HIGH FREQUENCY FORCE SENSING WITH PIEZORESISTIVE CANTILEVERS

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ABSTRACT

We present the design, fabrication and characterization of sub-micron piezoresistive silicon cantilevers for high frequency force detection. The cantilevers are fabricated by a simple three-mask process and doped using $POCl_3$ diffusion, which enables high doping levels and negligible lattice damage. Devices have a force resolution of 298 pN from 1 Hz – 50 kHz (f_0 = 187 kHz) and 678 pN up to 100 kHz (f_0 = 419 kHz), the highest combination of force resolution and measurement bandwidth to date.

KEYWORDS

piezoresistor, cantilever, force sensor

INTRODUCTION

Microcantilevers have been used to gain insight into numerous physical, chemical and biological phenomena based upon measuring the deflection of the cantilever. Cantilever strain can be determined using a variety of techniques, incluing optical, thermal, piezoelectric and piezoresistive. Although optical readout based upon an off-chip light source and sensor is the most common, on-chip electronic sensing is well suited for parallel operation or situations where optical access is inconvenient or impossible. Of the on-chip methods, piezoresistive sensing based upon semiconductor or metal strain gauges has been demonstrated to scale well to nanomechanical systems [1].

On-chip piezoresistive sensing also performs particularly well in high frequency force-sensing applications where the minimum laser spot size for optical detection limits cantilever size reduction. This leads to increased damping in both air and liquids and an increase in the cantilever spring constant, both of which are detrimental to high frequency force sensing. These are less of an issue for topography imaging, where stiff (e.g. 150 N/m) cantilevers and overall system optimization have lead to video-rate atomic force microscopy (AFM) systems [2]. However, for the study of ultra-fast (microsecond) biological phenomena such as mechanotransduction, there is a need for an integrated force sensor and actuation system with pN resolution and measurement bandwidth > 100 kHz in liquid. In this work we report progress in the development of sub-micron piezoresistive cantilevers optimized for high-frequency, pN resolution force sensing.

DESIGN

Our cantilevers were designed for several different frequency ranges (Table 1) taking Johnson, Hooge and amplifier noise into account. An approach similar to Harley's [3] was used with modifications to design for an arbitrary doping profile. Although piezoresistive cantilevers have been fabricated as thin as 60nm [4], yielding sub pN force resolution, all force sensing designs to date have been optimized for frequencies below 10 kHz

In addition to optimizing the devices for high frequency, we utilized 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 used in p-type piezoresistors. We used diffusion doping rather than ion implantation or epitaxy because it enables high surface concentrations and shallow junctions with minimal lattice damage via readily available atmospheric pressure $POCl_3$ furnaces.

Table 1: Cantilever geometric design parameters.

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

FABRICATION AND METHODS

Fabrication is straightforward and consists of three lithography steps. Four-inch (100) p-type (boron, 10 ohm-cm) SOI wafers (340 nm device layer, 400 nm buried oxide, 375 μm handle) are used. First, wafers are doped using $POCl_3$ diffusion at 800C for 35 minutes. The phosphorus doped oxide is stripped in HF, reducing the cantilever thickness to 320nm. The cantilevers are patterned in the (100) direction by reactive ion etching (RIE) with Cl_2/NH_4, stopping on the buried oxide. This defines the cantilever, active piezoresistor, and temperature compensation piezoresistor. All lithography was performed on an ASML PAS5500 stepper with 3D align used for the backside step. Aluminum (1500 Å 99% Al/1% Si) is blanket sputtered and patterned by wet etching to form the bondpads. No freckle etch was performed to minimize noise. Finally, lithography is performed on the backside of the wafer and DRIE is utilized to etch the handle, stopping on the buried

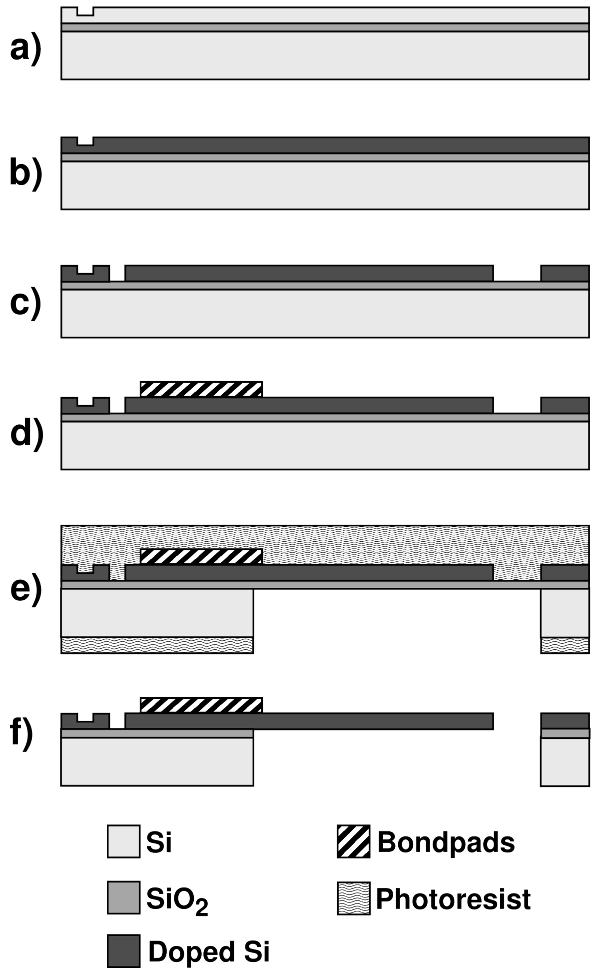

Figure 1. Fabrication process. After etching alignment marks (a), the SOI wafers are blanket doped with phosphorous (b). The device layer is patterned and etched, stopping on the BOX (c). The wafers are metallized and patterned (d). Backside DRIE is performed (e) and the BOX is removed (f).

oxide. Thick photoresist (Shipley 220-7) is used to protect the frontside and mask the DRIE. Afterwards, the photoresist is stripped from both sides and the buried oxide is removed by RIE in CHF_3/O_2 plasma to release the cantilevers. 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.

We measured the concentration profile of electrically active dopants with spreading resistance analysis (Solecon Laboratories, Reno, NV).

A balanced quarter Wheatstone bridge was used to characterize cantilever performance. For all measurements, cantilevers were glued and wirebonded to a printed circuit board (PCB), and the wirebonds were coated with epoxy. Noise measurements were performed in a grounded metal box for electrical and light isolation. For noise 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

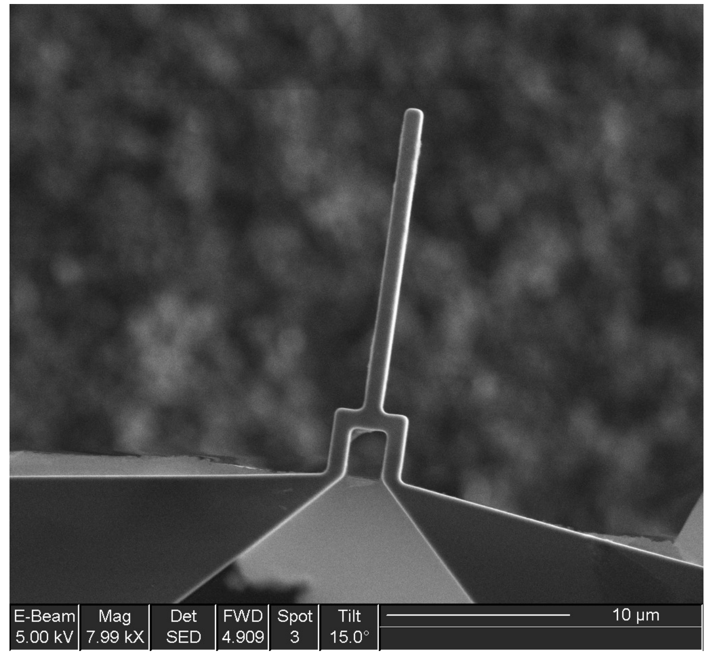

Figure 2. Scanning electron micrograph of device design #4.

as previously reported in [5]. Cantilever stiffness is calculated from the resonant frequency, which is used to calculate force sensitivity from the displacement sensitivity measured by LDV.

RESULTS AND DISCUSSION

We designed the cantilevers in order to optimize the minimum detectable force within a specified measurement bandwidth rather than their deflection resolution at resonance. However, the cantilevers were capable of detecting their thermomechanical resonance in air (Figure 3) with a noise floor of 15 pm/rtHz.

Typical device noise power spectral density data is shown in Figure 4. We approximated the number of

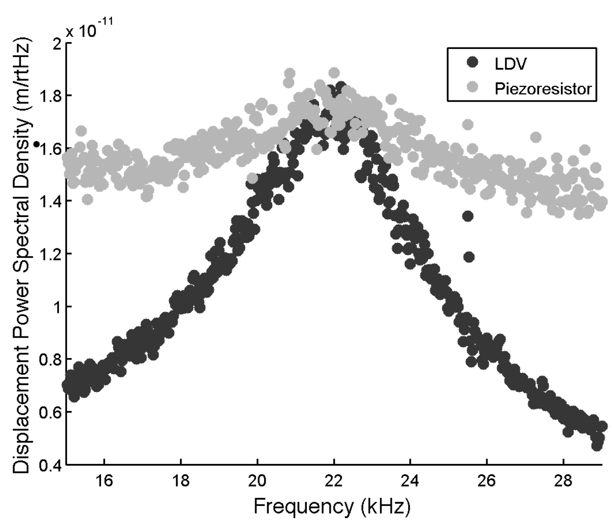

Figure 3. Device #1 self-sensing its thermomechanical resonance in air at resonance without external actuation.

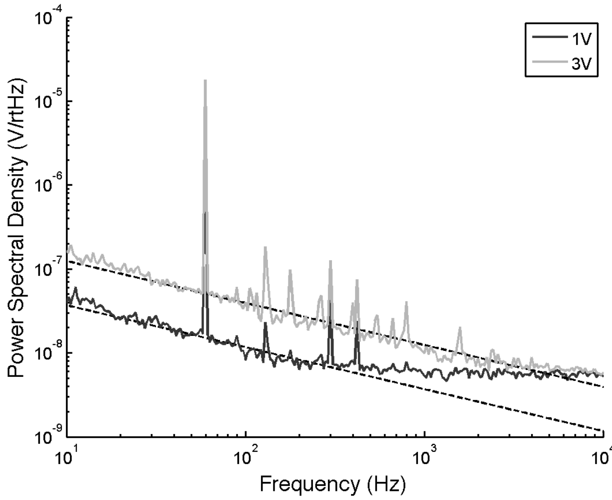

Figure 4. Noise power spectral density for cantilever #2 at bridge bias voltages of 1V and 3V. 1/f noise fits the Hooge model (dashed lines) and the thermal noise floor matches the expected value. The plotted data includes the cantilever noise as well as the instrumentation amplifier noise which will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

carriers (N) in the piezoresistor based upon the measured dopant concentration profile (Figure 5) and found that the Hooge 1/f noise model fit the data well. We measured α as 1.7e-5, which is comparable to previously reported results for epitaxial piezoresistors [6], but is higher than the lowest values reported for ion-implanted piezoresistors with a long anneal [7]. It is possible that the presence of electrically inactive phosphorus atoms from the diffusion process could act to increase alpha, or it could be due to uncertainty in the value of N in this or previous work.

Force resolution can be computed by computing the ratio of the RMS electrical noise to the force sensitivity, previously derived by Park et al [8], by

$$F_{min} = \frac{\sqrt{\dfrac{\alpha V_{bias}^2}{N} \ln\left(\dfrac{f_{max}}{f_{min}}\right) + 4 k_b T R (f_{max} - f_{min})}}{\dfrac{3\left(l - \dfrac{l_p}{2}\right)\pi}{2wt^2} \beta^{¿} \gamma V_{bias}}$$

(Equation 1)

where V_{bias} is the bias voltage across the piezoresistor, f_{min} and f_{max} define the measurement bandwidth, R is the piezoresistor resistance, N is the number of carriers in the piezoresistor, β* is the efficiency factor of the doping profile, and γ is the ratio of the piezoresistor resistance to the total resistance of the device. The computation of force resolution and β* are based upon Harley's experimental fit of piezoresistance factor to doping concentration [6]. γ is approximately 0.65 for our designs,

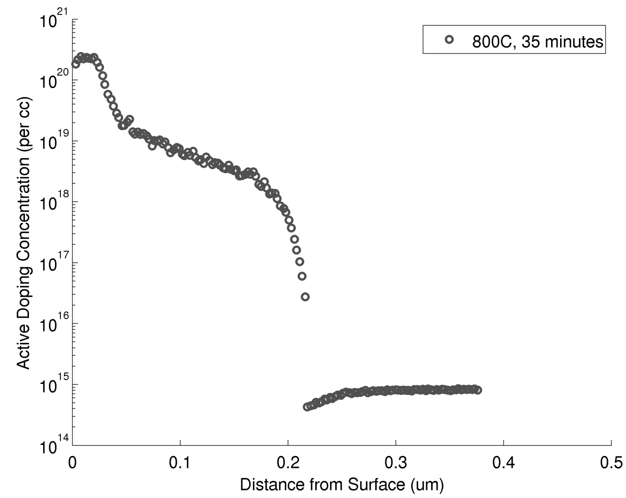

Figure 5. Experimentally measured electrically active dopant profiles. The cantilever is approximately 320 nm in thickness, and is doped throughout its thickness in the 800C, 35 minute process. In contrast with epitaxially fabricated piezoresistors, a junction depth of one third of the cantilever thickness is not ideal.

The 1/f noise parameter α was determined by fitting the Hooge model to the noise power spectral density (PSD) for all designs with multiple bias voltages as in Figure 3.

The computed force resolution and performance of the device designs presented are summarized in Table 3, and compared with previous work in Figure 4. The theoretical force resolution is calculated from Equation 1, whereas the experimental force resolution was calculated from the experimentally determined sensitivity. The deviation in force resolution for the smaller cantilevers, particularly designs #3 and #4, is due to lower than expected

Table 2: Experimentally determined electrical parameters. N_z, R_s and β were determined from the spreading resistance analysis results (N = 3 wafers), while α was computed from the device noise power spectral density (N = 14).

Temp (ºC)	Time (min)	N_z (N/µm^2)	Rs (Ω/□)	β*	α
800	35	6.95e6 ± 5.30e5	120.4 ± 2.9	0.321 ± 0.005	1.71e-5 ± 1.60e-5

Table 3: Experimentally determined device performance. The minimum frequency for all designs is 1 Hz and V_{bias} = 2 V. The theoretical model agrees well with the experimental results for the first design, but the higher frequency cantilevers have lower sensitivity than expected.

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

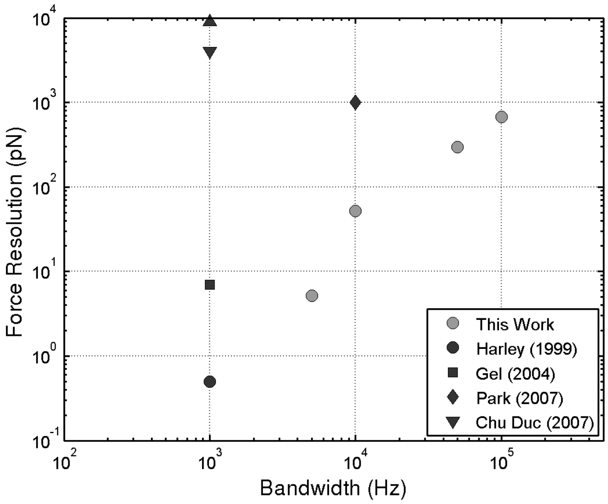

Figure 5. Force resolution data in the literature for piezoresistive cantilevers operating between 1 Hz and the upper frequency noted in the figure. Our cantilevers can operate at significantly higher frequencies for the same force resolution.

sensitivity. Sensitivity was measured with LDV, and the size of the laser spot (~10µm) is comparable to the size of the smaller cantilevers, potentially reducing the measured sensitivity. Improved sensitivity measurements are ongoing.

CONCLUSIONS

We designed, fabricated and tested sub-micron piezoresistive silicon cantilevers for high frequency force detection. The cantilevers are fabricated by a simple three-mask process and doped using $POCl_3$ diffusion, which enables high doping levels and negligible lattice damage. Despite their low stiffness (10 – 30 mN/m) and thickness (320 nm), we achieved yield in excess of 80%. We demonstrated devices that have a force resolution of 298 pN from 1 Hz – 50 kHz (f_0 = 187 kHz), and 678 pN from 1 Hz to 100 kHz (f_0 = 419 kHz). In the future we plan to integrate these devices with high speed actuation systems for biological studies.

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