L^{-3} \\
f_0 &\propto L^{-2}
\end{aligned}
$$

- So making a shorter cantilever means smaller deflections, larger forces, higher resonant frequencies
  - Design #2 = 425um long → 70 nm/V, 14 pN/V (0.2 pN/nm)
  - Design #4 = 100um long → 10 nm/V, 550 pN/V (50 pN/nm)
- Stiffness/force of design #4 can be reduced by reducing the width, either by focused ion beam (FIB) machining the current devices or in fab v2

Actuation Simulations

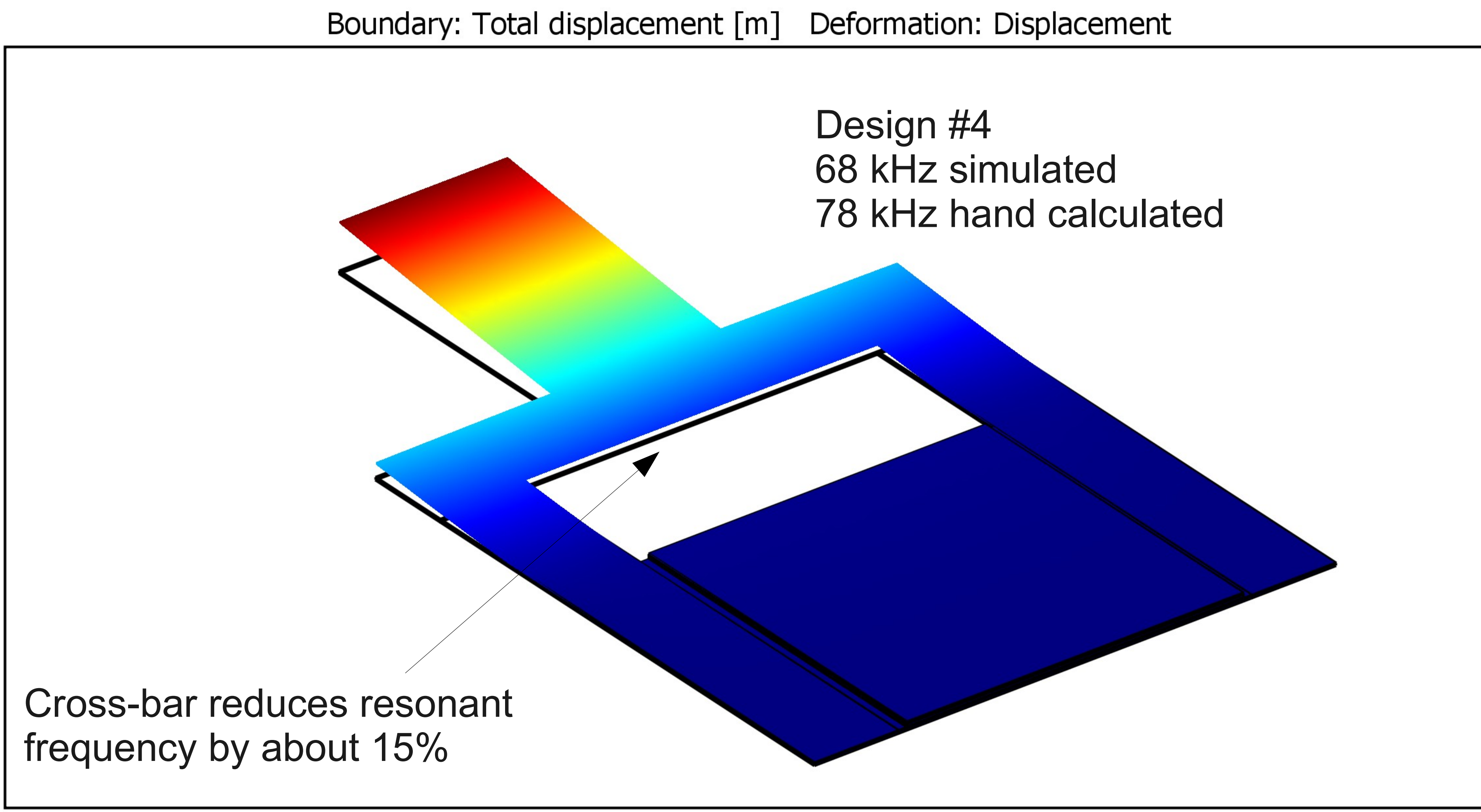


Have working piezoelectric actuation simulation. Have not systematically compared with experimental results yet, but order of magnitude accurate.

Resonant Frequencies and Stiffness

- I don't have accurate numbers for these yet
  - Can easily measure using laser doppler vibrometry but was looking at the wrong frequencies in the last round of measurements
- Using hand calculated stiffness for now, will use simulated stiffness once I have experimental resonant frequencies to validate model

Resonant Frequency Simulation

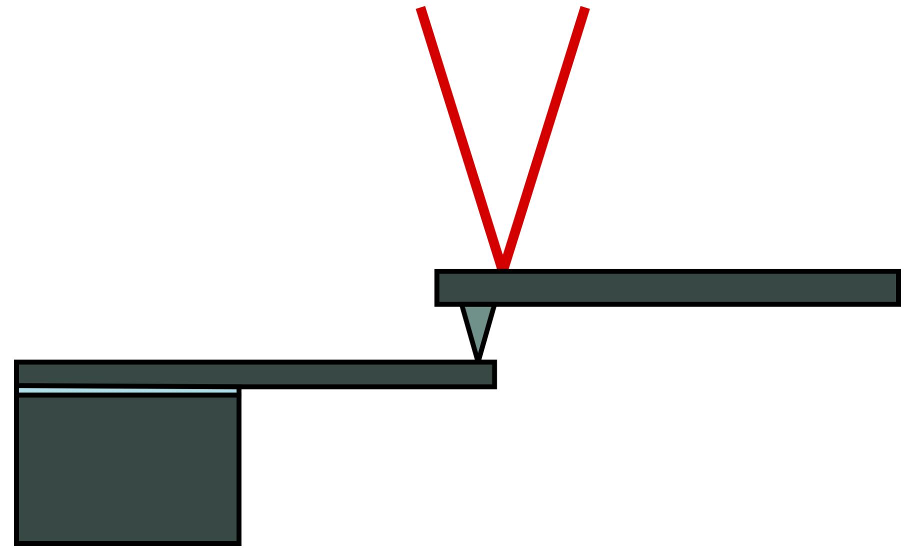


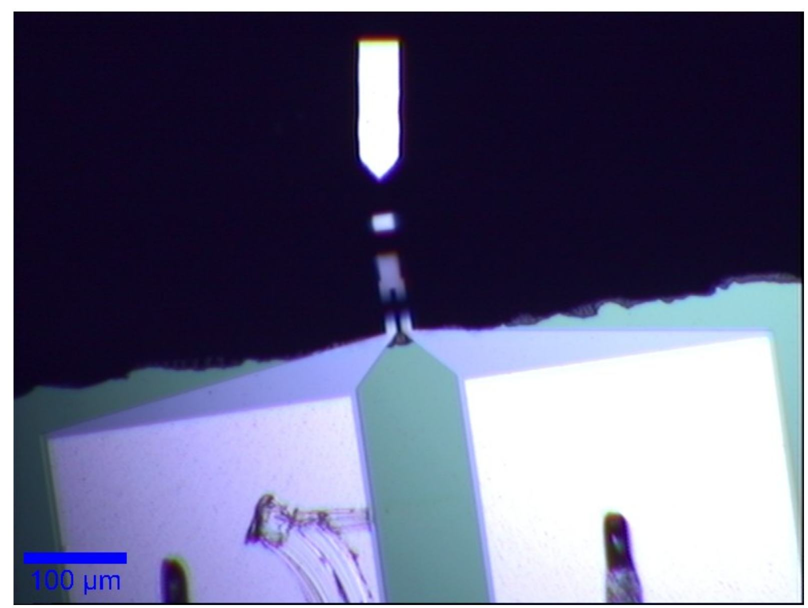
Cross-Talk

- I made detailed cross-talk measurements in December
- Right now I'm working on adding the cross-talk effect to the feedback model
- It is going to take at least a week, so I will present those results in mid-January along with the other ongoing measurements
- There are two possible rise-time limitations in the system: electrical cross-talk (closed loop only), and beam dynamics (closed and open loop). As long as the cross-talk is slower than the dynamics (i.e. we filter our command voltage), then cross-talk will not be an issue. So I'm working on finding that threshold.

Measuring PR Sensitivity

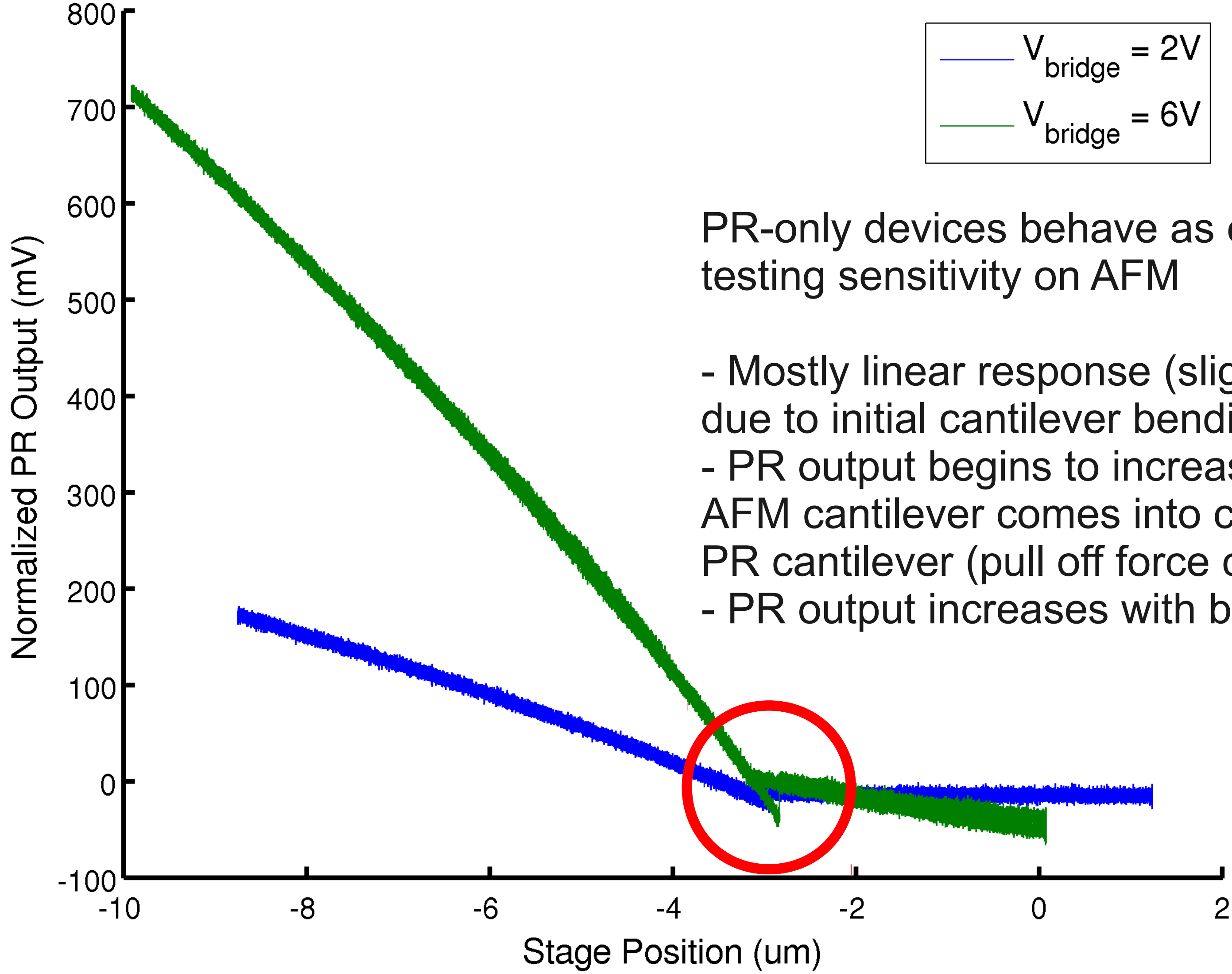
- Have had capacitive cross-talk problems when using the standard PR calibration setup in the lab
    - Recently reduced cross-talk by 50x with better shielding, but inertia loading just doesn't scale well to small cantilevers
    - Maybe be due to looking at wrong resonant frequencies, will try again
- Either way, AFM solves cross-talk problem





Note: banding due to optical interference

PR-Only Sensitivity



PR-only devices behave as expected when testing sensitivity on AFM

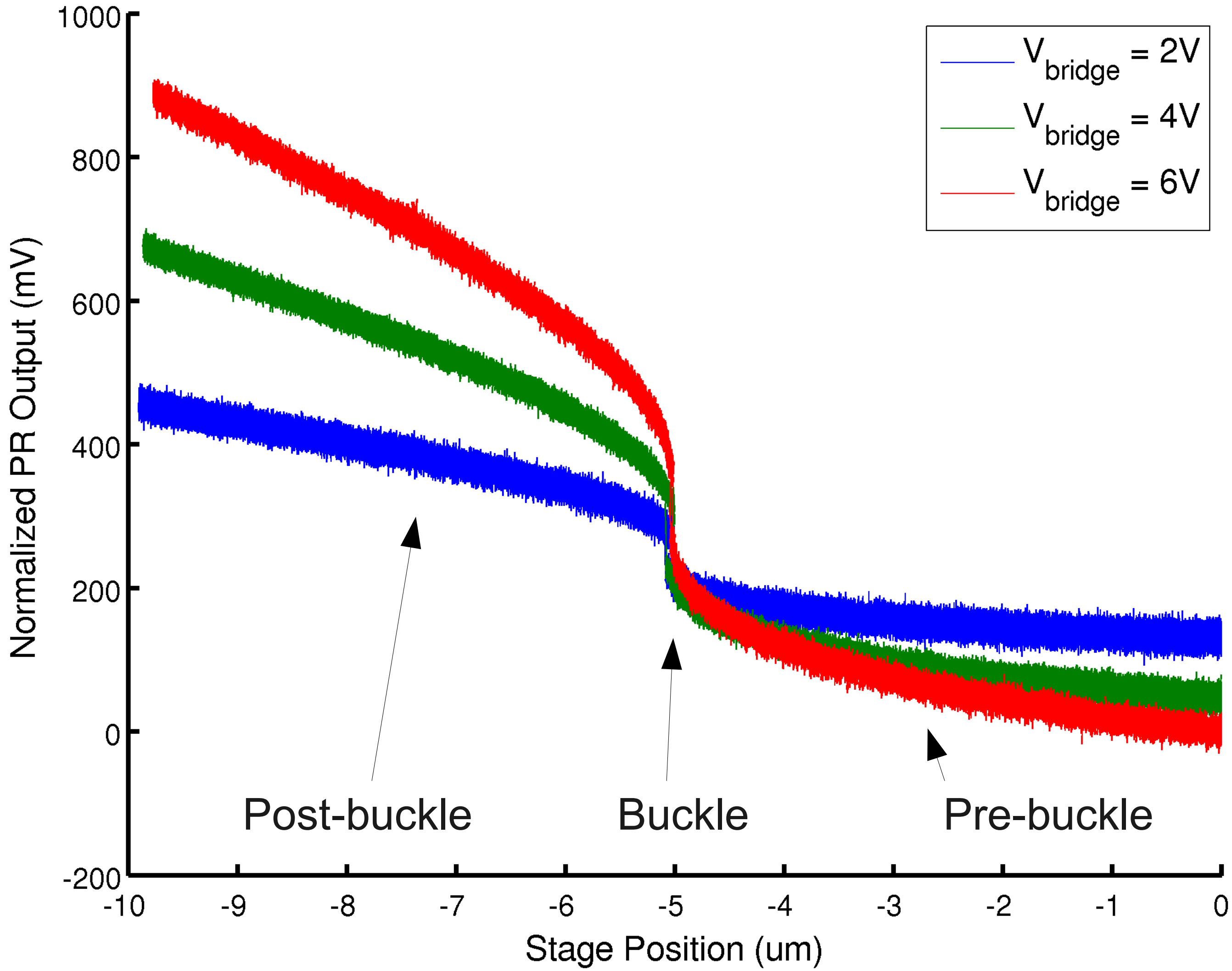
- Mostly linear response (slightly nonlinear due to initial cantilever bending)
- PR output begins to increase as soon as the AFM cantilever comes into contact with the PR cantilever (pull off force circled below)
- PR output increases with bias voltage

PR+PE Sensitivity

- Not as straightforward
- PR output doesn't change until the device has been visibly deformed
- After pushing some more, the PR output changes drastically (“buckles”) and behaves linearly after that
- The problem appears to be worse for longer devices (which is a good thing if so, because we need the short devices anyway)

PR+PE Sensitivity

Device #14 – Design #2 (400um long)

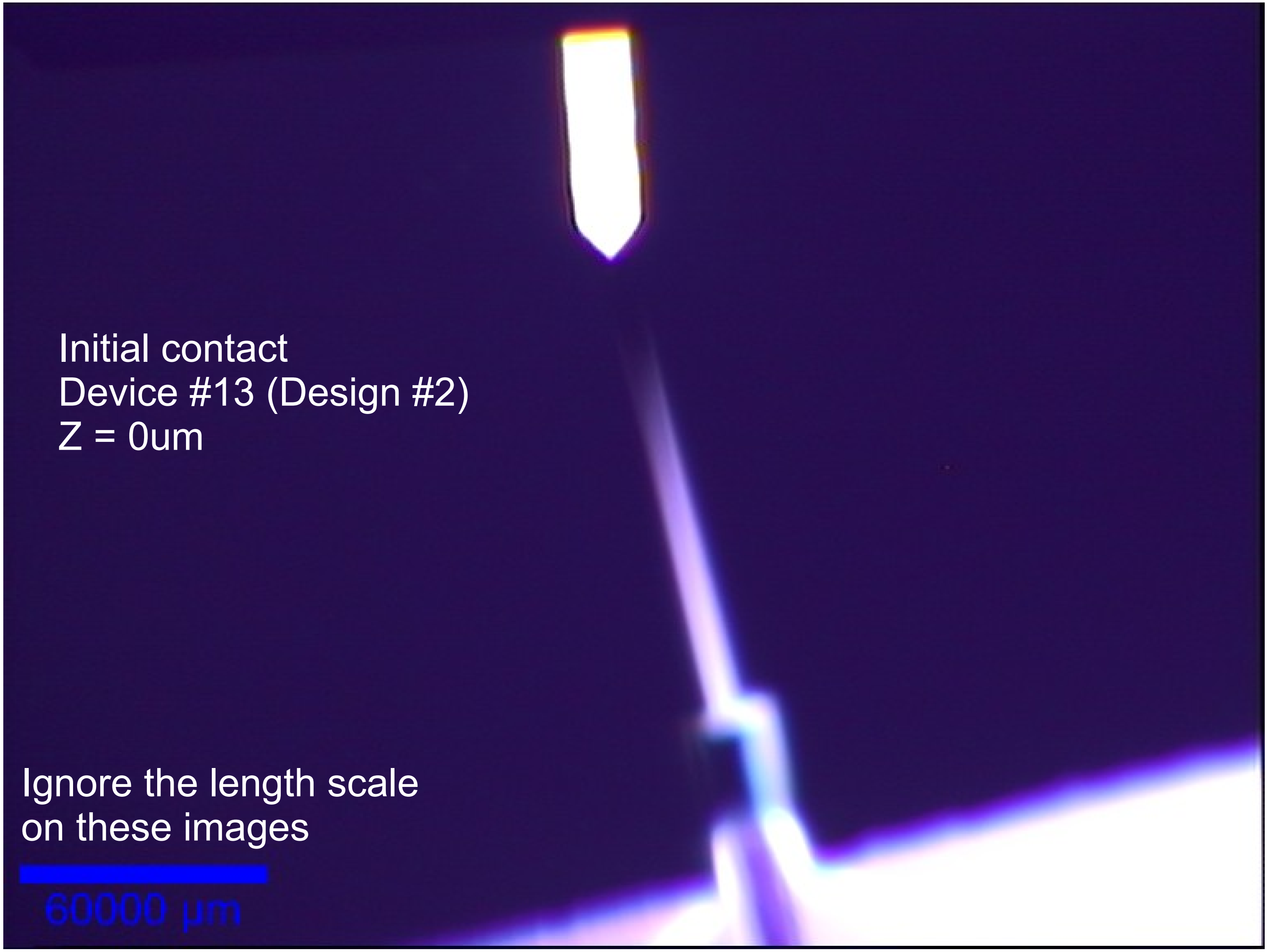


The PR output does not start to change immediately when the AFM cantilever touches the tip.

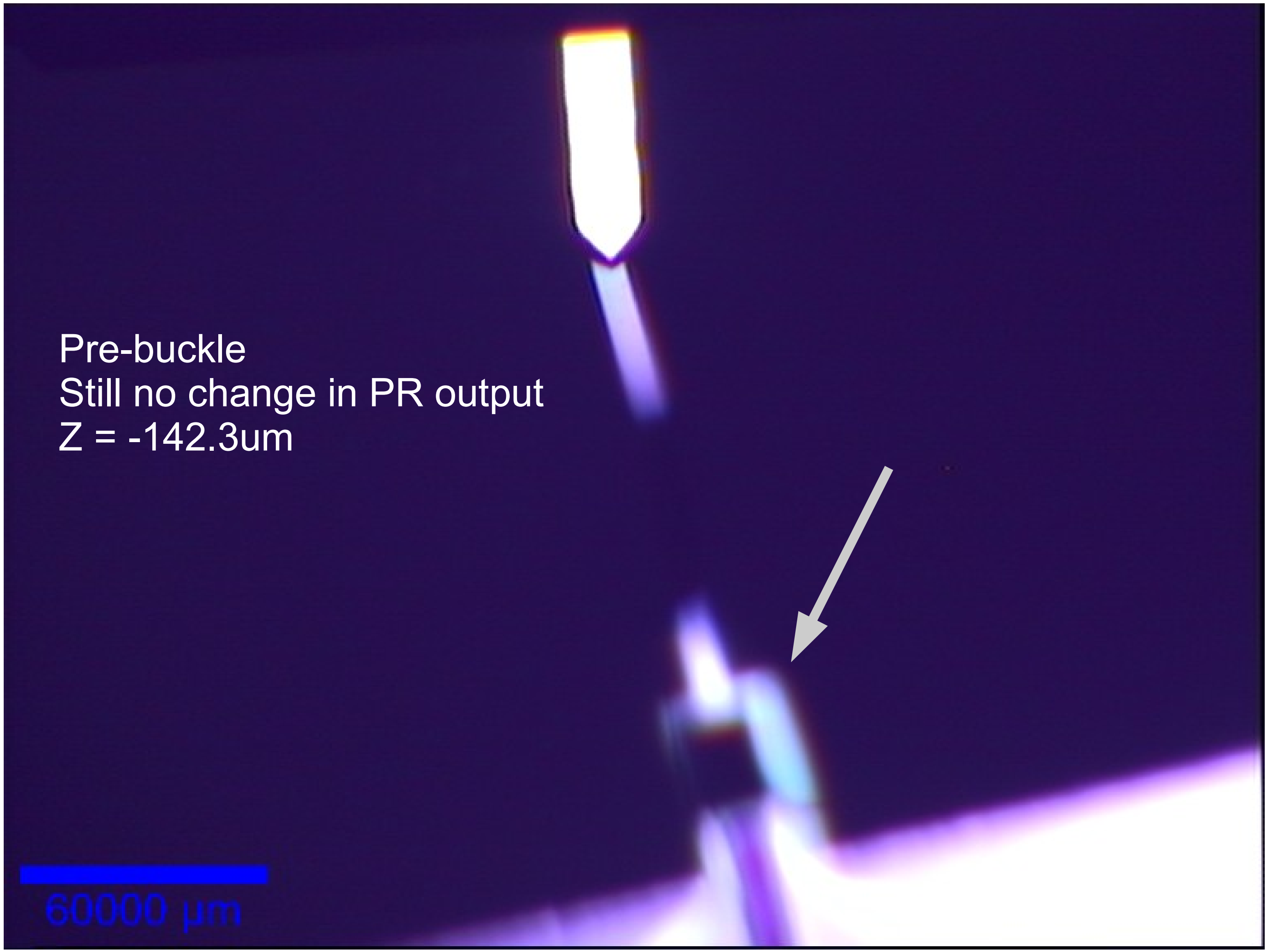
At first, all of the bending occurs out at the tip of the PR+PE device and not where the PR is located.

Eventually it reaches a threshold point, at which the device appears to controllably buckle (see images on next slide).

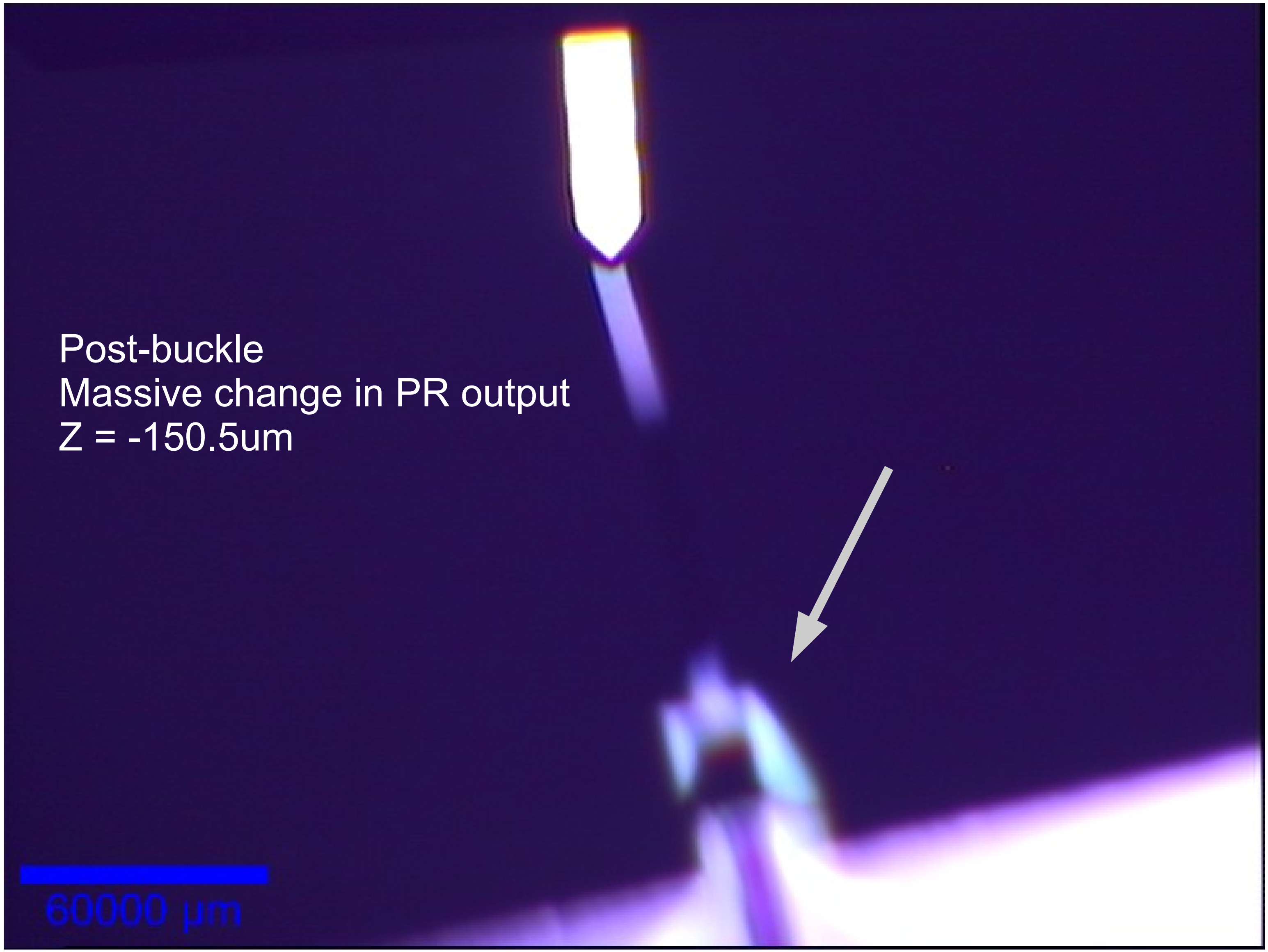
PR+PE Buckling



PR+PE Buckling

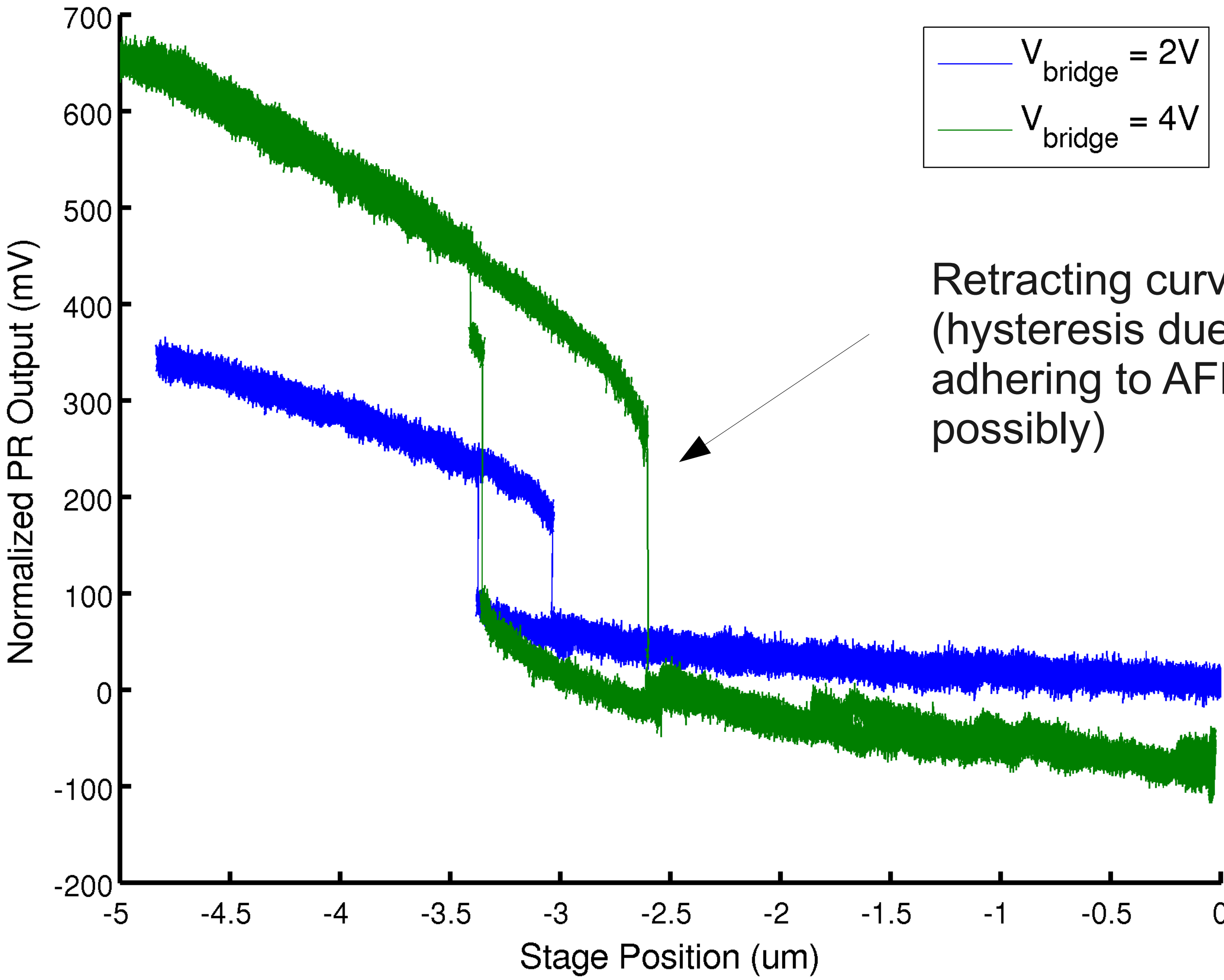


PR+PE Buckling



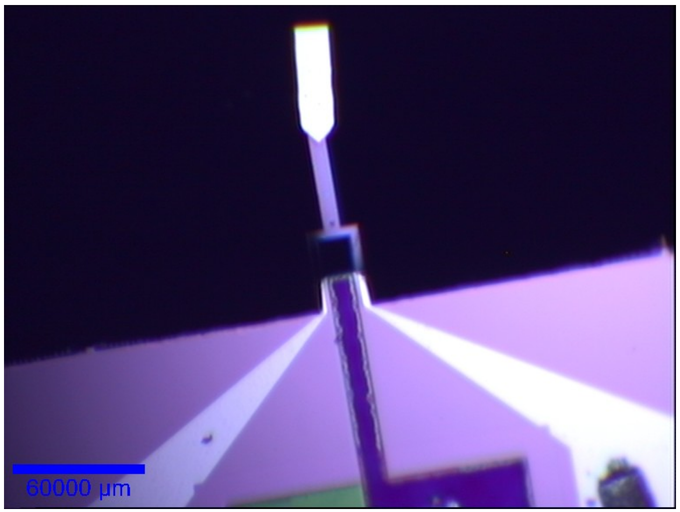
PR+PE Buckling

Device #13 – Design #3 (200um long)

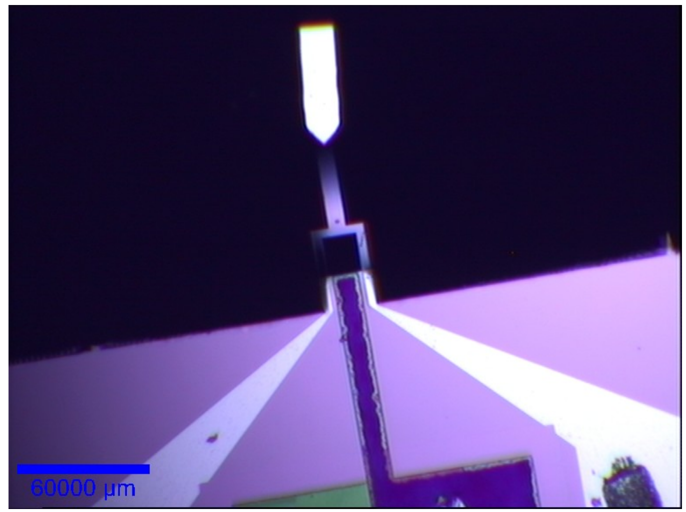


Retracting curve on right (hysteresis due to PR+PE device adhering to AFM cantilever possibly)

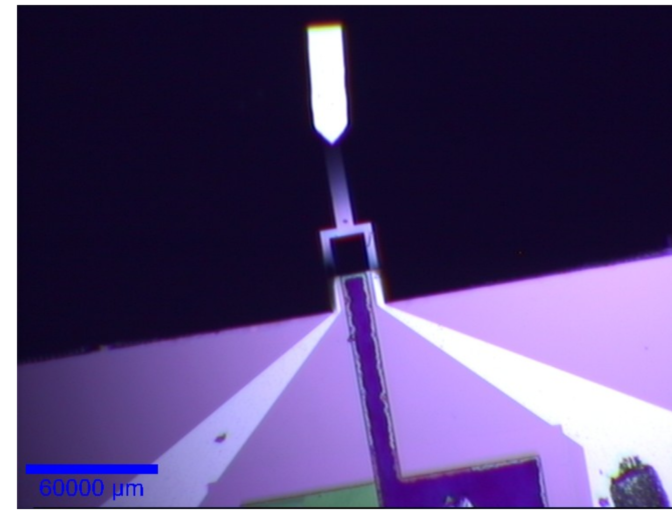
PR+PE Buckling



Initial Contact
Z = 0



Pre-buckle
Z = -24um



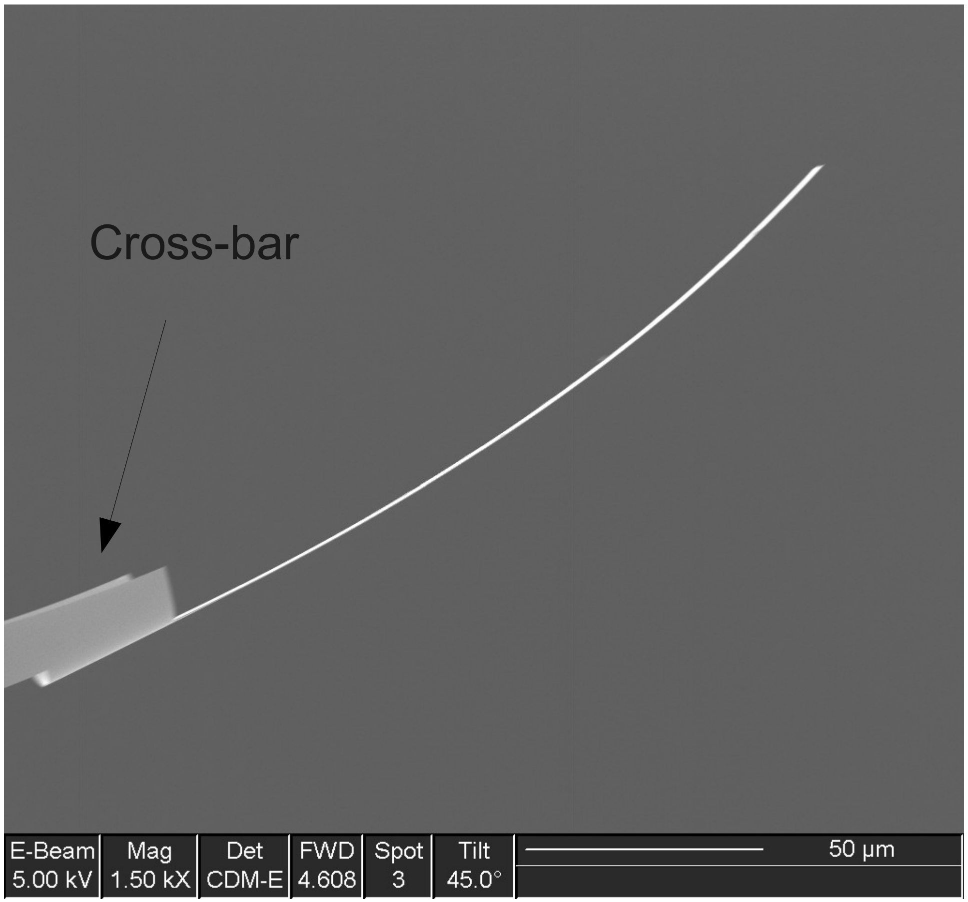
Post-buckle
Z = -27um

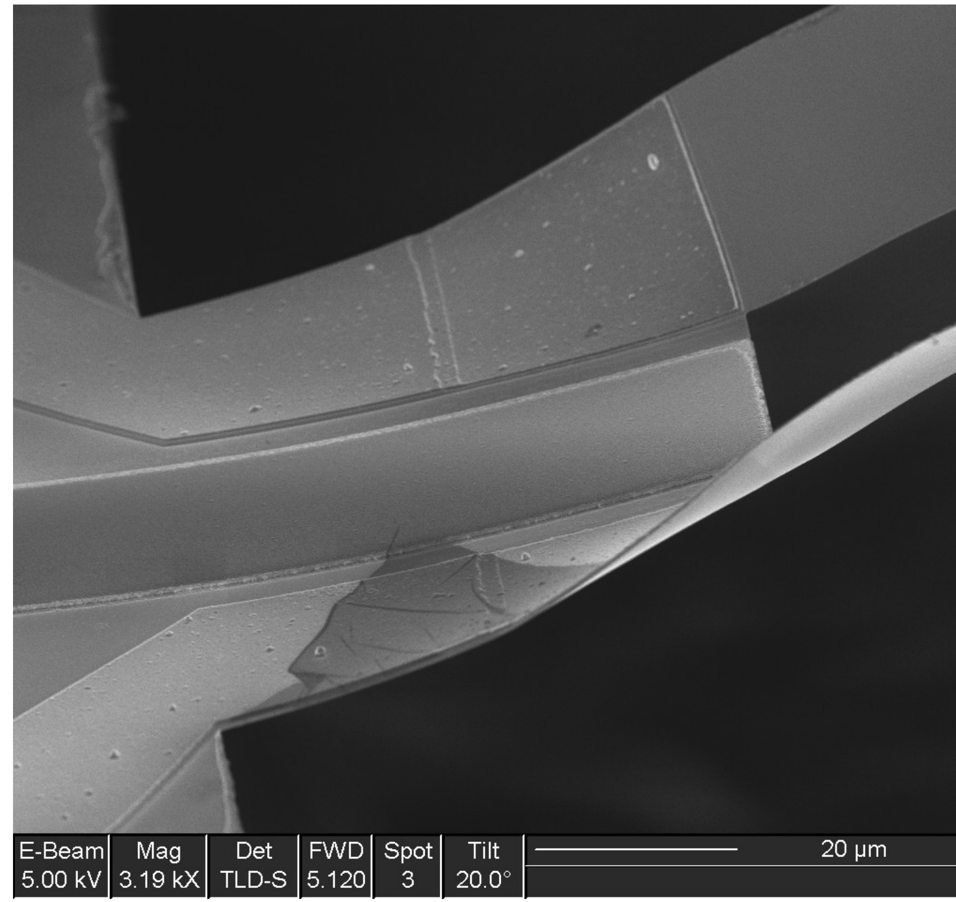
At this point I can't say what the “threshold force” is before the PR actually works. These initial measurements were done with a very stiff AFM probe (40 N/m), but I'll redo the measurements with a probe about 400x softer so that I can get some approximate force numbers.

PR+PE Sensitivity

- Needing a large initial force to “turn-on” the PR is a very bad thing, and there are a few obvious questions...
- What is causing this?
  - I think that it is caused by dopant-induced stress which bends the cross-bar region in the transverse direction. This stiffens the cross-bar, so that small forces only deflect the tip of the device and not the regions where the PR is located.
- How large is the turn-on force?
  - Unclear at this time, will do additional AFM measurements with a softer AFM probe in January to determine this. Possibly up to 10s of nN.
- Does it affect all designs or might some be usable?
  - From looking at the devices under the microscope, the longer devices have more lateral curvature so it might be better for design #4, but I don't have good intuition for this.
- Can it be fixed in the next fabrication run?
  - Yes, I can deposit a thin compressive film on top of the cantilevers so that they are flat rather than curved. In separate work I've looked at my PR-only devices (which also have bending) and come up with a model that fits the observed bending, so can compensate future devices.

Potato Chipping (SEM)

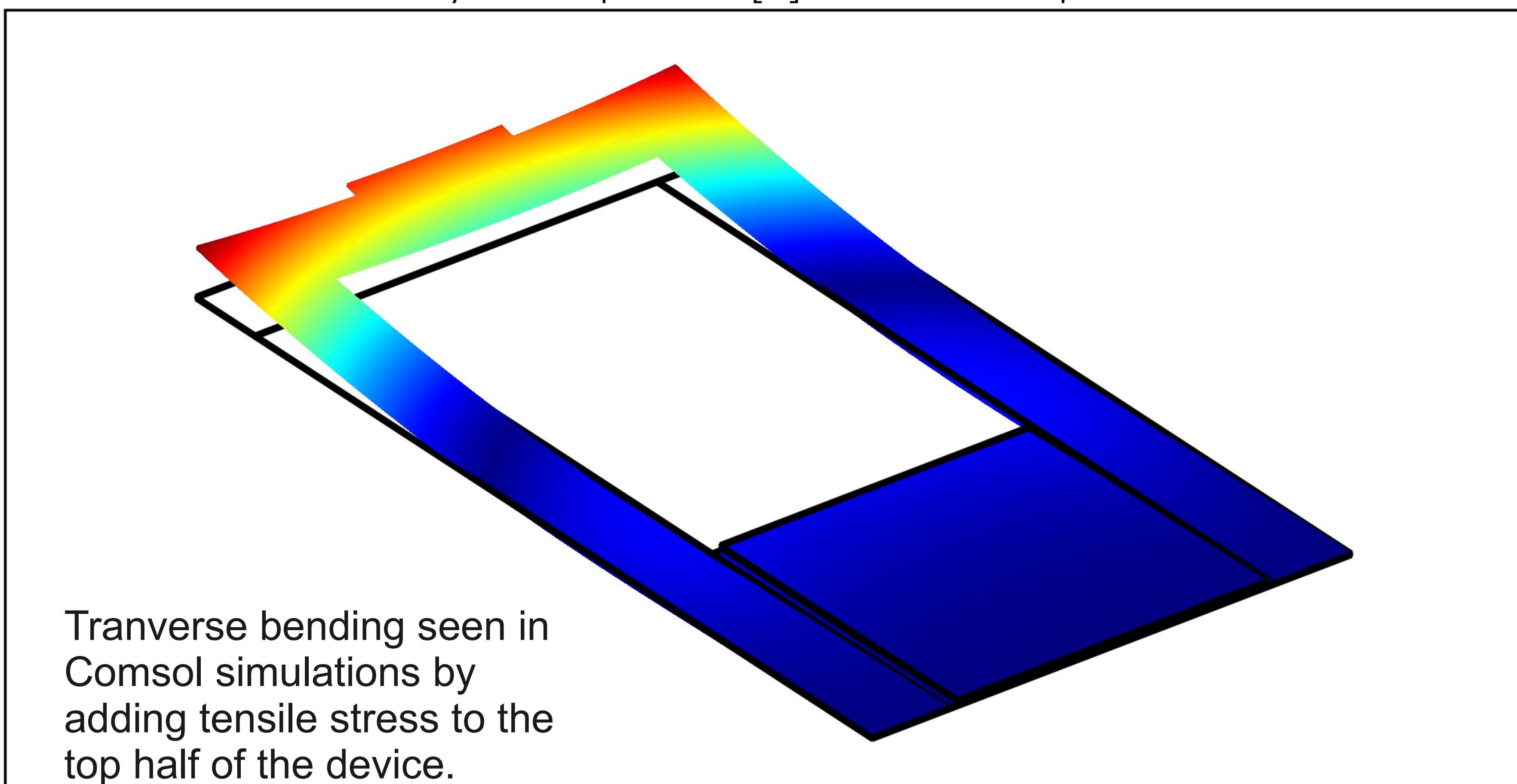




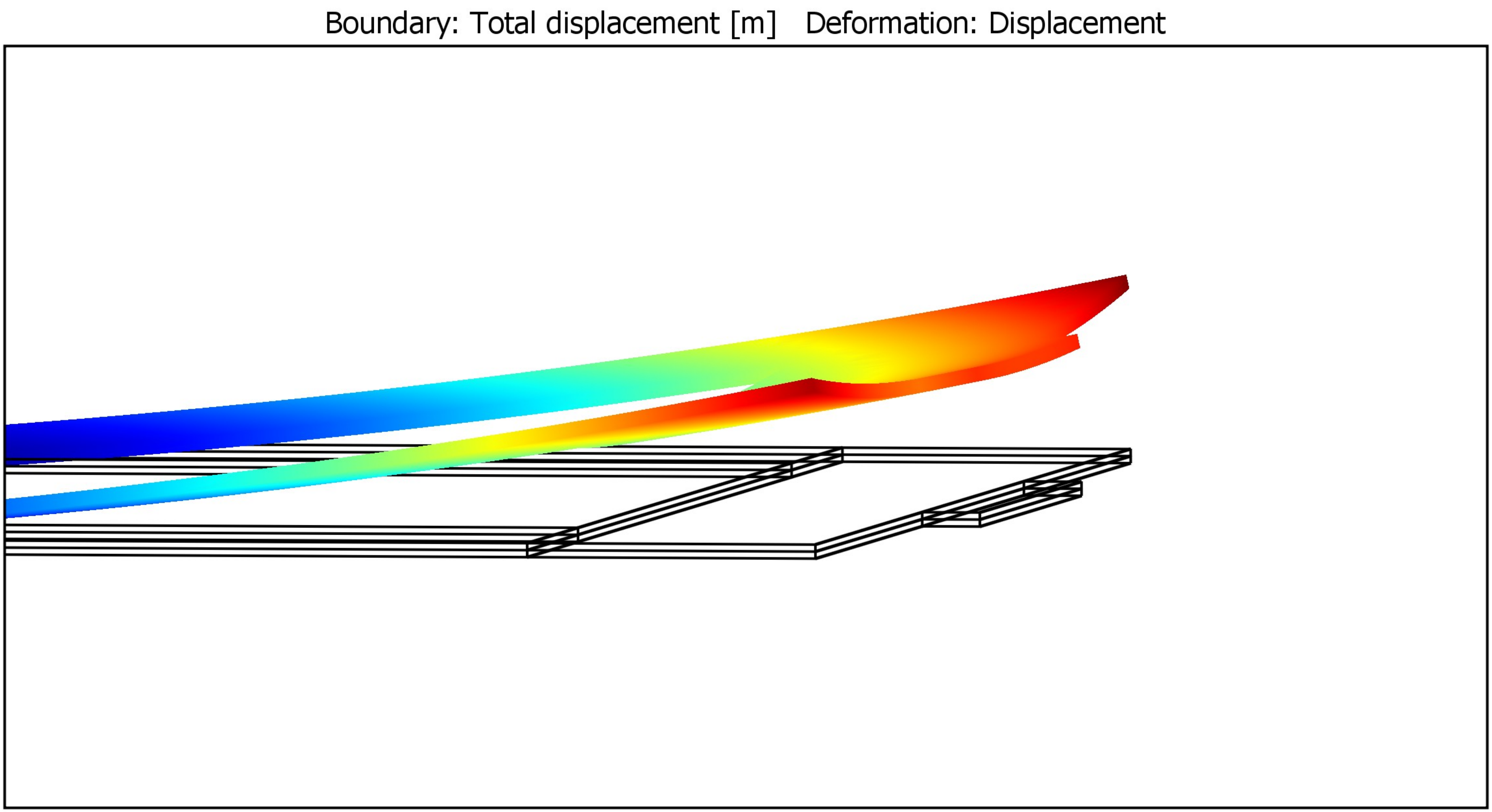
Hypothesis: the lateral bending stiffens the cross-bar region so that force applied to the tip of the cantilever doesn't initially bend the PR region (left of the cross-bar in the first SEM)

Potato Chipping (Comsol)

Boundary: Total displacement [m]   Deformation: Displacement



Potato Chipping (Comsol)



Sensitivity Conclusion

- If the PR requires an activation force to be functional, then it becomes much less useful for force feedback
- However, it could still be used for purely open loop measurements if that would be useful (i.e. use only the PE actuator and use as a soft, high frequency probe)
- If transverse bending is causing the problem (other ideas very welcome), then we're stuck between a rock and a hard place
  - Bending caused by high dopant concentration at surface, so want to minimize it. But low surface concentration leads to non-ohmic contacts (remember I-V measurements).
- There is some variability in dopant concentration among devices, so I might be able to find a few in the sweet spot with ohmic contacts and minimal bending.
- Next steps: Characterize several devices with design #4 (the short, high frequency version) to see if this is still a problem.

Next Steps

- Cross-talk modeling
- Test more devices of design #3 and #4
- Measure PR output vs. force
- Parylene coat and underwater testing

Next Steps

- Main projects in the past year
  - PR characterization (noise, sensitivity)
  - PR design
  - PR dopant induced bending analysis
  - PE characterization
  - Initial PR+PE characterization
- For the next mask layout I have material properties data rather than guesses and can do more in-depth FEA now that the PR design is straightforward
- Also device testing is figured out now

Misc Note – Design #4

- The change in resistance of the transverse (T) section is opposite that of the longitudinal (L) sections due to the piezoresistive properties of silicon
- We usually want the L sections to be much longer than the T sections, otherwise they cancel out
- This design uses longer T, shorter L sections. Should have high sensitivity but hasn't been measured yet
- I thought that this design was useless (due to short L sections) until I ran the numbers again, <u>which is why I didn't test it until now</u>