High Frequency Force Sensing with Piezoresistive Cantilevers

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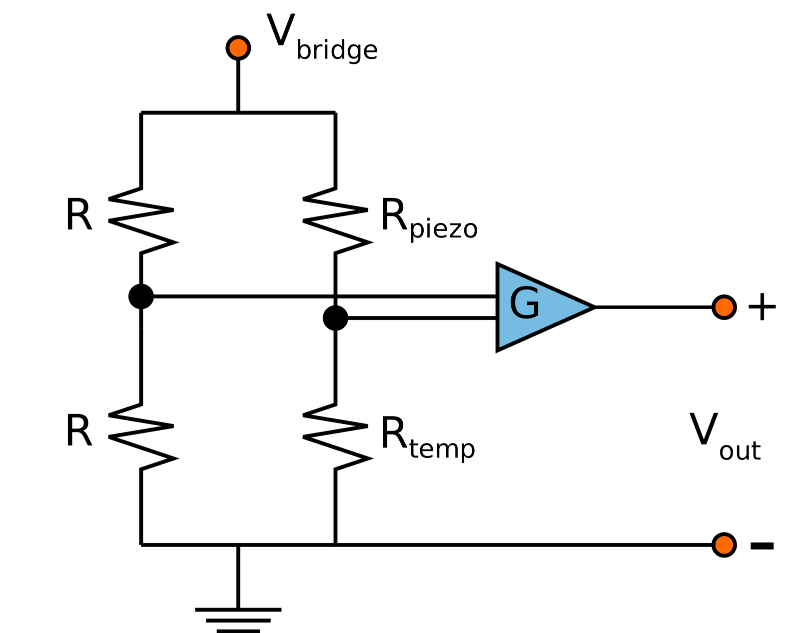
Introduction

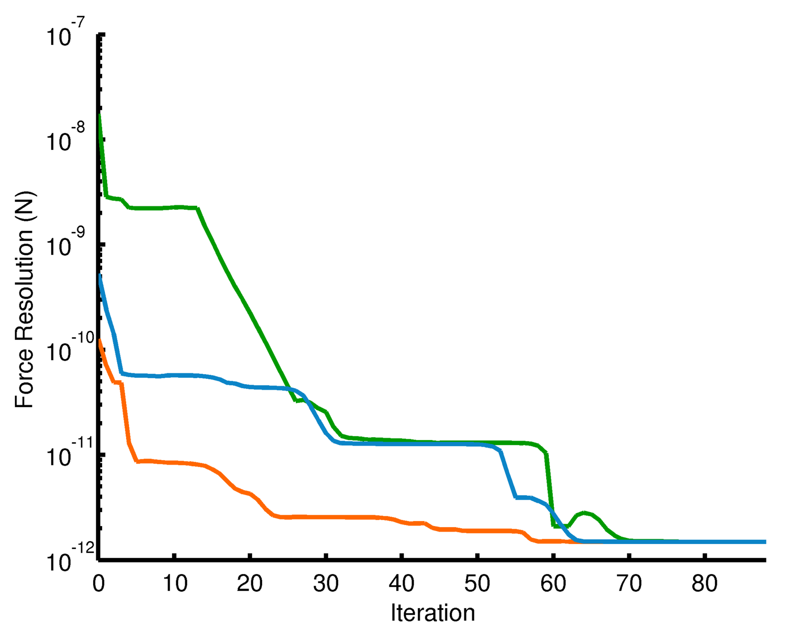
Microfabricated cantilever beams are widely used in force, topography and biochemical sensing applications by transducing a signal via cantilever deflection. Methods to detect cantilever bending can be divided into off-chip (e.g. optical) and on-chip methods (e.g. piezoresistive, piezoelectric, thermal). On-chip electronic detection scales well to large arrays, situations where optics are inconvenient, and low-cost applications (e.g. commercial pressure sensors).

Piezoresistive detection is particularly well suited for high frequency broadband force sensing. We have developed piezoresistive cantilevers for measuring pN - nN scale forces at frequencies up to 100 kHz for studying the biomechanics of mechanosensitive cells. The fabrication is a simple three mask process and the piezoresistors are n-type (phosphorus) formed by diffusion.

Experimental Setup and Piezoresistor Design

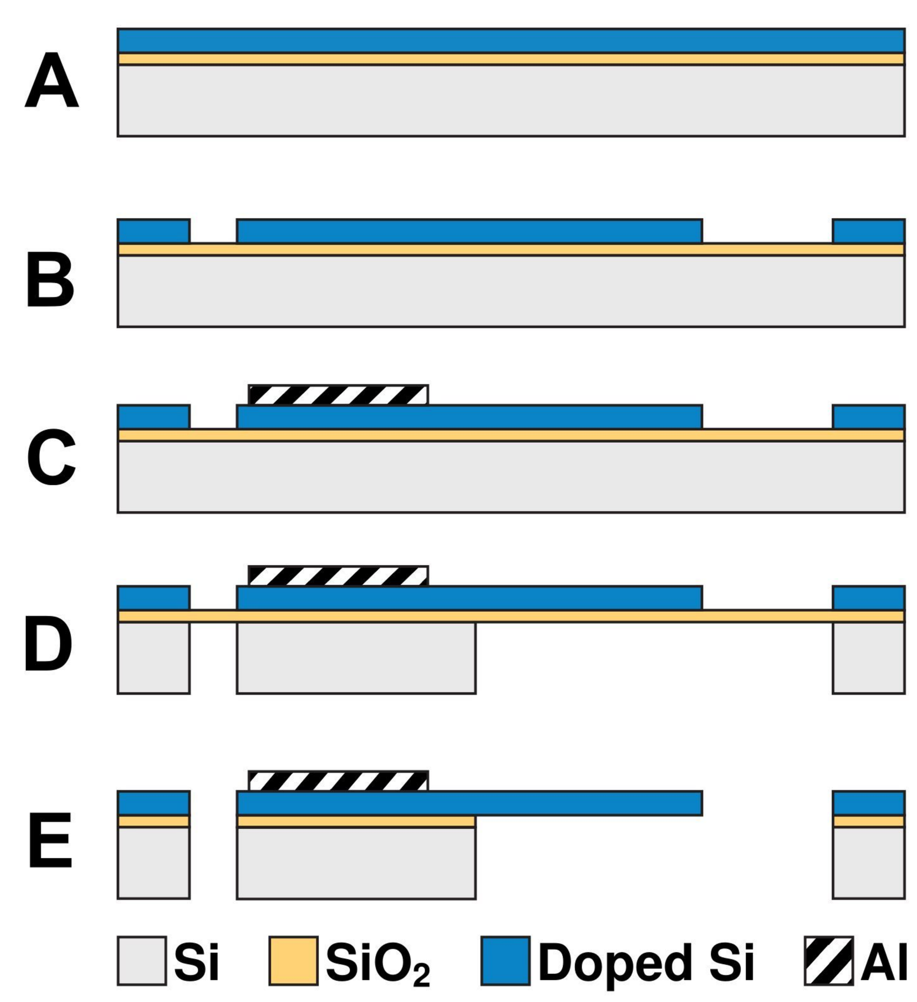


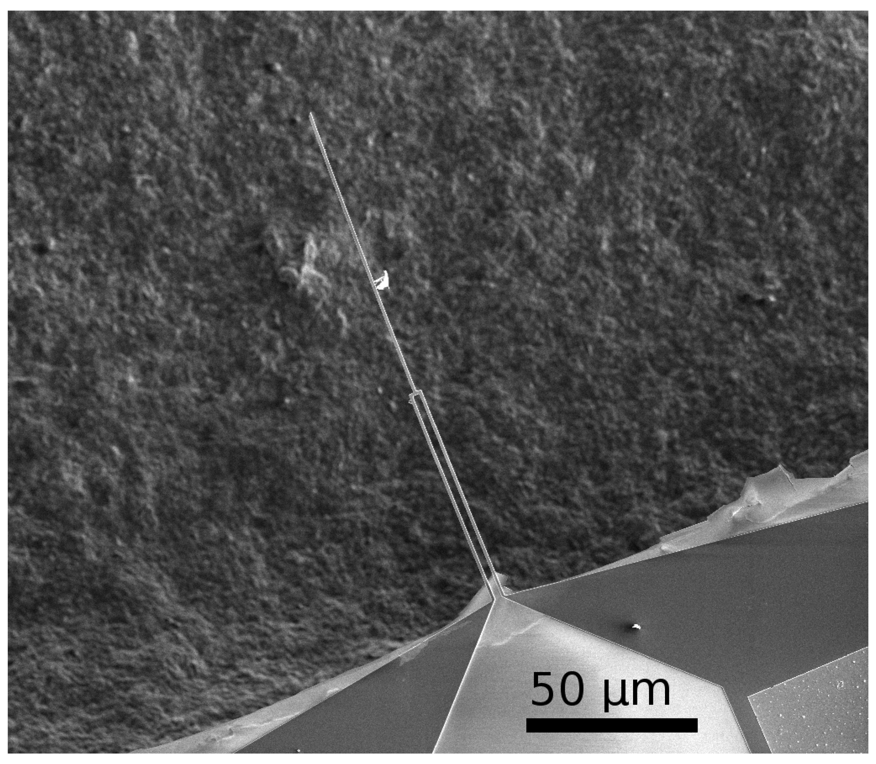
Noise and sensitivity were measured using a Wheatstone bridge. Noise was measured on a signal analyzer ahd sensitivity was measured using laser doppler vibrometery.



The cantilevers were designed using an iterative optimizer. Design and operating constraints (e.g. power) were enforced during the optimization process.

Device Fabrication





Starting from 4" (100) p-type (10 ohm-cm) SOI wafers (340 nm device layer, 400 nm buried oxide, 375 micron handle)

(a) Blanket dope the wafers using $POCL_3$ diffusion at 800C for 35 minutes. Strip the phosphorus doped oxide in HF.

(b) Pattern the cantilevers in the (100) direction by RIE with Cl_2/NH_4, stopping on the buried oxide to define the cantilever and piezoresistors.

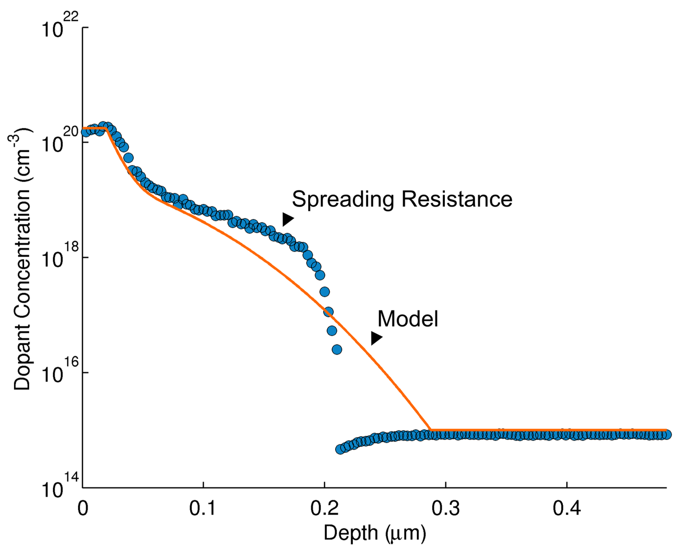
(c) Sputter 150 nm 99%/1% Al/Si and wet etch to define the bondpads.

(d) Protect the frontside of the wafer with photoresist and perform backside lithography (ASML PAS5500 with 3D align). Etch the backside by DRIE stopping on the buried oxide.

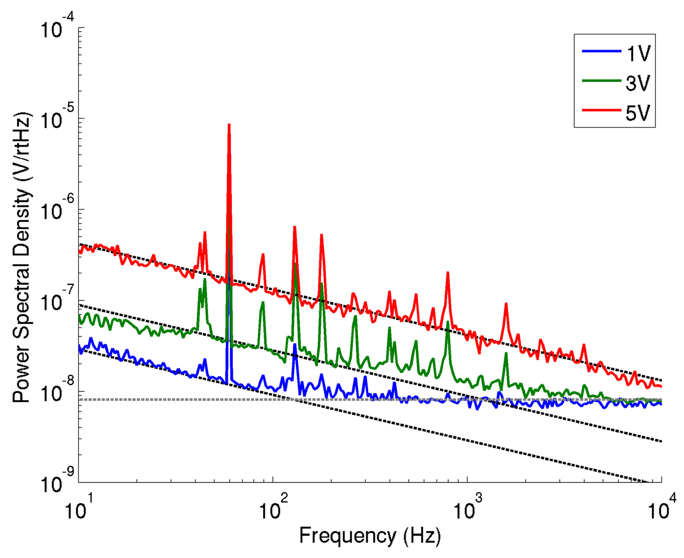
(e) Strip the photoresist and etch the buried oxide by RIE in CHF_3/O_2 plasma to release the cantilevers.

A forming gas anneal (450°C, 30 min) forms ohmic contacts.

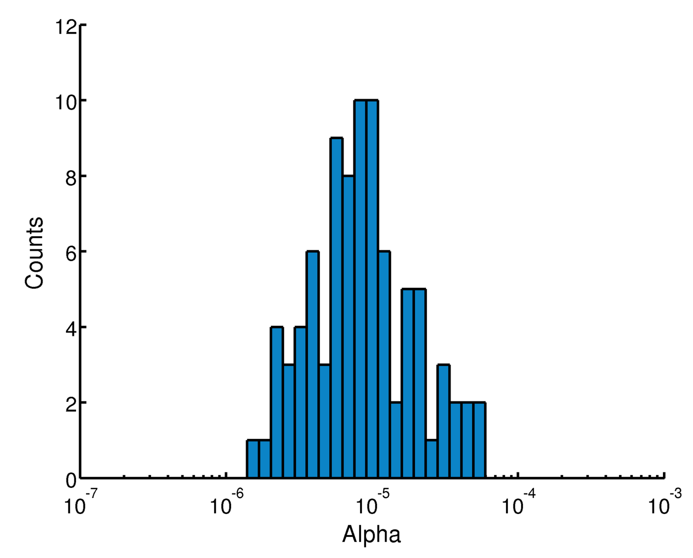
Results and Discussion



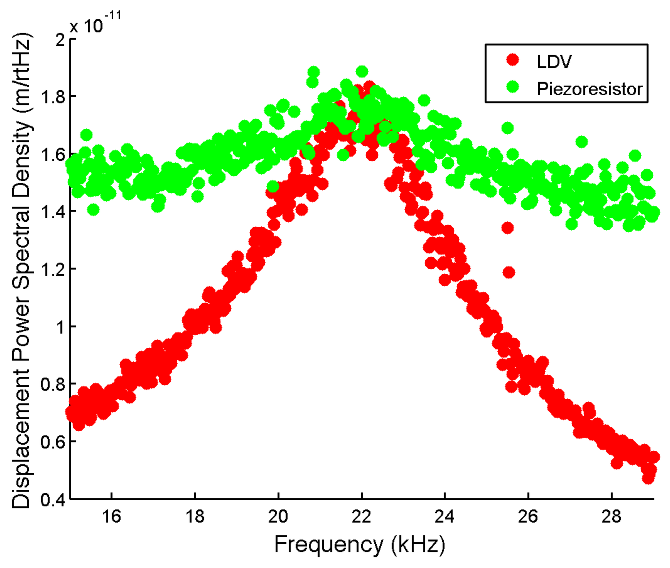
The dopant profiles were measured using spreading resistance analysis for accurate design modeling.



The Hooge model for 1/f noise accurately modeled the piezoresistor noise power spectral density (PSD). The plotted noise includes includes amplifier noise; the piezoresistors were designed to be relatively noisy.



The Hooge coefficient (α) was computed from the noise PSD and the number of carriers. Measured values range from 2e-6 to 6e-5 (μ = 1e-5), which compare well with data in the literature for piezoresistors fabricated by epitaxy and ion implantation with moderate post-implantation annealing.



The cantilevers were able to self-detect their thermomechanical resonance in air.

Force resolution depends on the cantilever geometry, piezoresistor processing, and operating conditions. Optimal design is a tradeoff between Johnson noise, Hooge (1/f) noise, and sensitivity.

Experimental results match the theory well for large cantilevers. The discrepancy for smaller cantilevers is under investigation.

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

Conclusions

We have designed, fabricated and tested sub-micron piezoresistive silicon cantilevers for detecting biomechanical forces at the pN scale.

Early results indicate that diffusion provides a simple, robust piezoresistor doping method. With proper design, diffusion can be used to fabricate cantilevers that are conventionally addressed using epitaxy (nanometer scale) and ion implantation (micron scale). Benefits of diffusion include minimal lattice damage and high dopant concentration.

On-going work is focused on integrating high speed force sensing and actuation into a single device.

Acknowledgements

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