HIGH FREQUENCY FORCE SENSING WITH PIEZORESISTIVE CANTILEVERS

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We designed, fabricated and characterized piezoresistive cantilevers for high frequency force-sensing and imaging applications, achieving a force resolution of 451 piconewtons from 1 Hz – 50 kHz (f_0 = 187 kHz) and 1.3 nanonewtons up to 100 kHz (f_0 = 419 kHz), the highest frequency-resolution force sensors to date to the best of our knowledge.

Microcantilevers have been used to gain insight into numerous physical, chemical and biological phenomena. Although optical readout is commonly utilized, the cantilever dimensions are limited by laser spot size. This leads to increased damping in air and liquids at high frequencies, limiting imaging bandwidth and the study of ultra-fast phenomena. For high-speed force-sensing and imaging, electronic readout using piezoresistive or metal strain gauges is an alternative approach that scales to nanometer dimensions [1].

Our cantilevers were designed for several different frequency ranges (Table 1) taking intrinsic Johnson, Hooge and extrinisic amplifier noise into account. An approach similar to Harley's was used [2] with modifications to optimize for an arbitrary doping profile. Although piezoresistive cantilevers have been fabricated as thin as 60nm [3], all force sensing designs to date have been optimized for frequencies less than 10 kHz. In addition to high frequency performance, our piezoresistors use n-type doping rather than the more widely used p-type doping, which enables identical force resolution and natural frequency for thicker cantilevers due to the higher longitudinal piezoresistive coefficient and lower modulus in the (100) direction compared to the (110) direction. Additionally, we have used diffusion doping rather than ion implantation or epitaxy because it enables high surface concentrations with minimal lattice damage and shallow junctions.

Fabrication is straightforward and consists of three lithography steps. Four-inch (100) p-type (boron, 10 ohm-cm) SOI wafers (340nm device layer, 400nm buried oxide, 375 micron handle) are used. First, wafers are doped using $POCl_3$ diffusion at 800C for 35 minutes. We characterized our doping profiles using spreading resistance measurements for design. The oxide is stripped, reducing the cantilever thickness to 320nm. The cantilevers are patterned in the (100) direction using Cl_2/NH_4, stopping on the buried oxide. This defines the cantilever, active piezoresistor, and temperature compensation piezoresistor. Sputtered aluminum (1500Å Al/1% Si) is deposited and patterned to form the bondpads. Finally, lithography is performed on the backside of the wafer and DRIE is utilized to etch the handle, stopping on the buried oxide. After the buried oxide is etched in CHF_3/O_2 plasma, a forming gas anneal (N_2 + 4% H_2, 450C, 30 minutes) is used to form ohmic contacts. Yield was greater than 80%. A finished device is shown in Figure 2.

A balanced quarter Wheatstone bridge was used to characterize cantilever performance. For all measurements, cantilevers were glued, wirebonded to a PCB, and the wirebonds were coated with epoxy. Noise measurements were performed in a metal box for light and electrical isolation. For electrical characterization, a DC bias is applied to the bridge and the signal is amplified with a low noise instrumentation amplifier (INA103) and recorded with a spectrum analyzer (HP3562A). Laser Doppler velocimetry (LDV) is used to measure displacement sensitivity and frequency response as previously reported [4]. Cantilever stiffness is calculated from the resonant frequency, which is used to calculate force sensitivity from the displacement sensitivity measured by LDV.

Cantilevers were capable of self-sensing their thermomechanical resonance in air (Figure 3). Typical noise power spectral density is shown in Figure 4. RMS voltage noise in the noted measurement bandwidth and the measured sensitivity are used to calculate the force resolution (Figure 4). Design and performance are summarized in Table 1 for the four designs tested to date.

Word Count: 596

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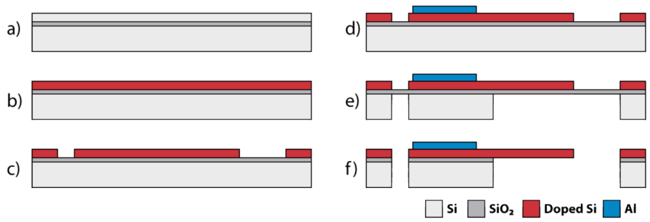

Figure 1. Fabrication process. SOI wafers (a) are blanket doped with phosphorous (b). The device layer is patterned and etched, stopping on the BOX (c). The wafers are metallized and patterned (d). Backside DRIE is performed (e) and the BOX is removed (f).

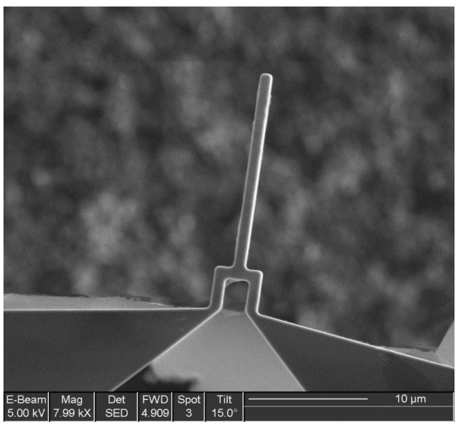

Figure 2. Scanning electron micrograph of device design #4.

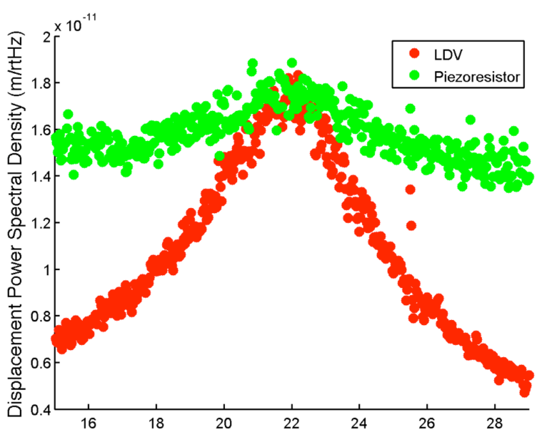

Figure 3. Device #1 self-sensing its thermomechanical motion in air at resonance without external actuation. Displacement power spectral density was recorded for both LDV and the piezoresistor for comparison.

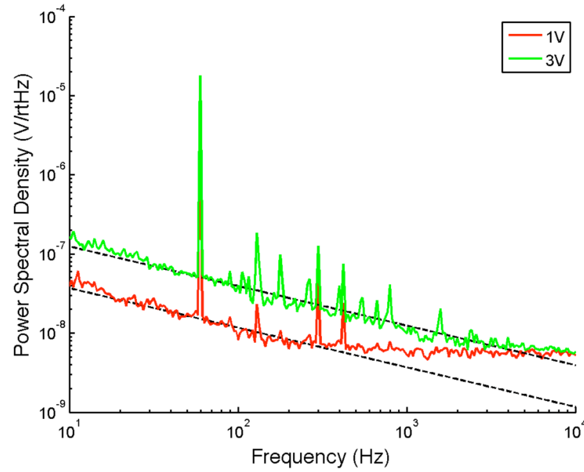

Figure 4. Noise power spectral density for cantilever #2 at bridge bias voltages of 1V and 3V. 1/f noise fits the Hooge model (dashed lines) and the thermal noise floor matches the expected value. The plotted data includes the cantilever noise as well as the instrumentation amplifier noise which will be used for experiments at frequencies up to several hundred kHz.

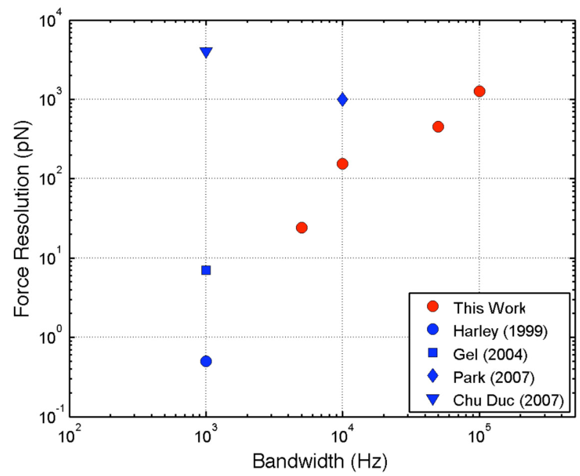

Figure 5. Force resolution data in the literature for piezoresistive cantilevers operating between 1 Hz and the upper frequency noted in the figure. Our cantilevers can operate at significantly higher frequencies for the same force resolution.

Table 1. Designed and measured cantilever properties. A balanced quarter Wheatstone bridge with temperature compensation piezoresistor was used for measurements and the bridge was biased at 3V.

	Design						**Measured Performance**							
#	t (nm)	l_{leg} (um)	w_{leg} (um)	W_{tip} (um)	L_{total} (um)	F_0 (kHz)	F_0 (kHz)	k (mN/m)	R (kOhm)	S (V/N)	F_{min} (Hz)	F_{max} (kHz)	V_{noise} (uV)	F_{res} (pN)
1	320	34	3	6	123	25.5	22.0	2.71	4.2	$1.25\mathrm{x}10^5$	1	5	2.96	24
2	320	24	5	10	88	49.83	66.4	27.7	2.5	$1.19\mathrm{x}10^4$	1	10	1.83	154
3	320	25	1	2	47	174.68	187.3	23.6	8.4	$7.85\mathrm{x}10^3$	1	50	3.54	451
4	320	35	1	2	35	315.0	419.5	9.69	3.5	$4.0\ \mathrm{x}10^3$	1	100	5.07	1268