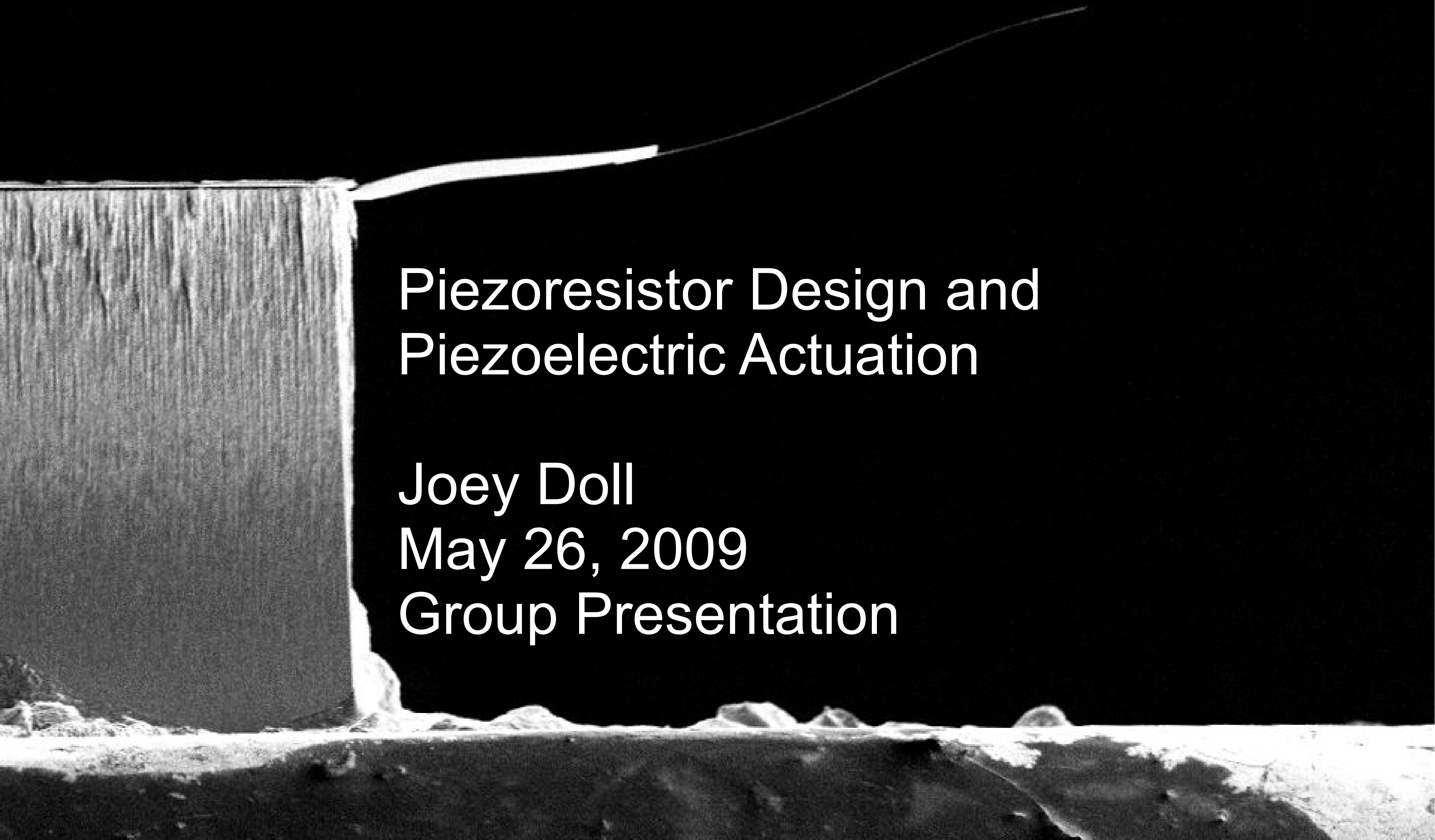


Piezoresistor Design and Piezoelectric Actuation

Joey Doll

May 26, 2009

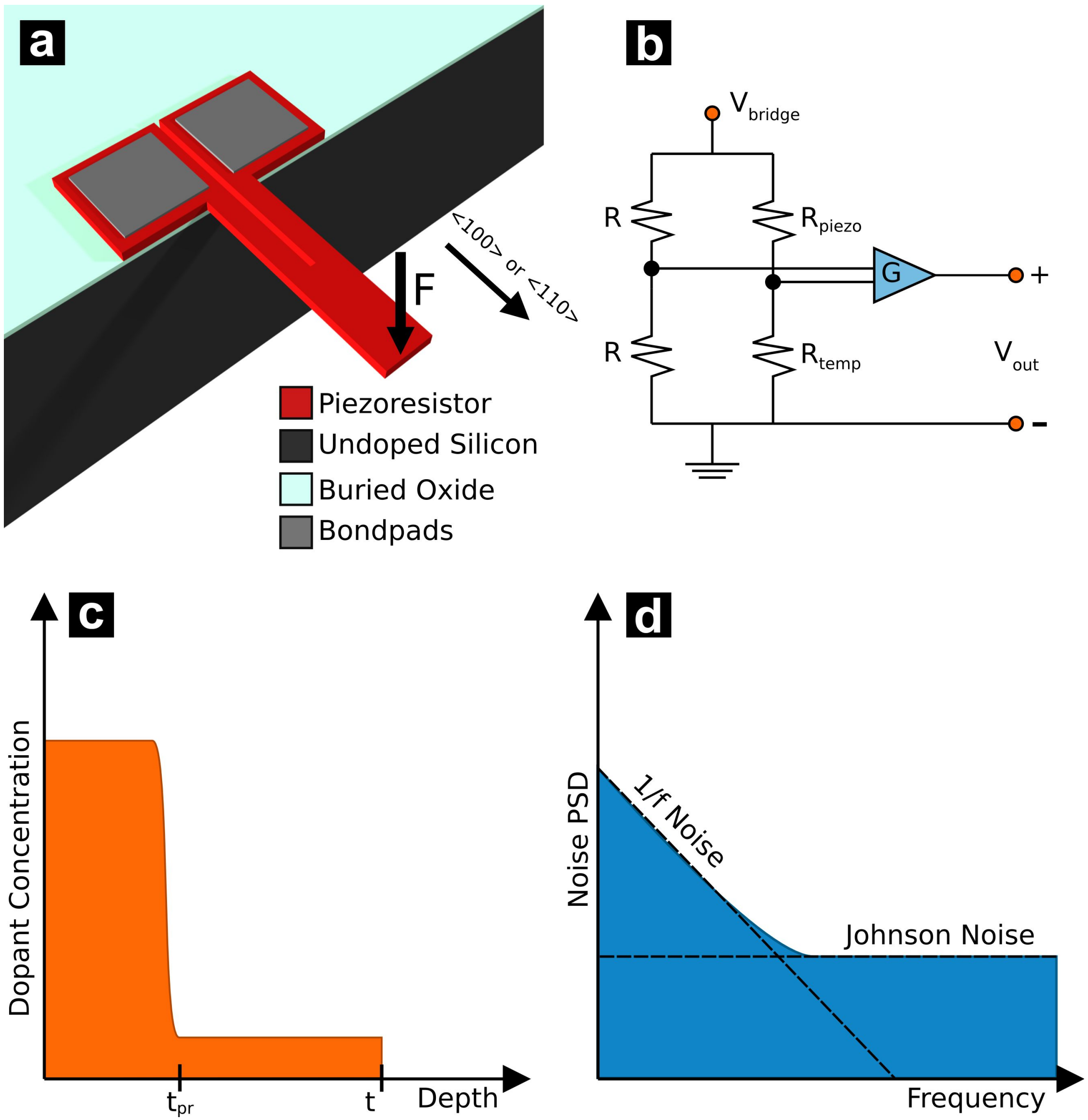
Group Presentation

Overview

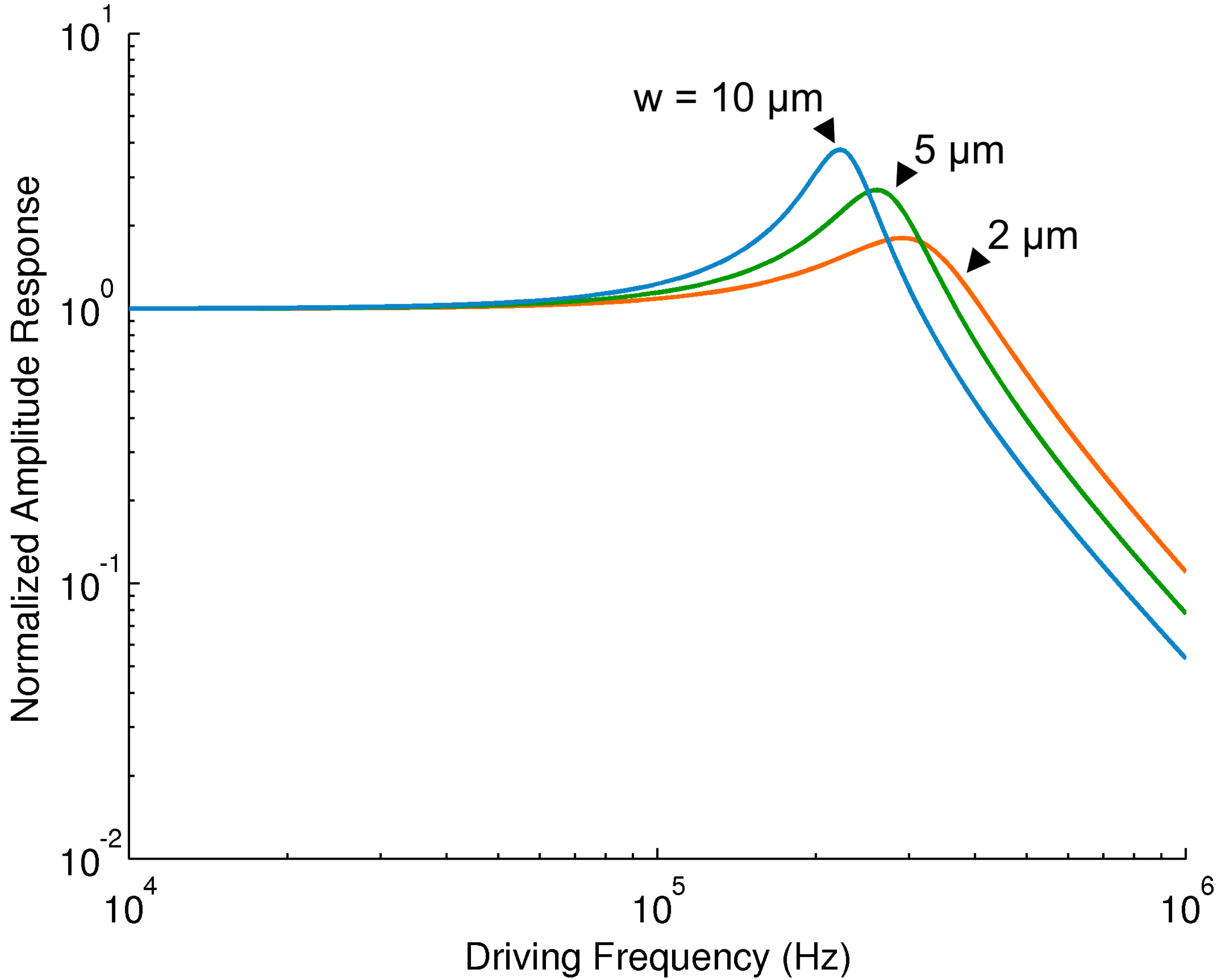
Prep Work	Fabrication	Characterization and Integration	Experiments
Piezoresistor design	Piezoresistive cantilevers	Noise and sensitivity	Cochlear Hair Cells
Initial piezoelectric characterization	Piezoelectric cantilevers	Material properties	Touch Receptor Neurons
Fabrication process flow	Combined devices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

Piezoresistor Design Optimization

- Harley (2000) investigated design optimization
- But some limitations
  - Only for epitaxy
  - Incomplete handling of constraints (power → dopant concentration)
  - Can't handle nonlinear processes (liquid damping, temperature, FEA)
  - Misapplied all the time (reasons?)

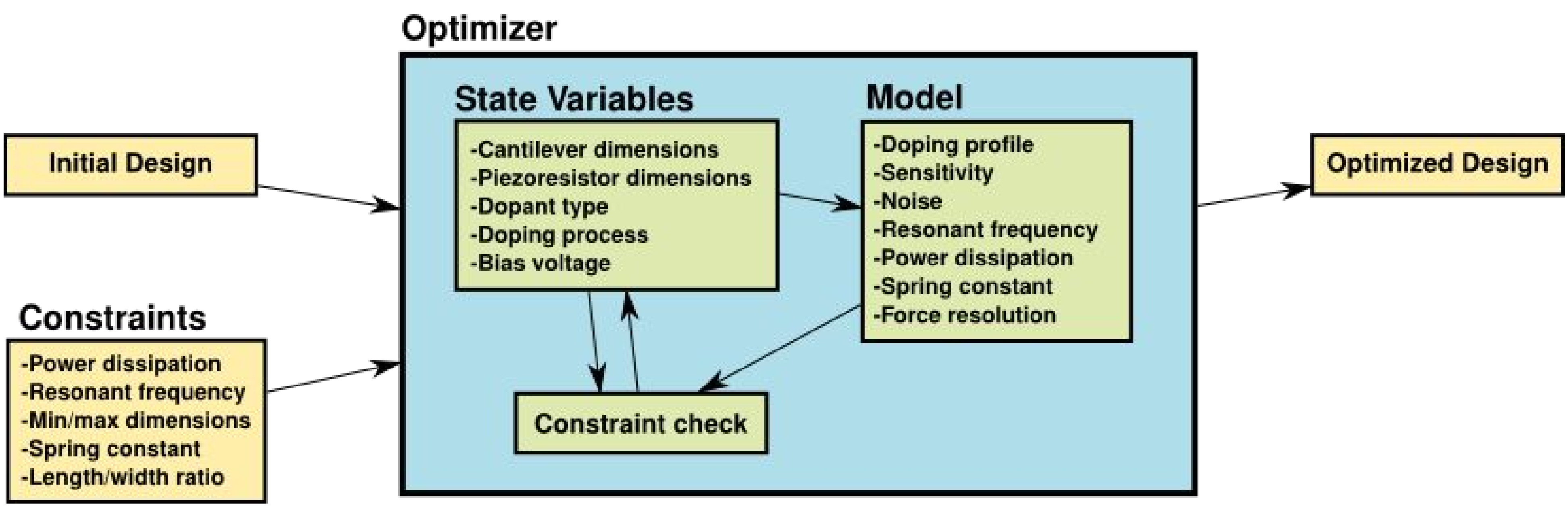


Cantilevers in Liquid

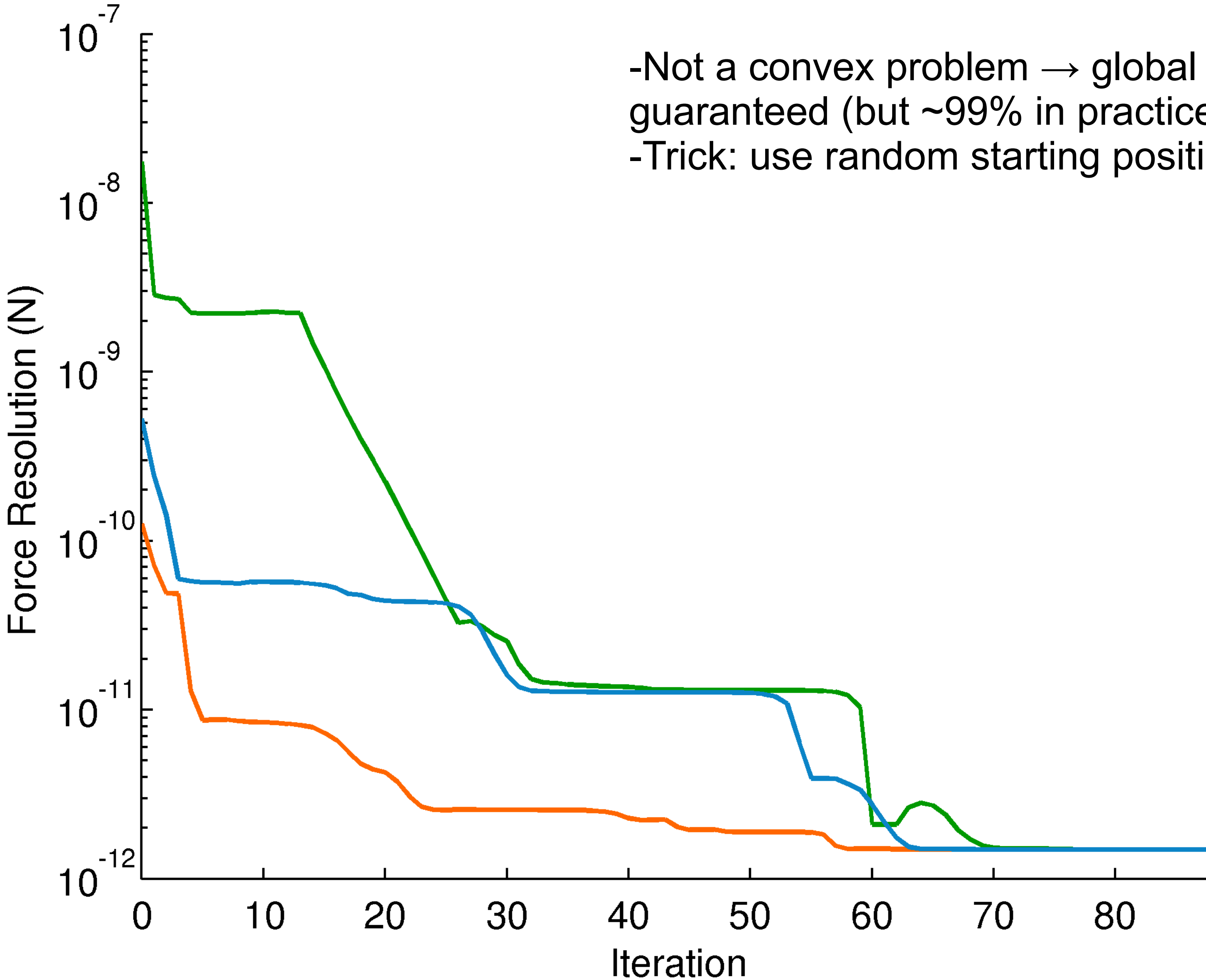


Piezoresistor Design Optimization

- Use standard optimization code (L-BFGS-B)
  - Available in Matlab, Python, C, etc.
  - Handles non-linear constraints and bounds
- Simple idea, some tricks in implementation (e.g. scaling)

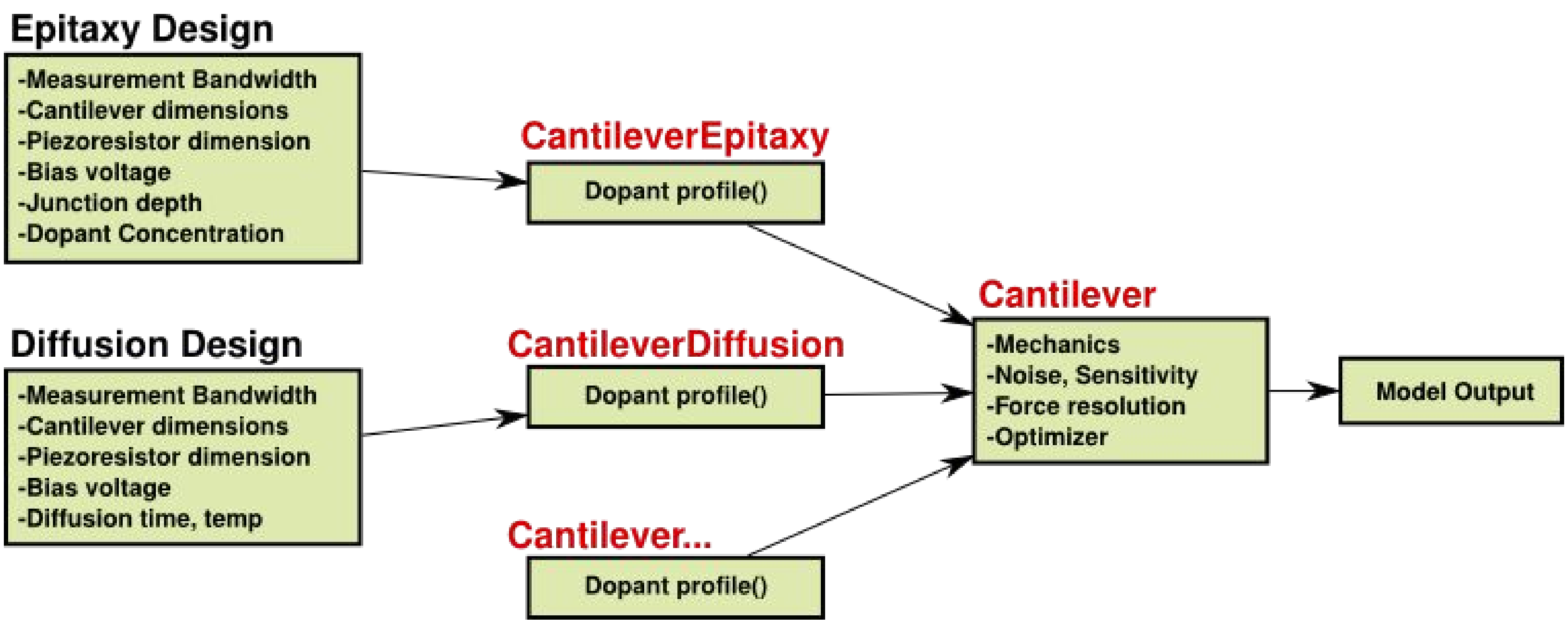


Local vs. Global Optima



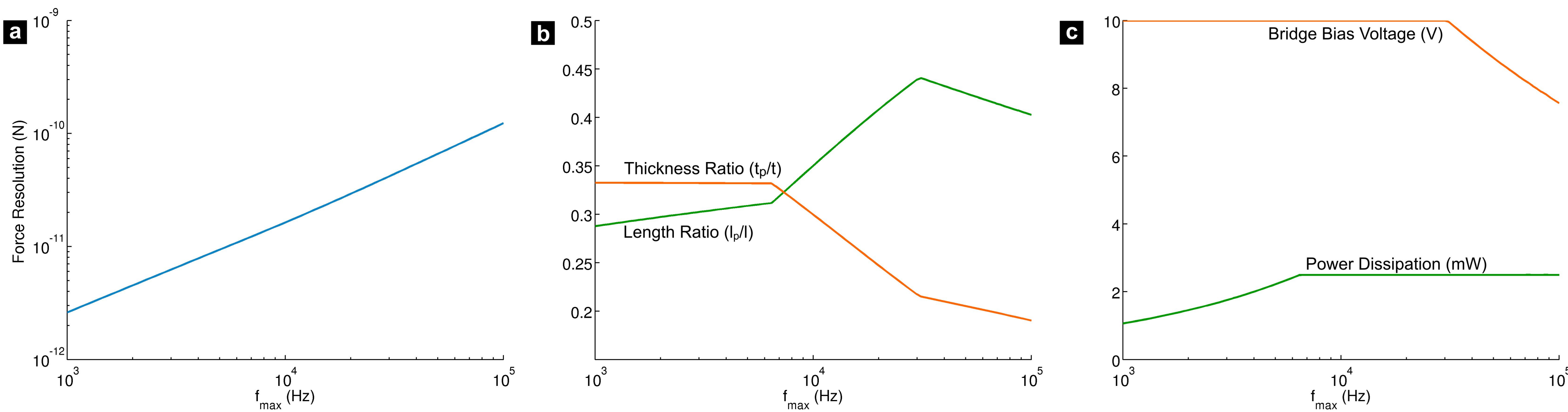
-Not a convex problem → global optimum not guaranteed (but ~99% in practice)
-Trick: use random starting positions, repeat

The Code



- Written in Matlab using Optimization Toolbox
- Object oriented, meant to be clean/extendable (plans for FEA down the line)
- Speed depends on model (10-15 sec for air, 1-2 min for water)
- Heavy lifting in Cantilever, specifics to particular fabrication processes in CantileverDiffusion etc.
- Code, examples @ microsystems.stanford.edu/piezod

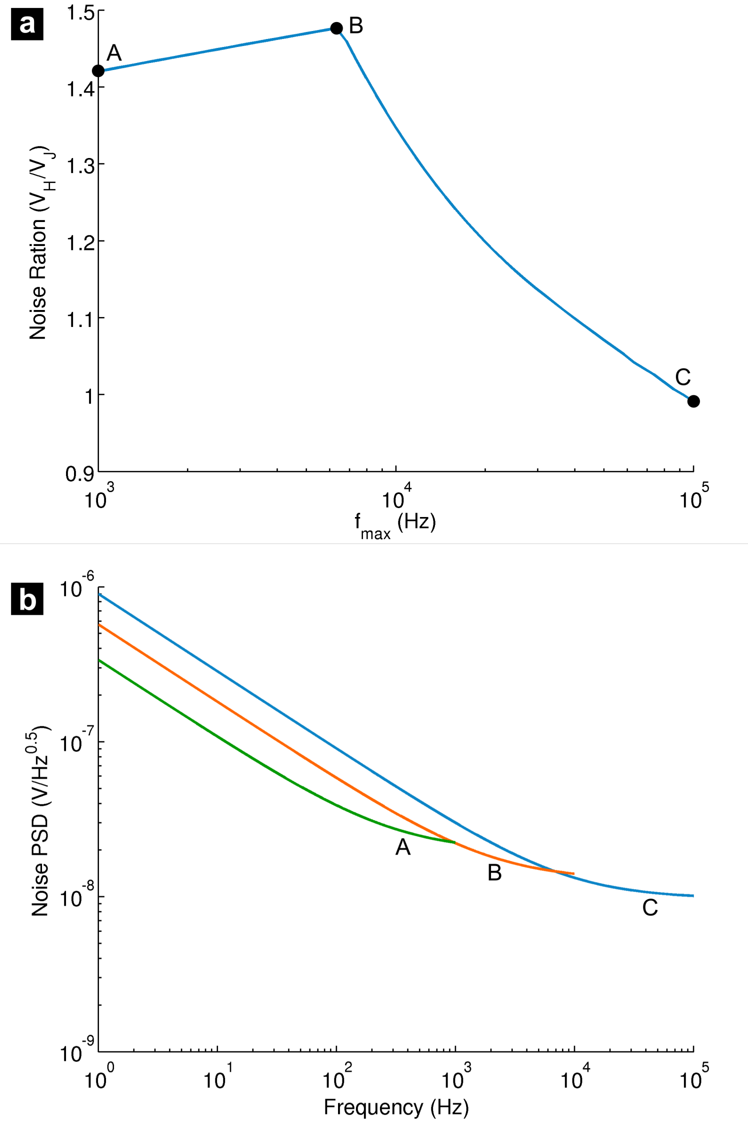
Some Optimization Results



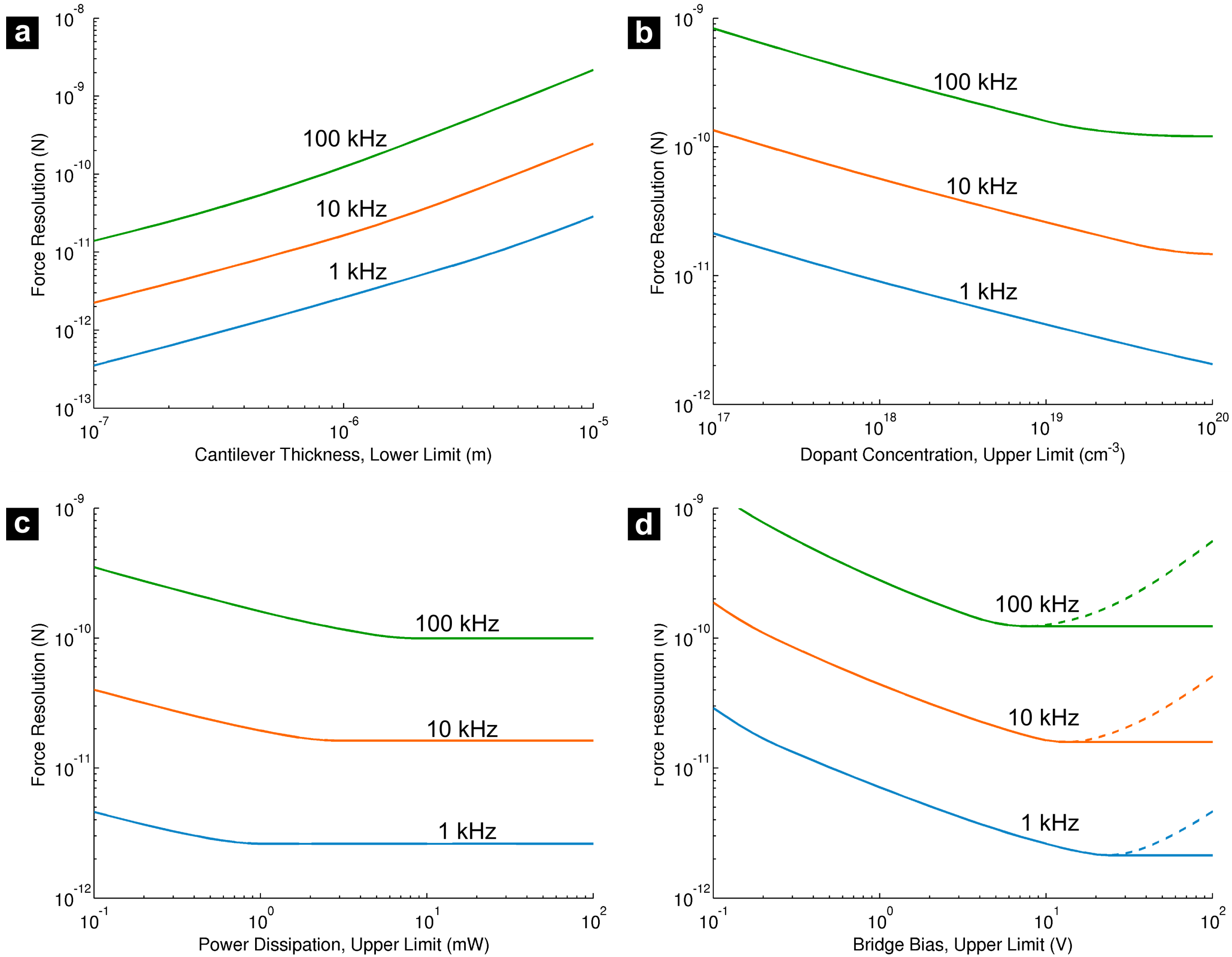
- Minimum detectable force increases with measurement bandwidth
  - Effect on noise, sensitivity
- Optimal design varies continuously
- Constraints matter

Some Optimization Results

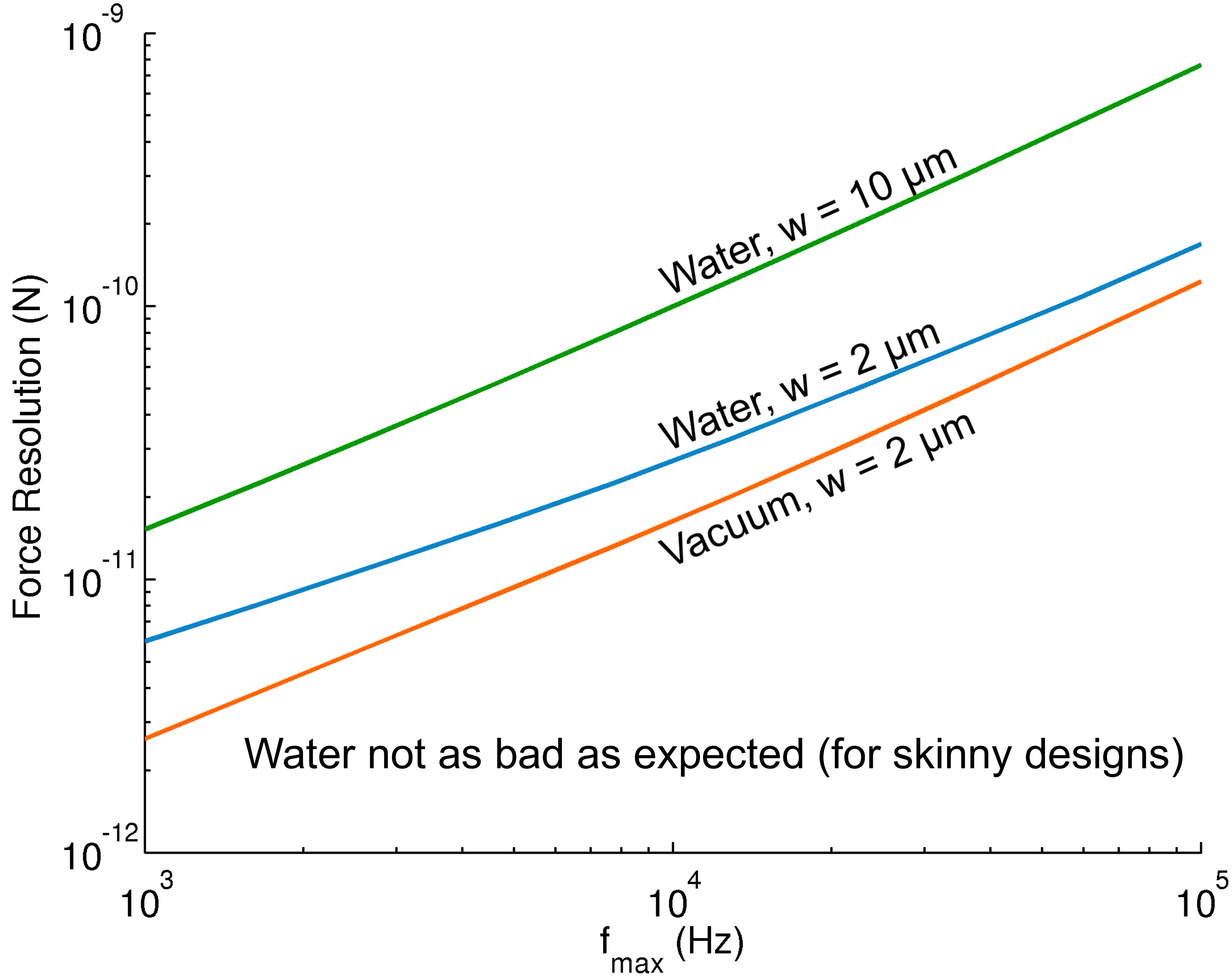
- Integrated Hooge and Johnson noise approx. equal for broadband force sensing
- Best device != quietest device
    - Benefit → easier testing



More About Constraints



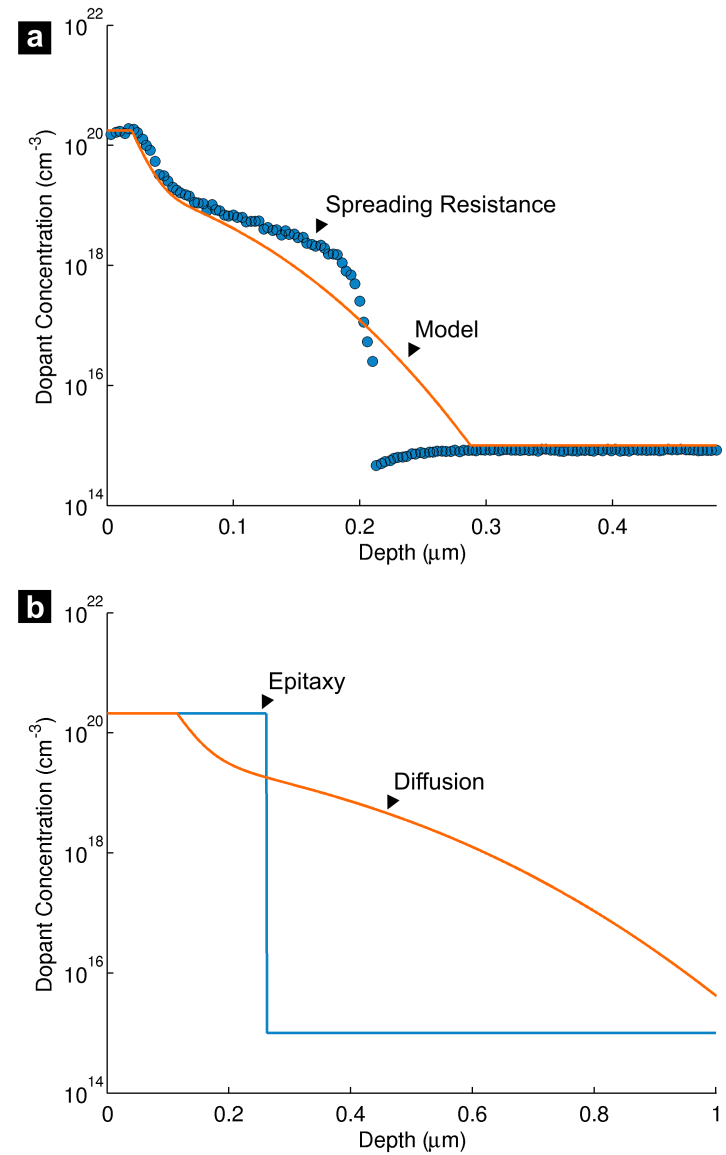
Water vs. Air



Force Resolution (N)
10^{-9}
10^{-10}
10^{-11}
10^{-12}
Water, w = 10 μm
Water, w = 2 μm
Vacuum, w = 2 μm
Water not as bad as expected (for skinny designs)
10^{3}
10^{4}
10^{5}
f_{max} (Hz)

Dopant Profile Comparison

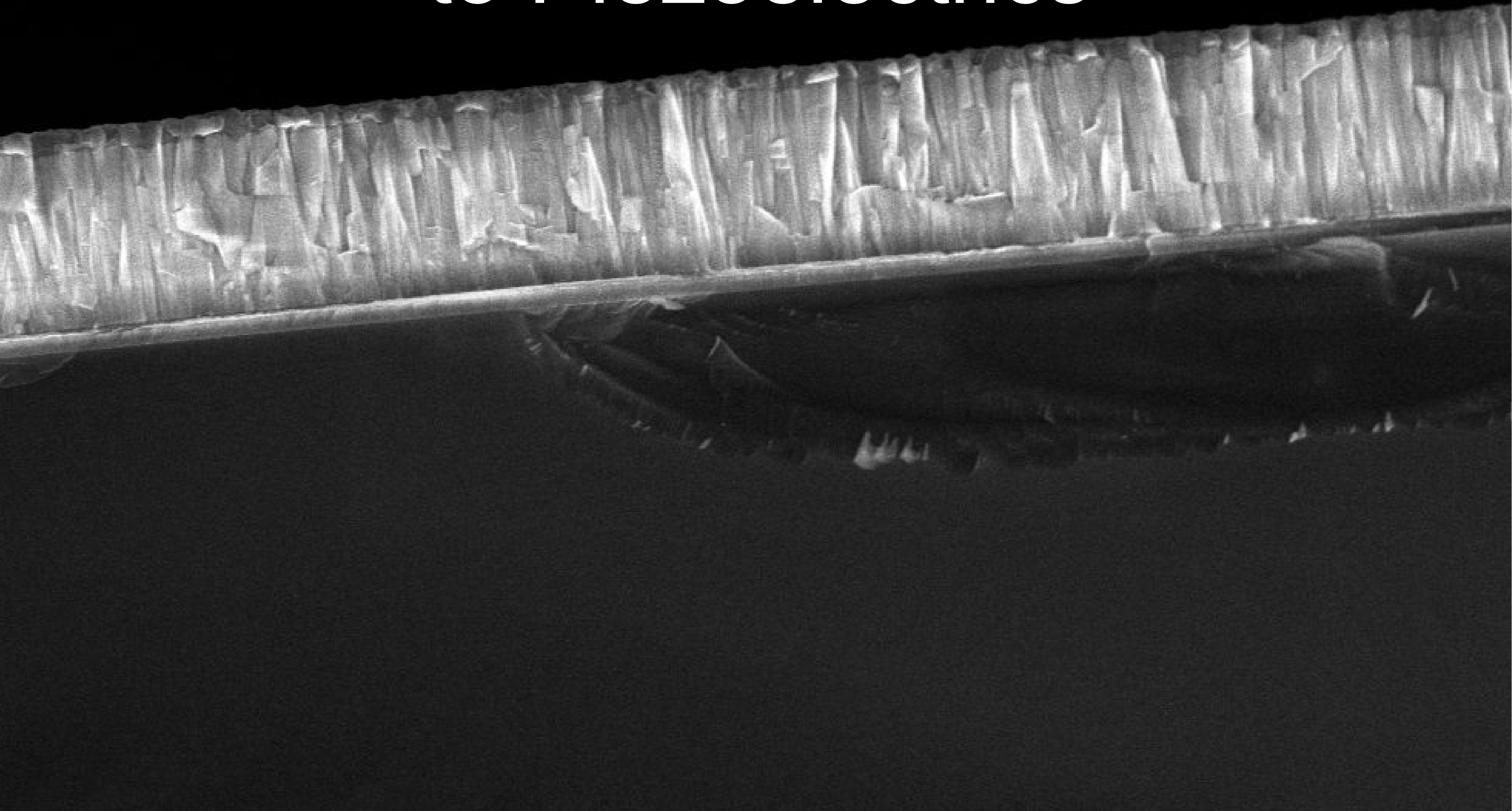
- Ideal junction depth doesn't generally equal 1/3 of cantilever thickness
- Depends strongly on constraints



PR Design Conclusions

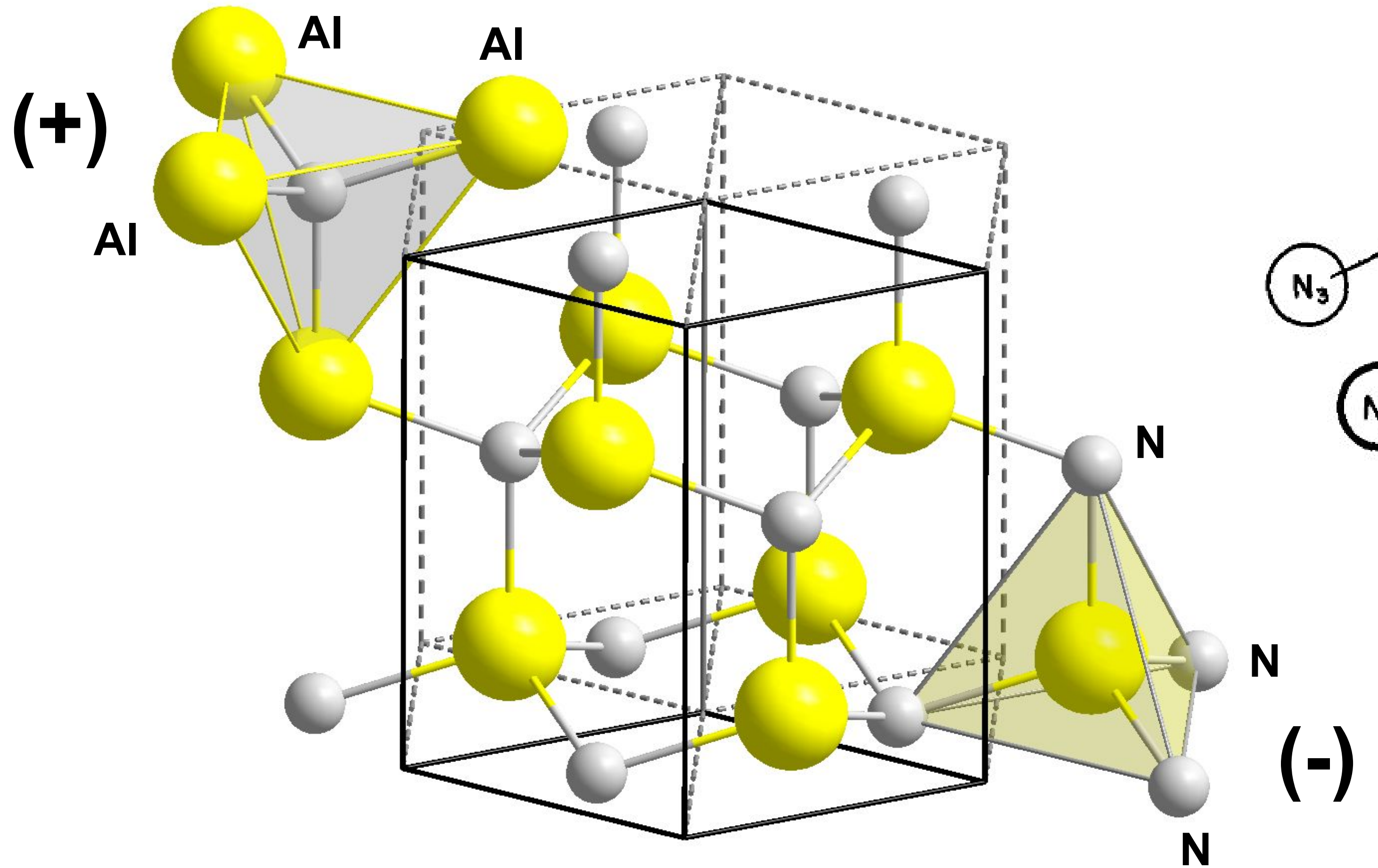
- Piezoresistive cantilever design is complicted
- Iterative numerical optimization worked surprisingly well → applicable to other problems
- Optimized designs depend very strongly on constraints, measurement bandwidth, doping process
- Use someone else's design at your own risk
- Hopefully this work will make it quicker and easier to generate designs

Switching Gears to Piezoelectrics



AlN Crystal Structure

- Wurtzite crystal structure
- Great material properties (6.2 eV band gap, stiffness, density, conductivity)
- Macroscopic piezoelectric response derived from microscopic grains
- Deposition via epitaxy, MOCVD, reactive sputtering (RF, pulsed DC)



http://en.wikipedia.org/wiki/Wurtzite_(crystal_structure)

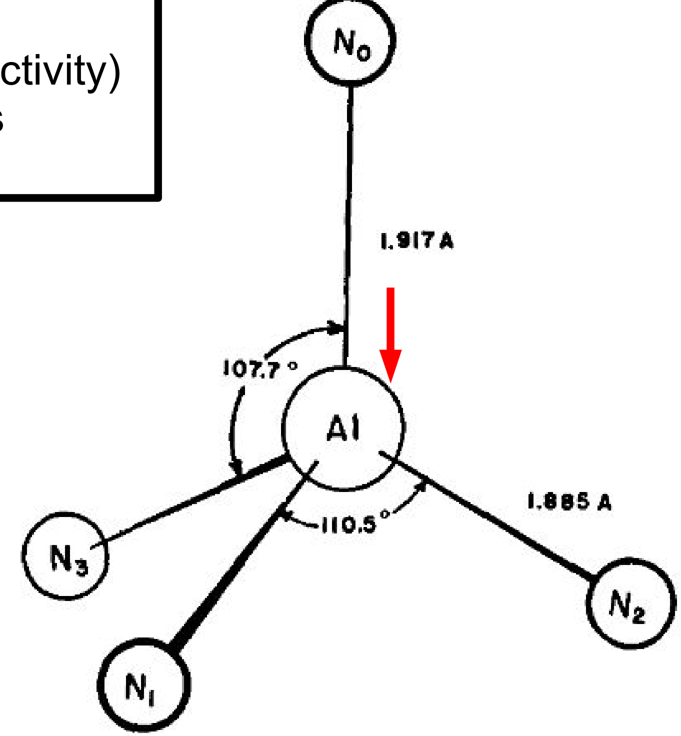


FIG. 1.

From Jeffrey, Parry, "Crystal structure of Aluminum Nitride", (1954)

Polarity

1) A uniform starting surface is crucial
2) Oxygen in the bulk leads to defects, but is less important than the surface
3) Can have zero piezoelectric response from good film texture

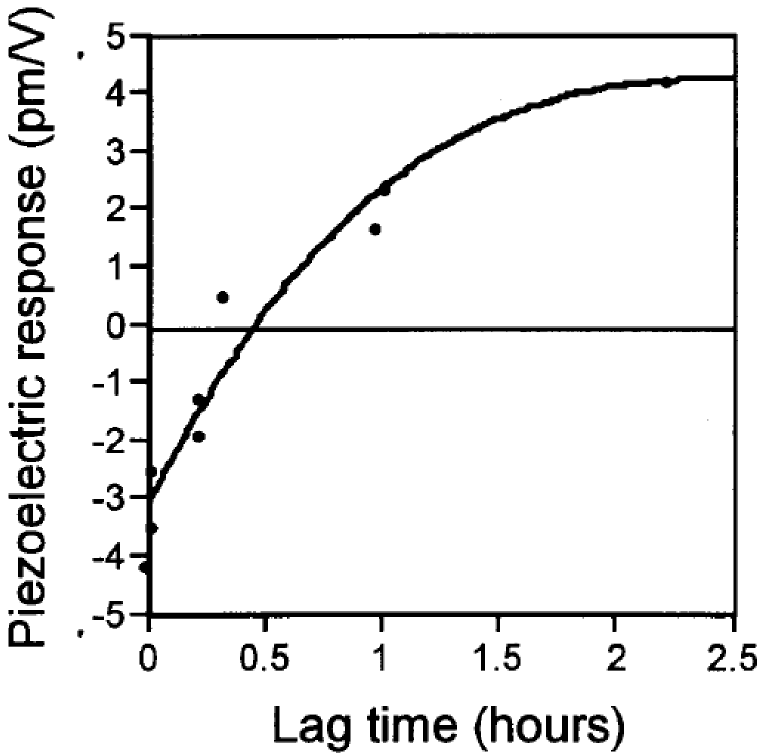
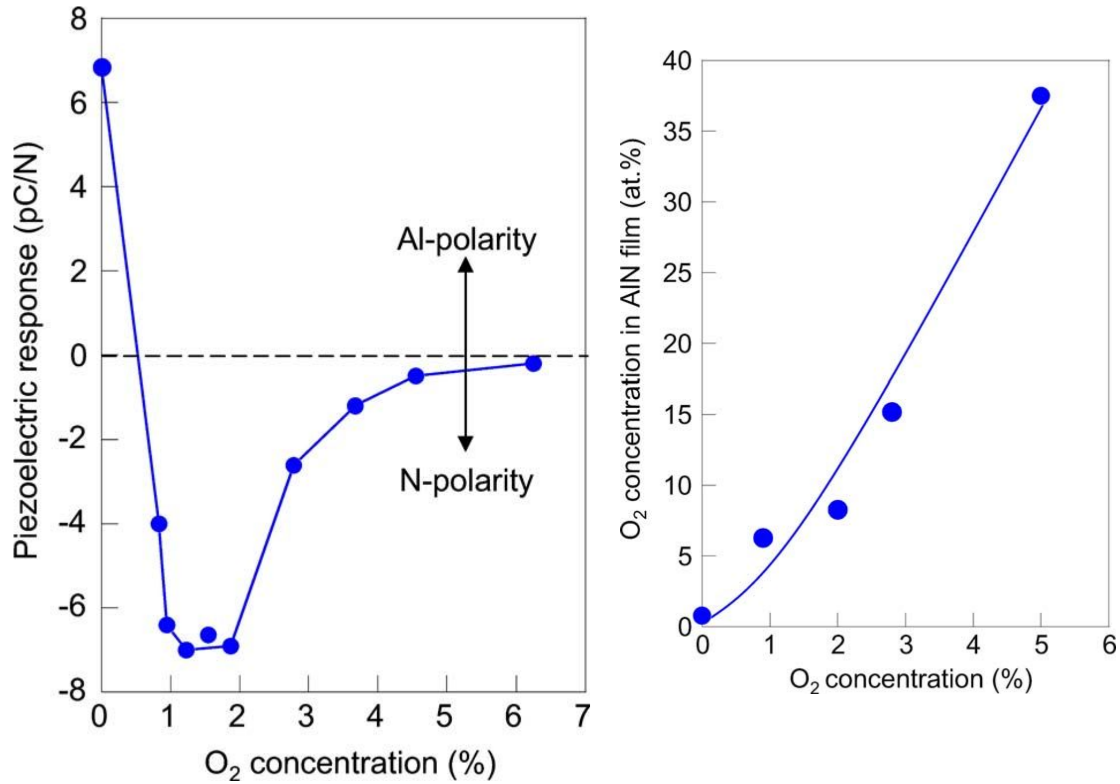


Fig. 1. Piezoelectric response as a function of lag time between deposition of Ru and AlN thin films.



From Ruffner et al, “Effect of substrate composition on the piezoelectric response of reactively sputtered AlN thin films” (1999)

From Akiyama et al, “Influence of oxygen concentration in sputtering gas on piezoelectric response of aluminum nitride thin films” (2008), Applied Physics Letters

Importance of Grain Alignment?

Jury still out on if grain alignment really matters for actuation performance

MOCVD on Si(111), in-situ clean

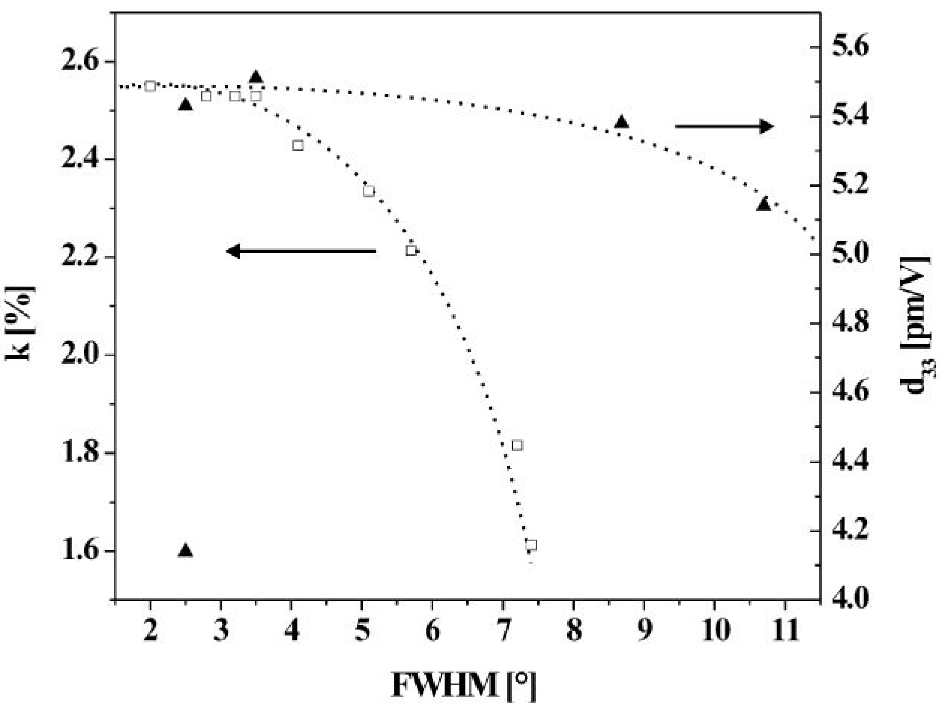


Fig. 7. Comparison of the dependency of the coupling factor k in % [13] and of the effective piezoelectric coefficient $d_{33\text{eff}}$ in pm/V (this work) on the FWHM in degree.

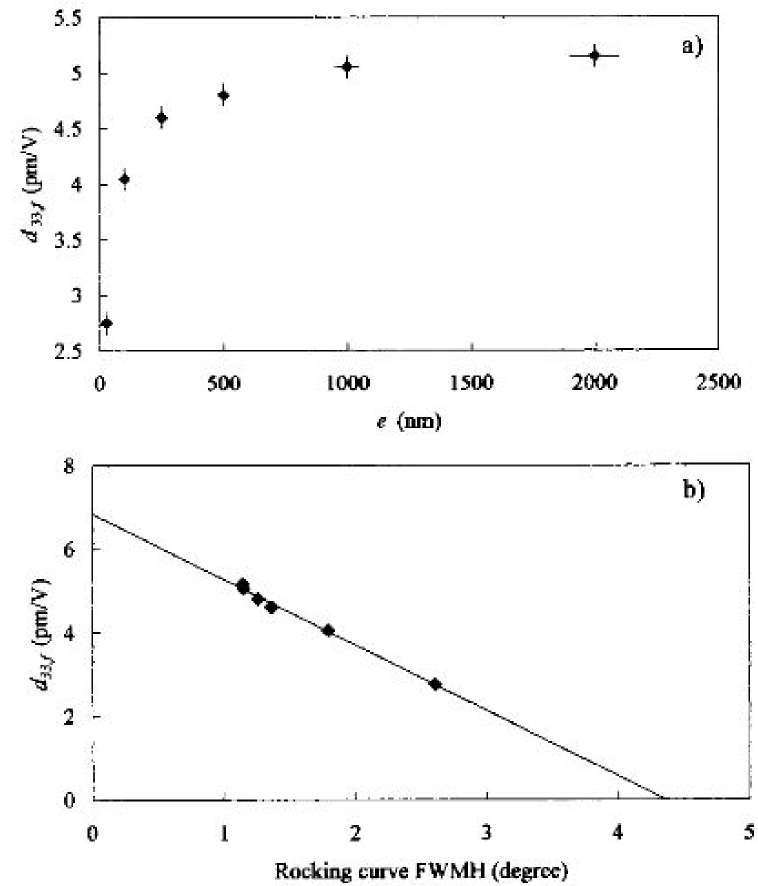
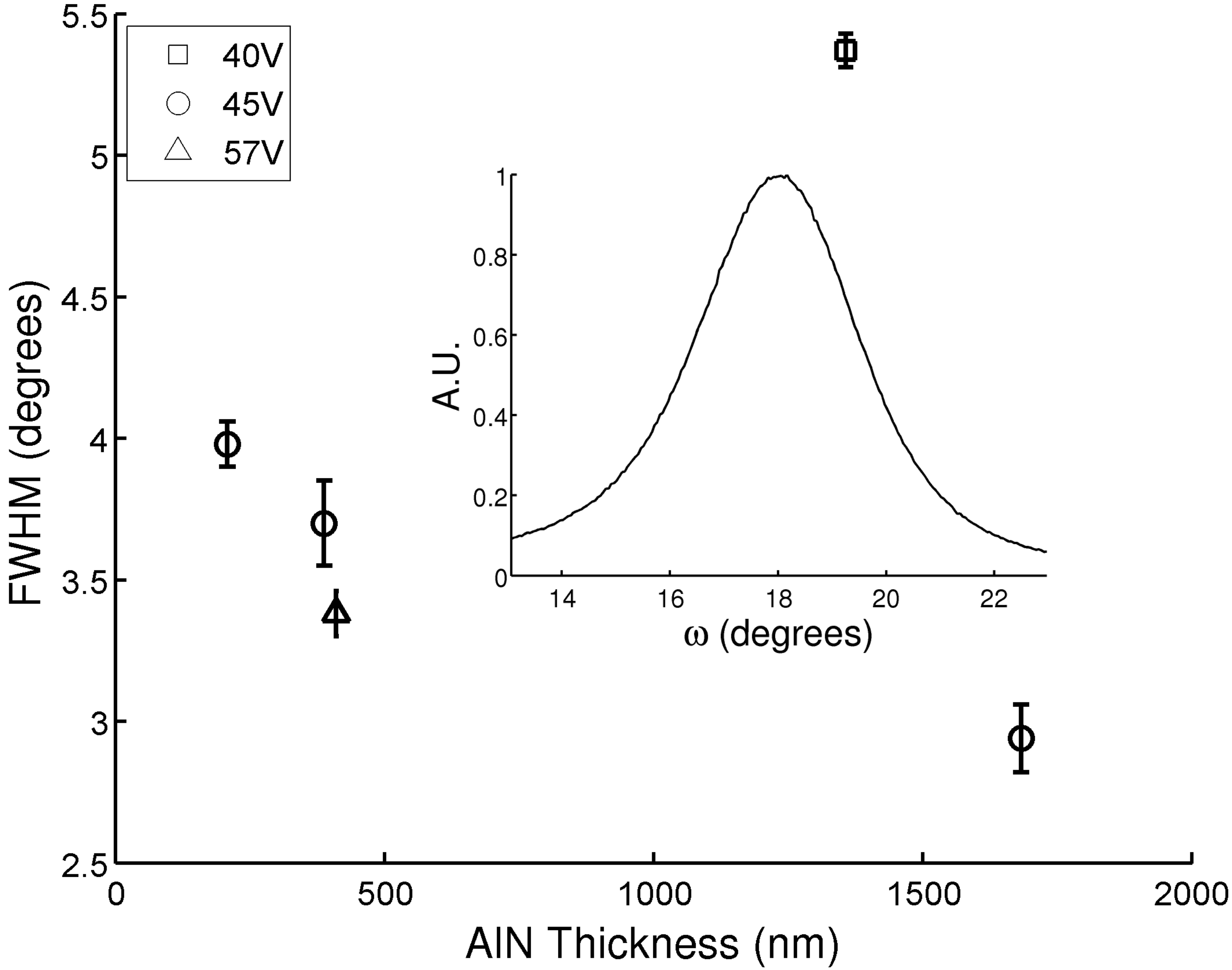


FIG. 7. Piezoelectric coefficient $d_{33,f}$ as a function of (a) AlN thin-film thickness and (b) rocking curve FWMH.

From Tonisch et al, "Piezoelectric properties of polycrystallined AlN thin films for MEMS application" (2006), SensActA

From Martin et al, "Thickness dependence of the properties of highly c-axis textured AlN thin films (2004), JVacSciTech

Film Characterization



AlN Fabrication

- CMOS compatible means many things
- Surface and bulk micromachined devices demonstrated on noble metals
- No piezoelectric process using CMOS compatible materials and processes reported to date

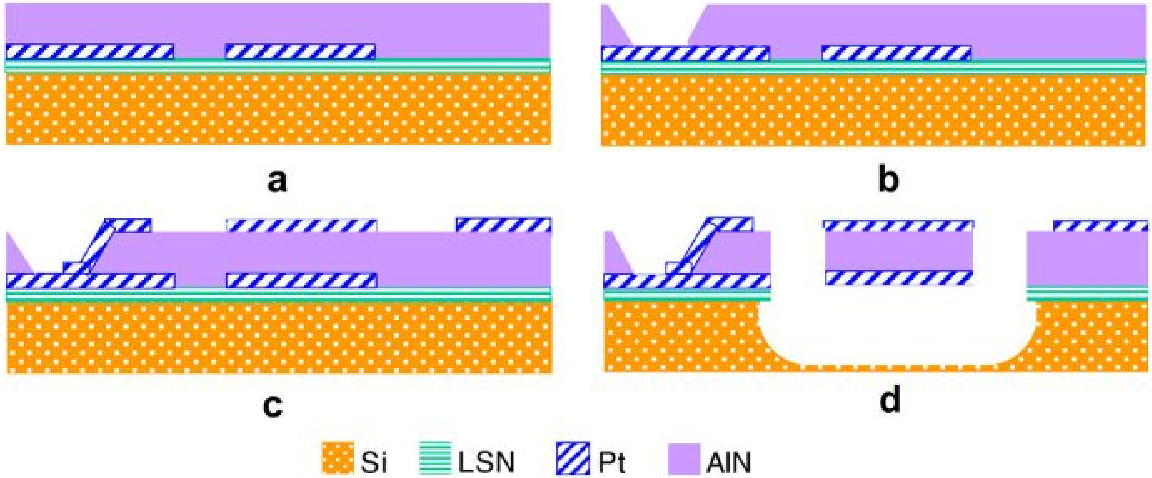
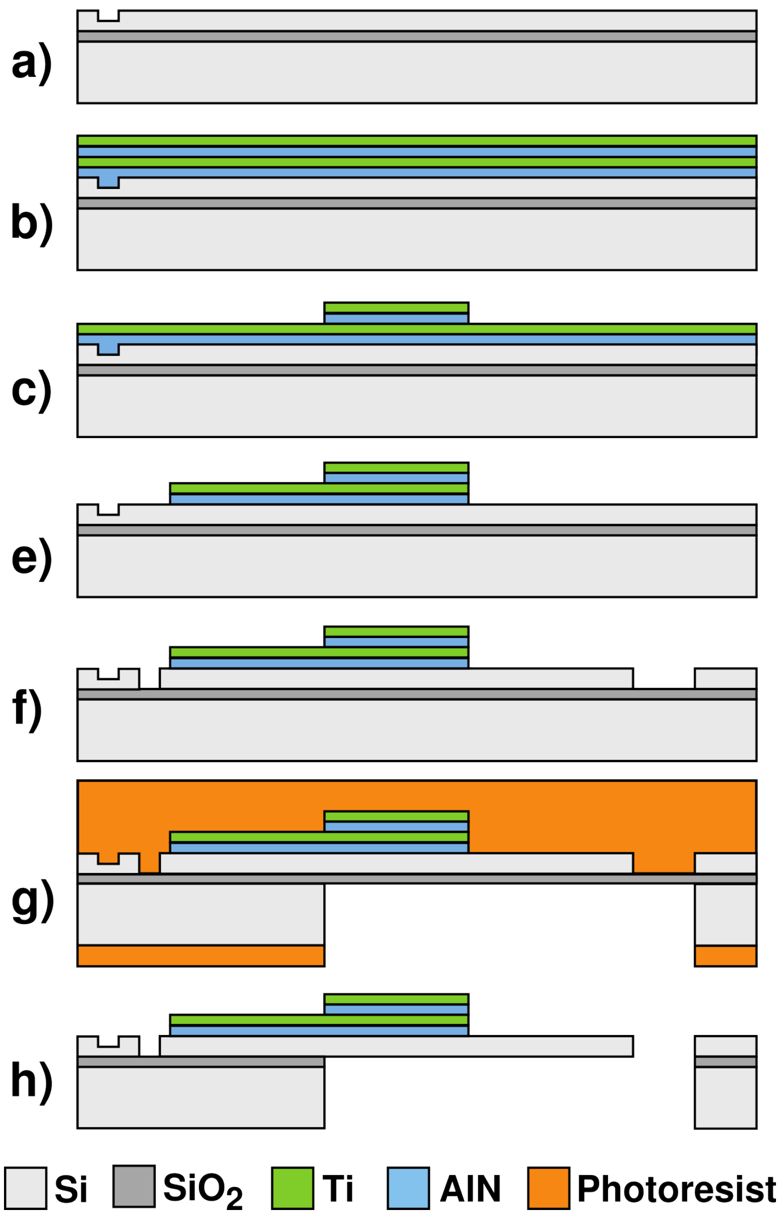


Fig. 9. Schematic representation of the fabrication process employed for the making of contour-mode AlN resonators. (a) Low stress nitride (LSN) deposition by LPCVD, followed by Pt patterning by lift-off and AlN sputter deposition; (b) Open via access to bottom Pt electrode through AlN. AlN is wet etched by 160 °C H_3PO_4; (c) Deposition of top Pt electrode and patterning by lift-off and (d) Cl_2-based dry etching of AlN resonant device and dry release in XeF_2.

From Piazza et al, “One and two port piezoelectric higher order contour-mode MEMS resonators for mechanical signal processing” (2007), SolidStateElec

AlN Fabrication



Start with SOI, alignment marks

Sputter AlN/Ti/AlN/Ti stack

Etch top Ti and AlN (HF and TMAH)

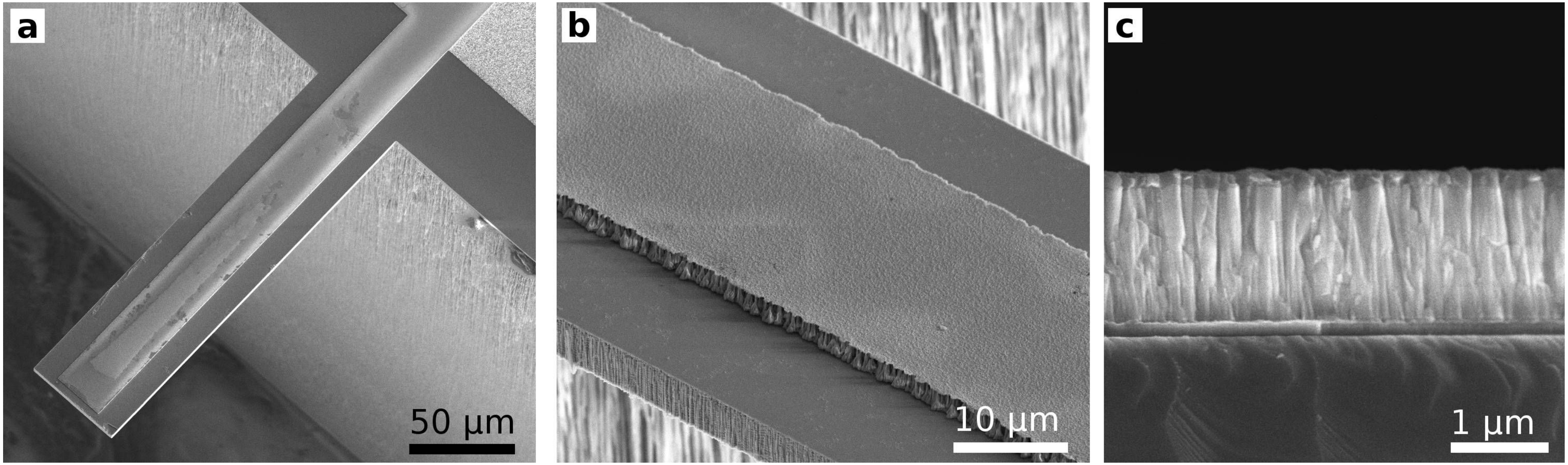
Etch bottom Ti and AlN (HF and TMAH)

Define cantilever by RIE or DRIE

Protect frontside, etch backside by DRIE

Release BOX by RIE

Finished Device SEMs

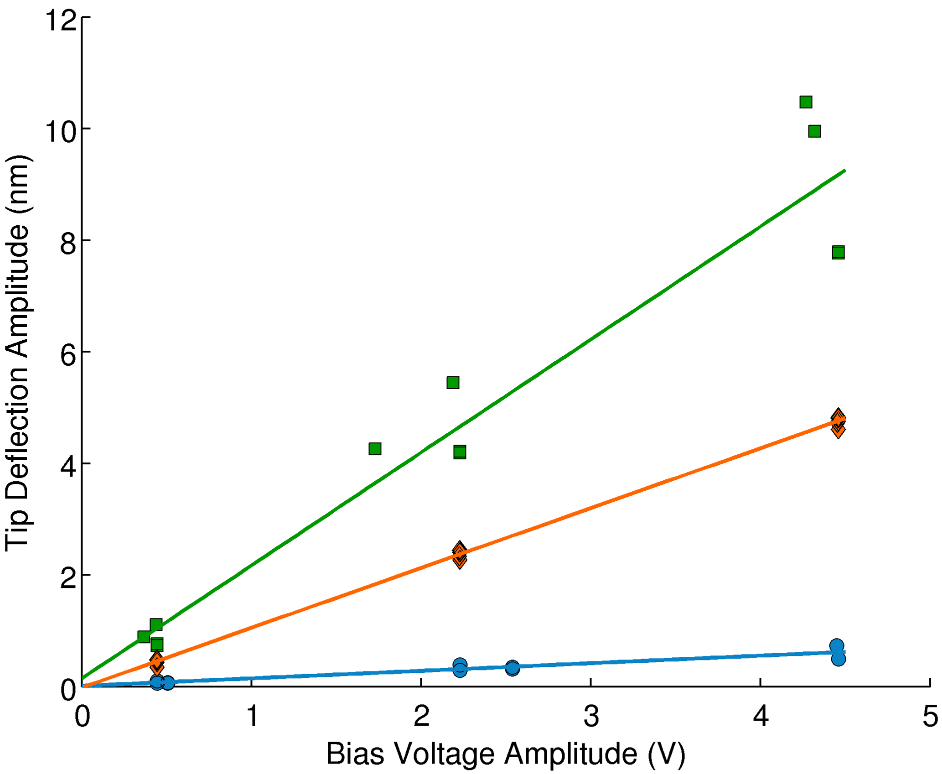


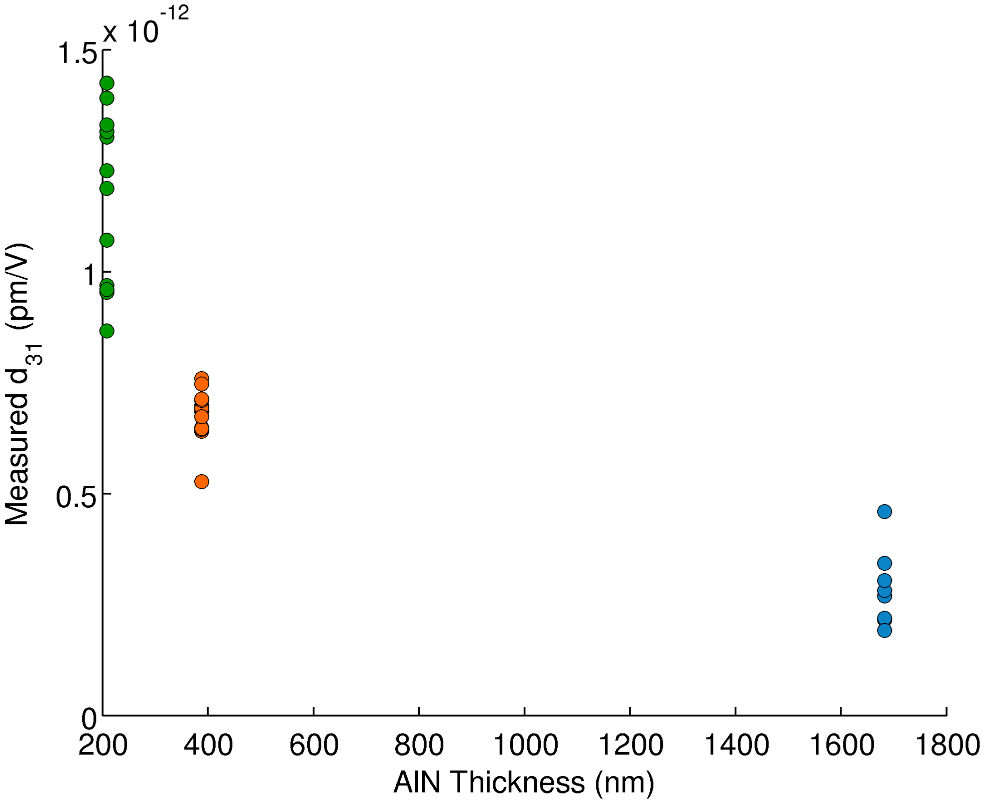
Fabrication/Testing Issues

- If Ti etch isn't complete, it masks the AlN etch
- Wirebonding issues (~30% success rate due to shorting, work in progress)

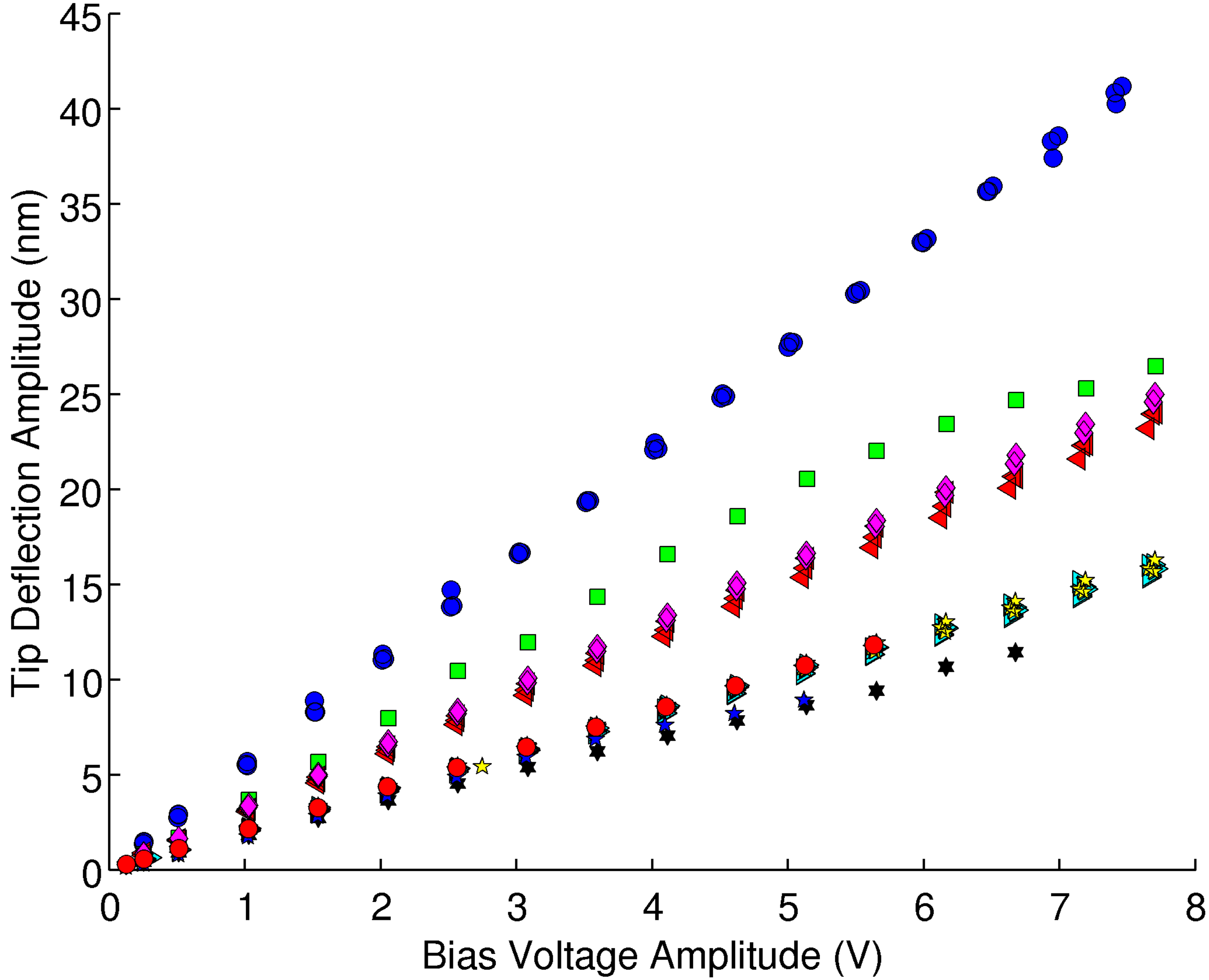
Wafer	Design #	Image #	Label	Status	Wirebonder	NOTES	Measured Instantaneous Resistance, Multimeter (Ohm)	Measured Impedance, 10 kHz (Ohm)
282-5	?		3*X	broken cantilever	mccullough		2.63E+01	26.57
282-5	3	17,18	3	medium impedance	mccullough		1.18E+04	10180
282-5	3		3B	medium impedance	kenny		8.50E+04	77600
282-5	3		3C	low impedance	kenny		3.30E+01	34.17
282-5	3		3D	high impedance	kenny	d31 done	Open	241300
282-5	1	14,15,16	1A	high impedance	mccullough	d31 done	1.80E+06	234900
282-5	1	19,20,21	1B	high impedance	mccullough	d31 done	Open	266800
282-5	1	22,23,24	1C	high impedance	mccullough	d31 done	Open	266400
282-5	1	25,26,27	1D	broken cantilever	mccullough		Open	268300
282-5	1		1E	low impedance	kenny		4.54E+01	41.98
282-5	2		2A	high impedance	kenny	d31 done	Open	262000
282-5	2		2B	low impedance	kenny		4.56E+01	48.03
282-4	1	11,12,13	1A	high impedance	mccullough	d31 done	Open	135400
282-4	1	7,8	1B	low impedance	kenny		1.96E+01	19.82
282-4	1	9,10	1C	low impedance	kenny		5.91E+02	533.2
282-4	1		1BX	missing	mccullough			
282-4	1	35,36,37	1CX	low impedance	mccullough + kenny		5.75E+01	51.98
282-4	1	38,39	1DX	low impedance	mccullough + kenny		4.33E+01	45.21
282-4	2		2A	low impedance	kenny		2.93E+01	29.83
282-4	3		3A	low impedance	kenny		1.24E+01	12.49
282-4	3		3B	low impedance	kenny		1.08E+01	11.05

Original Device Characterization

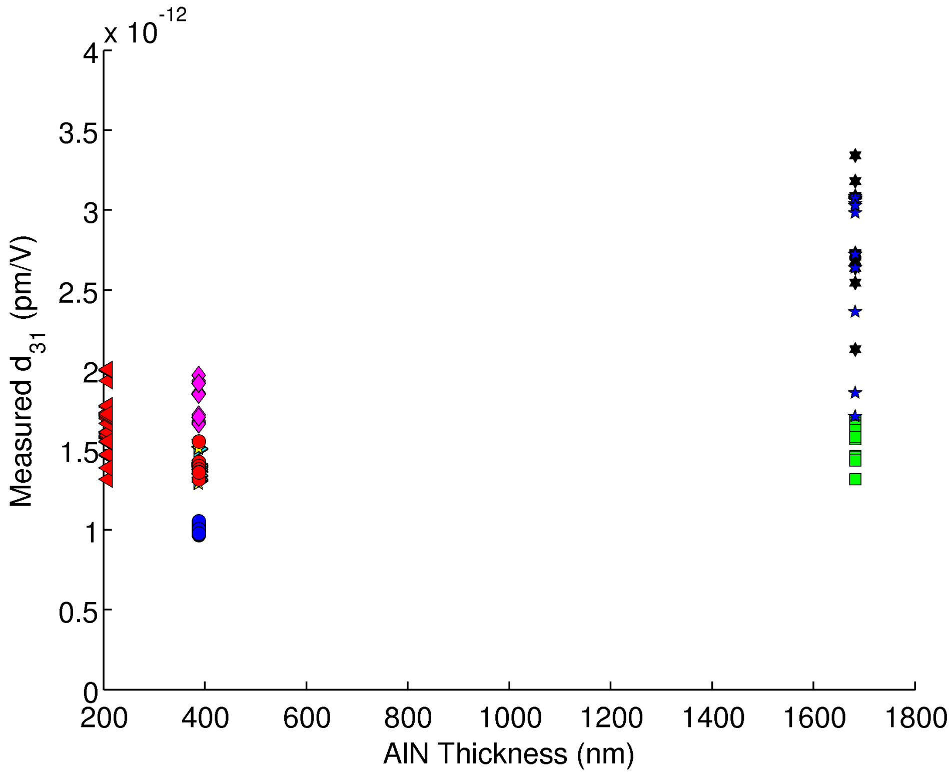


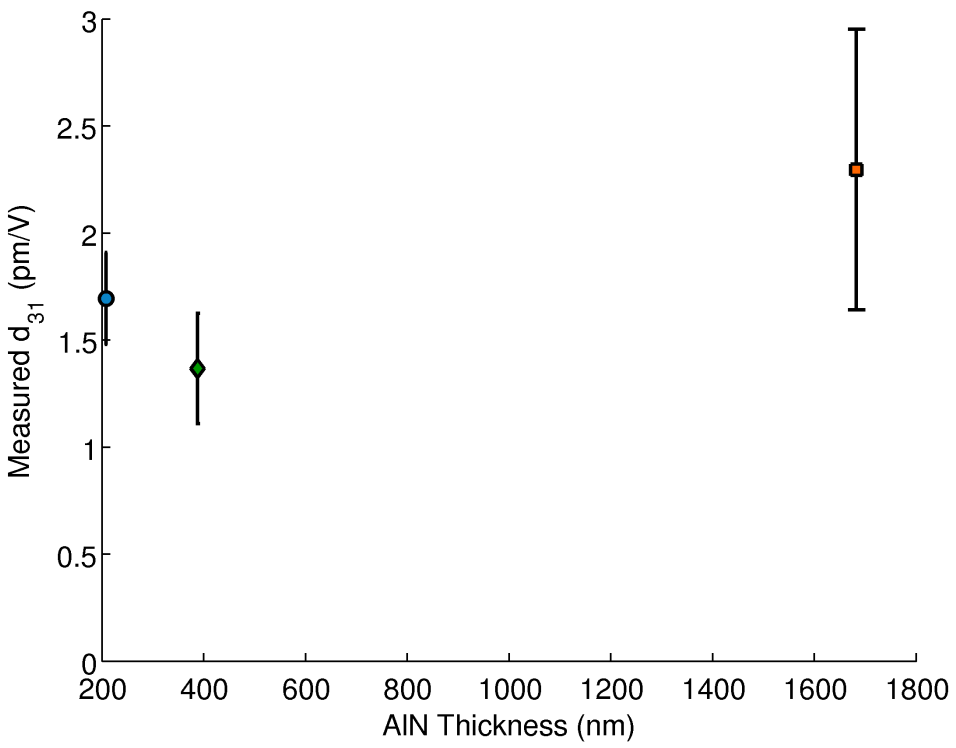


Recent Device Characterization

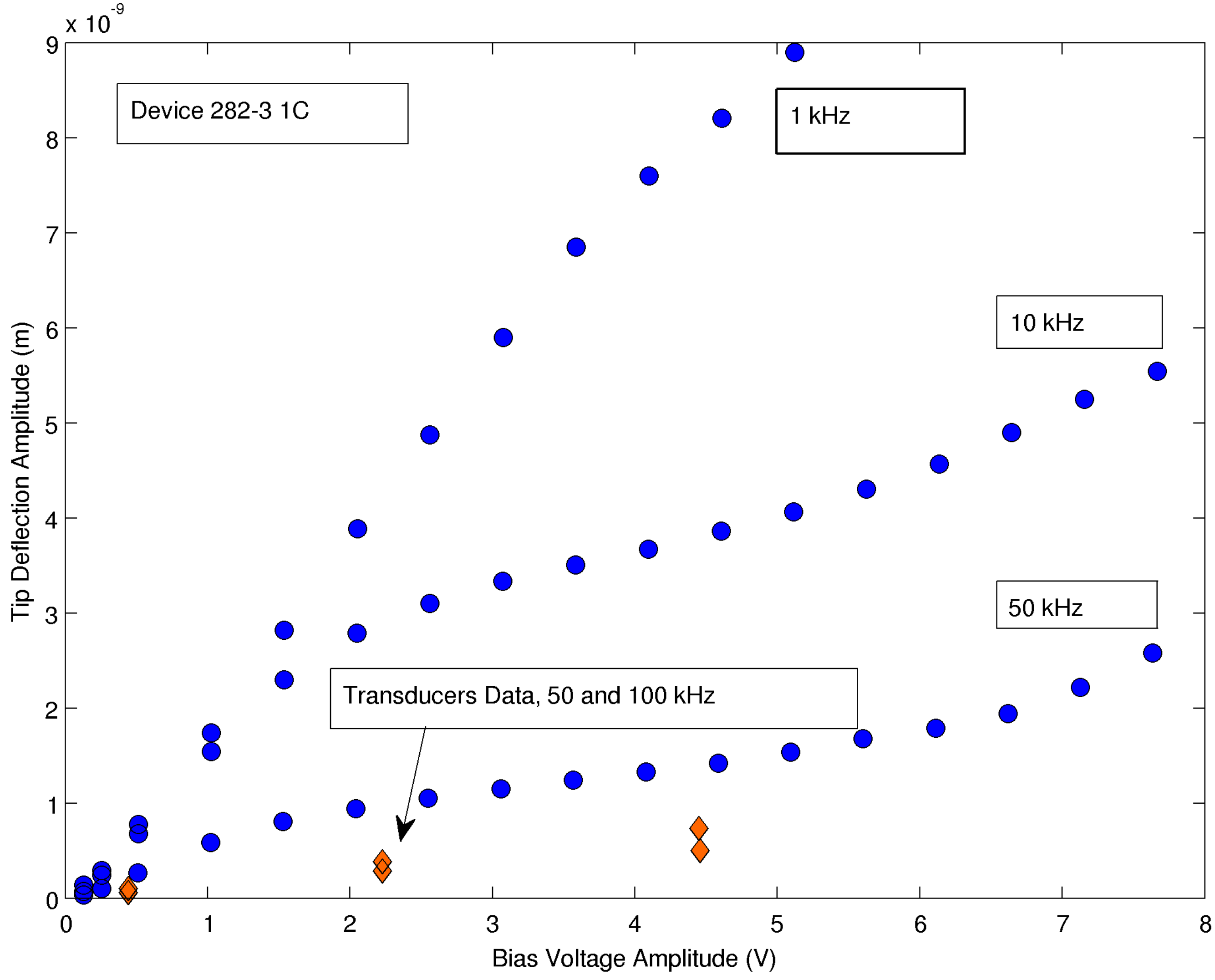


Recent Device Characterization





Why the Differences?



AlN Conclusions

- Optimized deposition process for AlN on Ti by pulsed DC sputtering
- Demonstrated a process for CMOS compatible micromachined MEMS actuators and characterized device performance
- Hopefully this will make piezoelectrics an easier option

Ongoing Work

- Test PR+PE devices
  - Verify PR, PE operation
  - Test cross-talk, impedance
  - Open loop actuation
- Integration issues
  - Closed loop system modeling
  - Integrated drive and sensing circuit