DESIGN OF PIEZORESISTIVE VS. PIEZOELECTRIC CONTACT MODE SCANNING PROBES

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Introduction

Scanning probes are widely used to characterize surface structures and forces. Piezoresistive (PR) and piezoelectric (PE) transduction are popular alternatives to optical methods. However, their performance has not been directly compared to date. We have combined analytical models with numerical optimization techniques in order to provide a comprehensive comparison of PR and PE cantilevers. We compare p-type (boron) epitaxial PR cantilevers with aluminum nitride (AlN) and lead zirconate titanate (PZT) PE cantilevers.

Design Optimization

We implemented the noise and sensitivity models in Matlab and use a standard parametric optimizer. The problem is not convex, so we start from random initial guesses until multiple converge to the same value. We previously used this approach for PR cantilever design **[4]**. The code is open-source and freely available **[5]**.

Optimization constraints

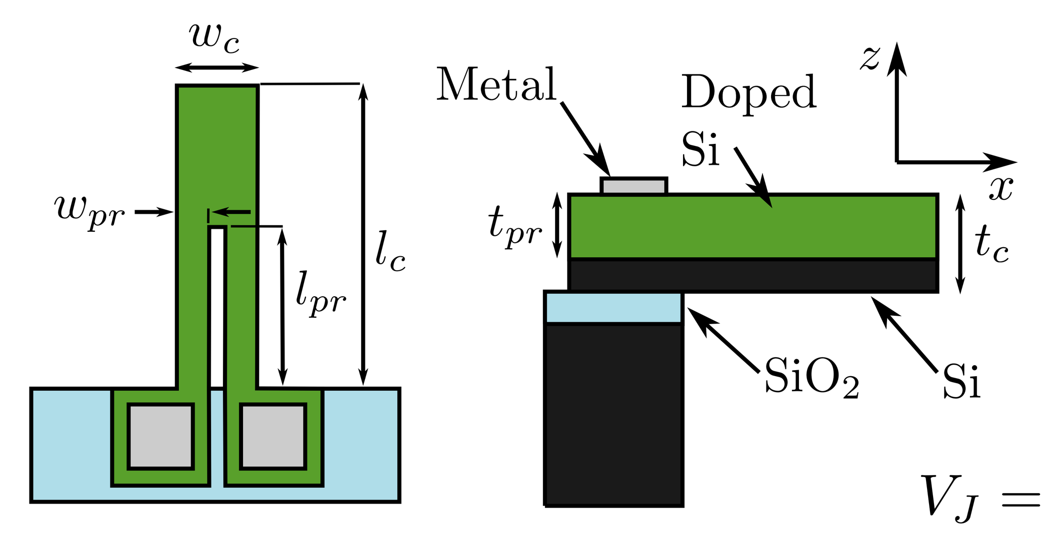
$$t_c \geq 1\ \mu\mathrm{m}$$
$$w_c \geq 5 t_c$$
$$l_c \geq 5 w_c$$
$$t_{pe} \geq 200\ \mathrm{nm}$$
$$R_{shunt} \leq 1\ \mathrm{T\Omega}$$
$$n \leq 4.4 \times 10^{19}/\mathrm{cc}$$
$$f_0 \geq 2 f_{max}$$
$$W \leq 1\ \mathrm{mW}$$

Material Properties

We used the following material properties in all calculations. However, piezoelectric film properties vary substantially. We treated this uncertainty by surveying the literature to find the range of typical property values, and used the Monte Carlo method to investigate their impact.

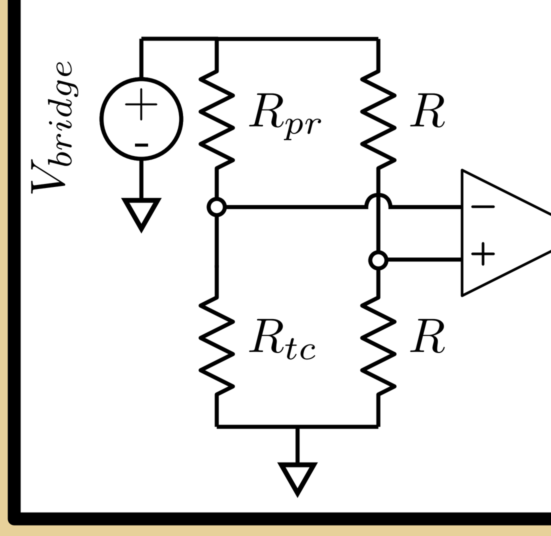
Matl	E (GPa)	ρ (kg/m^3)	d_{31} (pC/N)	ϵ_r	ρ (Ω-cm)
Si	169	2330	-	-	-
Ti	90	4500	-	-	-
AlN	396 ± 40	3260	2.2 ± 0.5	10.2 ± 0.5	10^{12}
PZT	55 ± 20	7550	70 ± 30	900 ± 300	10^{8}

PR Cantilever Model



The PR sensitivity is analyzed using Bernoulli beam theory, and the signal is transduced using a Wheatstone bridge. A temperature compensation PR is included. The model includes piezoresistor noise (Johnson, Hooge), amplifier voltage and current noise, and thermomechanical noise.

$$V_J = \sqrt{4 k_b T R_{pr}} \quad V_H = \sqrt{\frac{\alpha V_{bridge}^2}{2 N f}} \quad F_{TH} = \sqrt{\frac{2 k k_b T}{\pi f_0 Q}}$$



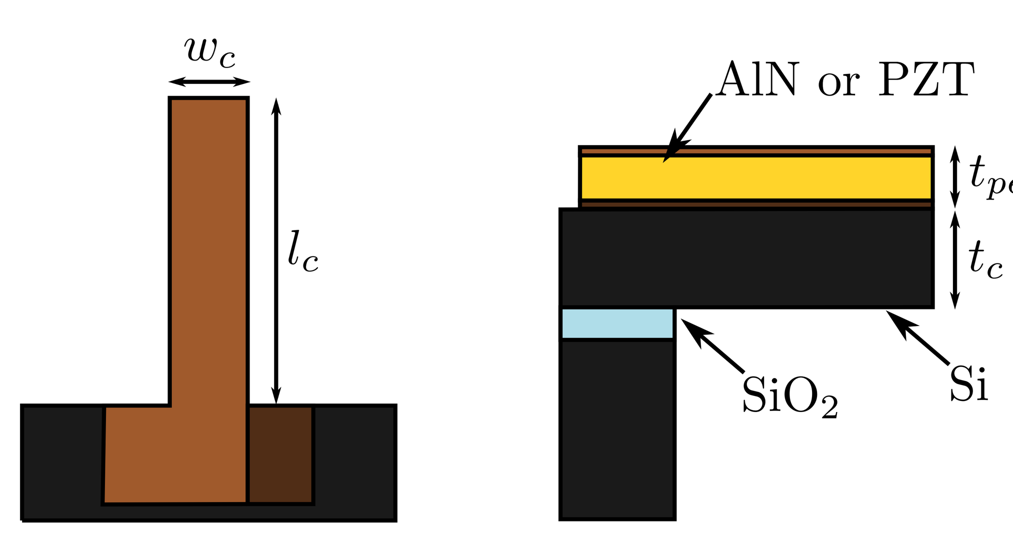
α = Hooge parameter
Q = Quality factor **[2]**
β^* = PR sensitivity factor
γ = Resistance factor
N = Number of carriers

$$V_A = \sqrt{A_{VJ}^2 + \frac{A_{IJ}^2 R_{pr}^2}{2} + \frac{1}{f}\left[A_{VF}^2 + \frac{A_{IF}^2 R_{pr}^2}{2}\right]}$$

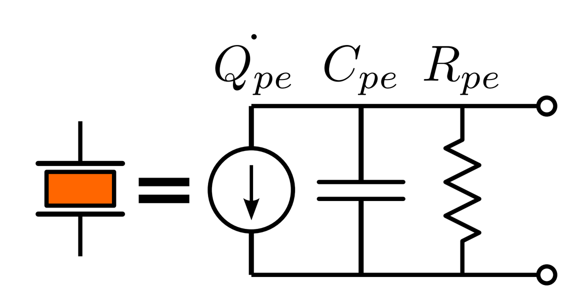
$$S_{FV} = \frac{\Delta V}{\Delta F} = \frac{3\pi_0 \beta^* \gamma (l_c - l_{pr}/2)}{2 w_c t_c^2} V_{bridge}$$

$$S_{XV} = \frac{\Delta V}{\Delta X} = \frac{3 E_c \pi_0 \beta^* \gamma (l_c - l_p/2) t_c}{8 l_c^3} V_{bridge}$$

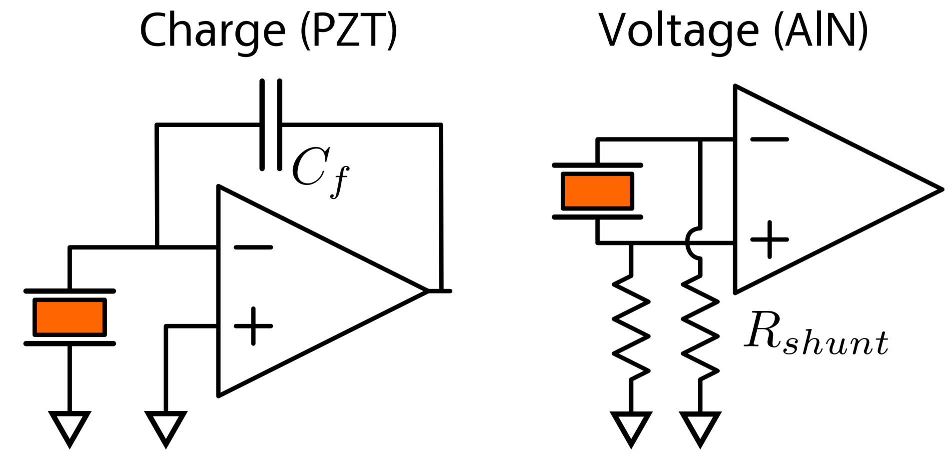
PE Cantilever Model



The PE sensitivity is analyzed using beam theory as in **[3]**. The model includes the metal electrode thickness (50 nm) and amplifier input capacitance (0.2 pF). The model includes PE Johnson noise, amplifier voltage and current noise, and thermomechanical noise.



$$V_J = \frac{\sqrt{4 k_b T R_{pe}}}{1 + 2\pi f R_{pe} C_{pe}}$$
$$Q_J = V_J C_{pe}$$



$$z_n = \frac{\sum_i z_i E_i A_i}{\sum_i E_i A_i} \qquad C_m = \frac{1}{\sum_i E_i (I_i + A_i (z_i - z_n)^2)}$$

$$S_{FQ} = \frac{\Delta Q}{\Delta F} = \frac{1}{2} d_{31} E_{pe} (z_n - z_{pe}) C_m l_c^2 w_c$$

$$S_{FV} = \frac{\Delta V}{\Delta F} = \frac{2\pi f S_{FQ} R_{pe}}{1 + 2\pi f R_{pe} C_{pe}}$$

Results and Discussion

Cantilever designs optimized for force sensing from 1 Hz to 10 kHz.

	PR	AlN	PZT
l_c (μm)	262	307	252
w_c (μm)	5	5	5
t_c (μm)	1	1	1
k (mN/m)	12	20	29
f_0 (kHz)	20	20	20
Q	13	13	13
l_{pr} (μm)	35	-	-
V_{bridge} (V)	3.8	-	-
t_{pr} (nm)	224	-	-
n (cm^{-3})	4.4x1019	-	-
R (kΩ)	3.6	-	-
W (mW)	1	-	-
t_{pe} (nm)	-	200	420
R_{pe} (Ω)	-	1.3x10^{12}	3.4x10^{8}
C_{pe} (pF)	-	0.7	23.7
MDF (pN)	13.8	47.9	109
MDD (nm)	1.2	2.4	3.8

Both cantilevers can approach the thermomechanical noise floor (which is roughly 1 pN for the designs above), which is the ultimate limit for optical detection. However, PR and PE cantilevers can be made smaller than their optical counterparts, potentially enabling superior resolution.

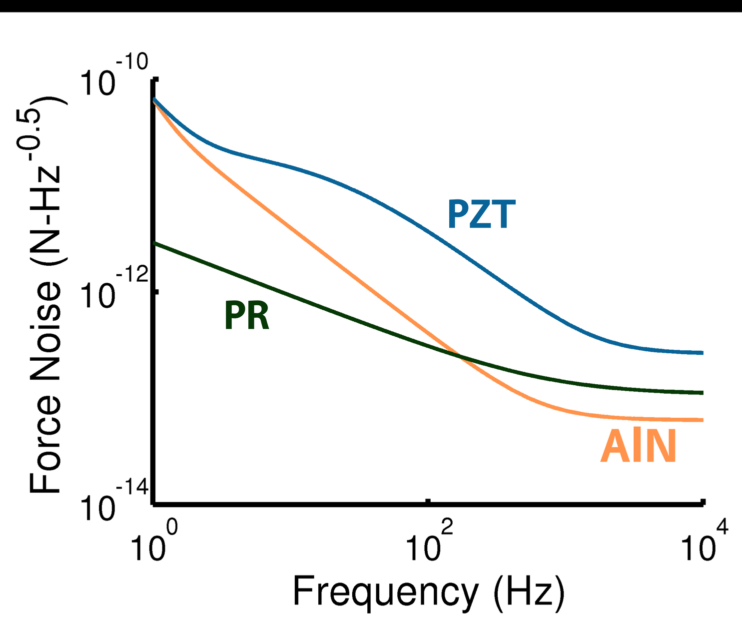


Figure 1. Force noise spectral density for the cantilevers in the table on the left. The thermomechanical noise floor is roughly 10 fN/rtHz.

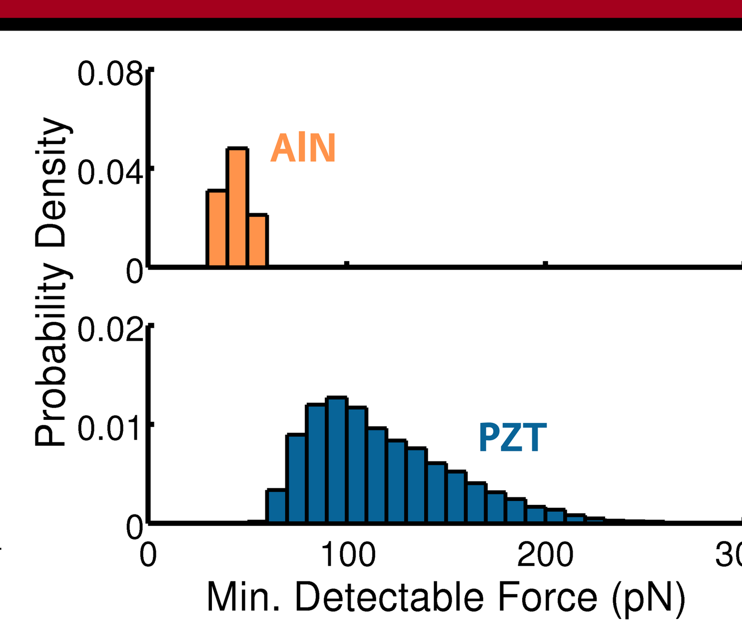


Figure 2. MDF probability density functions, calculated using the Monte Carlo method, can account for material property variation.

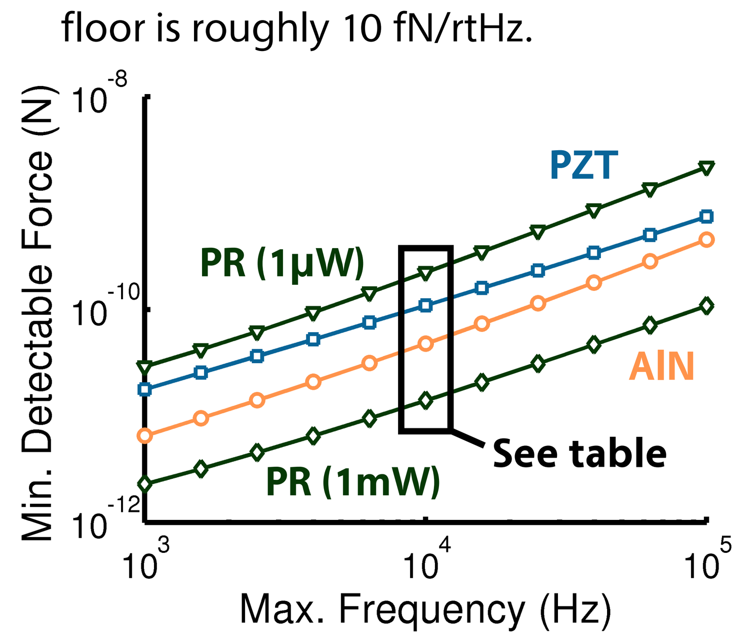


Figure 3. If power is limited to 1 microWatt, PE sensing outperforms PR sensing. But if 1 mW can be tolerated, PR sensing is preferable.

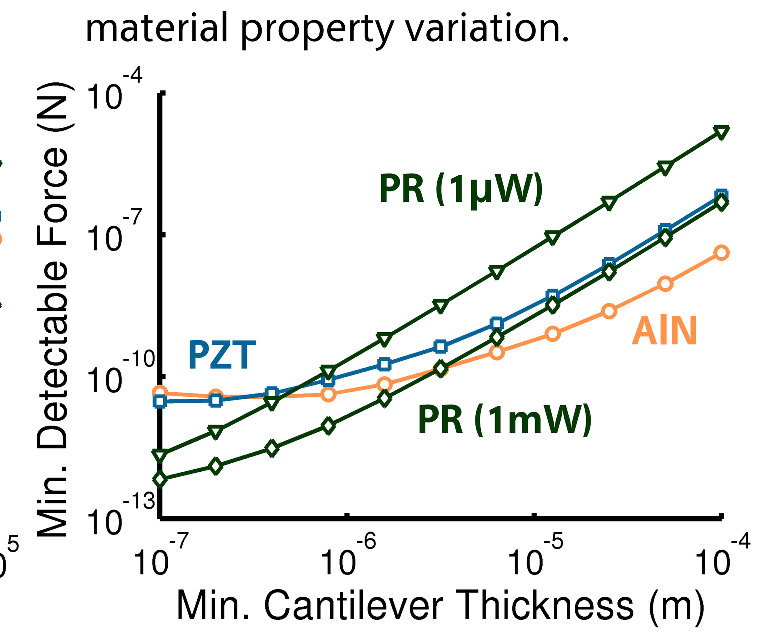


Figure 4. PR sensing is better suited for thin cantilevers while PE sensing is best for thick (> 5 micron), low power dissipation cantilevers.

Conclusions

The preferred sensor type depends on the particular design and fabrication constraints. But generally, PR cantilevers are better suited for thin beams (< 1 micron) while PE cantilevers are preferred for thick (> 5 microns) or lower power dissipation (< 0.1 mW) beams. Importantly, both are capable of atomic scale force and displacement measurements.

References

[1] S.-J. Park, J.C. Doll, A.J. Rastegar, and B.L. Pruitt, "Piezoresistive Cantilever Performance - Part II: Optimization", JMEMS (2010).
[2] C.A. Van Eysden and J.E. Sader, "Frequency response of cantilever beams immersed in viscous fluids ...", JAP (2007).
[3] M.S. Weinberg, "Working equations for piezoelectric actuators and sensors", JMEMS (1999).
[4] J.C. Doll, S.-J. Park, and B.L. Pruitt, "Design optimization of piezoresistive cantilevers for force sensing in air and water", JAP (2009).
[5] http://microsystems.stanford.edu/piezoD

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