Low 1/f noise, full bridge, microcantilever with longitudinal and transverse piezoresistors


Department of Mechanical Engineering, Stanford University, Stanford, California 94305, USA

(Received 29 June 2007; accepted 28 November 2007; published online 25 January 2008)

This paper reports on low 1/f noise, low corner-frequency, piezoresistive microcantilevers suitable for static and slowly time varying, force and displacement sensing applications such as chemical and biosensing. We demonstrate a full bridge, piezoresistive cantilever with greater than 140 dB dynamic range, a noise amplitude spectral density floor of 3.7 nV/√Hz at 0.1 Hz. At 1.0 Hz, the noise spectral density is 1.2 nV/√Hz equivalent to 10 pN/√Hz or 5 pm/√Hz. The force resolution over the frequency band of 0.1–100 Hz is 100 pN. © 2008 American Institute of Physics. [DOI: 10.1063/1.2825466]

Silicon microcantilevers with ion-implanted piezoresistors are favored for force and displacement sensing, especially for dynamic measurements. Lower 1/f noise piezoresistors are needed for chemical and biosensing applications which require static and low frequency measurement stability. Many existing sensors are designed for higher frequency levels. This leads to using low dopant concentration for piezoresistors, a choice that trades off slightly increased sensitivity for much higher noise. We use the empirical data of Harley and Kenny that both show the advantage of high doping. For example, when the peak doping concentration is increased from 10^{18} to 10^{20} cm^{-3}, 1/f noise decreases by an order of magnitude, but sensitivity decreases by only 45%.

As described elsewhere, cantilevers [Fig. 1(a)] were fabricated from single-crystal silicon-on-insulator wafers and were released by deep reactive ion etching. Piezoresistors, which were ion implanted at 50 keV, were positioned 130 μm from the fixed-edge restraint to avoid the subtractive, transverse tensile-stress region [Fig. 1(b)]. Four piezoresistors are configured in a full bridge to reduce thermal offset error. A full bridge provides four times the sensitivity and twice the noise compared to a single piezoresistor, increasing the signal-to-noise ratio by 6 dB. Table I compares noise for full bridge and single-resistor cantilevers with cantilevers from the literature, and tabulates selected process and performance parameters where available.

While origins of 1/f noise remain controversial despite eight decades of research, the cause is generally thought to be conductivity fluctuations. At zero V_{bias}, only the thermal noise is present. We use Hooge’s equation to model 1/f noise,

\[ S_f = \frac{\alpha V_{bias}^2}{N f^\alpha} \]  

where \( S_f \) is the noise power spectral density, \( N \) is the number of carriers, \( V_{bias} \) is the bias voltage, \( f \) is the frequency, \( \alpha \) is an empirical coefficient, and \( \alpha = n \). \( N \) depends on the piezoresistor volume and implant dose. Vandamme et al. showed that \( \alpha \) decreases for longer, higher temperature anneals which increase the crystal quality. The anneal diffusion length, \( \sqrt{D t} \), where \( D \) is the temperature-dependent, dopant diffusion coefficient and \( t \) is the anneal time, is a measure of anneal effectiveness and presumably, crystal quality.

In Fig. 2, we extend the plot of \( \alpha \) versus \( \sqrt{D t} \) of Harley and Kenny with data from our devices having a 1/f exponent, \( n = 1 \). Fleetwood and Giordano hypothesized that devices with \( n = 1 \) have the minimum achievable 1/f noise. We also fabricated devices with similar process conditions, but higher noise with \( n > 1 \). Presumably, these devices have ad-
TABLE I. Selected process variables and performance characteristics for different cantilevers including a full and a 1/4 active bridge with different doping and anneal conditions, as well as several devices from the literature. In comparing 1/f noise, we normalize the data by dividing by $V_{\text{bias}}$, giving units of nV/V $\sqrt{\text{Hz}}$ or Hz $^{-1/2}$.

<table>
<thead>
<tr>
<th>Boron dose (cm$^{-2}$)</th>
<th>Tortorose et al.$^{b}$</th>
<th>Pruitt et al.$^{c}$</th>
<th>Chui et al.$^{d}$</th>
<th>Harley and Kenny$^{e}$</th>
<th>Yu et al.$^{1}$</th>
<th>Yu et al.$^{5}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 x 10$^{16}$</td>
<td>1 x 10$^{14}$</td>
<td>5 x 10$^{14}$</td>
<td>1 x 10$^{15}$</td>
<td>5 x 10$^{14}$</td>
<td>NA</td>
<td>5 x 10$^{14}$</td>
</tr>
<tr>
<td>2.7 x 10$^{19}$</td>
<td>6.2 x 10$^{17}$</td>
<td>9 x 10$^{18}$</td>
<td>6 x 10$^{18}$</td>
<td>1 x 10$^{20}$</td>
<td>4 x 10$^{19}$</td>
<td>5 x 10$^{15}$</td>
</tr>
</tbody>
</table>

| Anneal temperature (°C) | 1100 | 1000 | 1000 | 1000 | 1000 | 700 | 950 |
| Anneal time (min)       | 50   | 52   | 10   | 40   | 16   | 180 | 10  |
| Spring constant (N/m)   | 2.1  | 17   | 5–100| 1–85 | 1.6  | 0.01| NA  |
| Sensitivity (V/N)       | 330  | 179  | −2000| 15   | NA   | 2 x 10$^{6}$| NA  |
| $\omega_0$ (kHz)        | 1.7  | 3.7  | 40–800| 1–6  | 280  | 50  | 12  |
| Resistance (kΩ)         | 1.8  | 16.8 | 2.5–7 | 5.8  | 5–30 | −16 | NA  |
| Johnson noise (nV/√Hz)  | 5    | 16   | 9    | 10   | 9–22 | 16  | 14  |
| Corner frequency (Hz)    | 0.6  | 20   | 45–750| 200  | 200  | 1000| 800 |

1/f noise at:
- 10 Hz (nV/√Hz) $^{5}$
- 10 Hz (nV/√Hz) $^{0.4}$
- 1 Hz (nV/√Hz) $^{1.2}$
- 0.1 Hz (nV/√Hz) $^{3.7}$

Four microcantilevers. $V_{\text{bias}}$ for the 1/4 bridge devices is 3.33 V, and 5.0 V for the full bridge device. The higher doped and devices with longer and higher temperature anneals show lower noise. The system noise floor was obtained down to 0.01 Hz by measuring the Johnson-dominated noise of a 0.68 kΩ piezoresistive bridge with 18 mVrms $V_{\text{bias}}$. The system noise was verified to be significantly lower than 3 nV/√Hz. The roll off above 30 Hz is due to the low pass filter.

FIG. 2. (Color online) $\alpha$ vs diffusion length with our data for higher $\sqrt{Dt}$ piezoresistors added to the plot of Harley and Kenny (see Ref. 2) showing a minimum $\alpha$ of 10$^{-7}$.

FIG. 3. (Color online) Amplitude noise spectral density for four microcantilevers. $V_{\text{bias}}$ for the 1/4 bridge devices is 3.33 V, and 5.0 V for the full bridge device. The higher doped and devices with longer and higher temperature anneals show lower noise. The system noise floor was obtained down to 0.01 Hz by measuring the Johnson-dominated noise of a 0.68 kΩ piezoresistive bridge with 18 mVrms $V_{\text{bias}}$. The system noise was verified to be significantly lower than 3 nV/√Hz. The roll off above 30 Hz is due to the low pass filter.

$\alpha$See Reference 7.
$b$See Reference 4.
$c$See Reference 3.
$d$See Reference 1.
$e$See Reference 2.
$f$See Reference 5.
$g$See Reference 6.

Because of the low 1/f noise in this work, total noise at indicated frequencies is dominated by thermal noise.

addition underlying noise generating mechanisms such as current constrictions, as suggested by Vandamme and Vandamme.14 Metal resistors have Hooge coefficients $\alpha$ of approximately 10$^{-2}$ and achieve low noise by high $N$. The Hooge coefficients for high concentration piezoresistors are much lower than for metal resistors.15 The larger diffusion lengths of higher temperature and longer time anneals, however, result in deeper junctions that lower device sensitivity. A full active bridge with its fourfold higher sensitivity more than compensates for the deeper junction and the lower piezoresistance coefficients at higher doping.

A HP3562A dynamic signal analyzer was used to measure resistor noise over the range of 0.1–100 Hz. Device A had higher noise and was measured with an AD 622 amplifier. For the others, we used a TI INA103 amplifier, which has low noise at intermediate frequencies (1 nV/√Hz at 500 Hz), in a modulation/demodulation circuit. The bridge was excited with a 5 $V_{\text{rms}}$ sinusoidal signal. Random fluctuation of piezoresistor conductivity $\sigma$ is the source of 1/f noise. Since

$$\Delta V_o = \frac{V_{\text{bias}}}{\Delta \sigma},$$

where $\Delta V_o$ is the change in bridge output, the bridge is a natural modulator. The modulated output was amplified (1000 gain) and the bandpass-filtered with center frequency (500 Hz) and bandwidth (~200 Hz) to reduce the effect of

Downloaded 13 Jul 2009 to 171.67.216.22. Redistribution subject to AIP license or copyright; see http://apl.aip.org/apl/copyright.jsp
noise folding. The signal was demodulated with an AD630 multiplier and low-pass, three-pole filter (100 Hz). As shown in Fig. 3, we achieved a very low system noise floor lower than 3 nV/√Hz from 0.01 to 1.0 Hz. Above 1.0 Hz, the system noise remains flat.

Table II compares four devices with three different implant doses and anneal conditions. Devices C and D, with $5 \times 10^{16}$/cm$^2$ high dose implants and high $\sqrt{D_t}$ anneals, have very low $1/f$ noise. We determined cantilever sensitivity using a previously reported laser Doppler vibrometer technique.\(^3\) At 1 Hz, the noise amplitude spectral density of the full active bridge is equivalent to 10 pN/√Hz or, in terms of displacement, to 5 pm/√Hz. The result was confirmed by thermomechanical excitation of the cantilever [Fig. 1(c)]. Over the frequency band of 0.1–100 Hz, the force resolution is 100 pN. In the bandwidth of 0.1–10 Hz, the dynamic range of the full active bridge for a full scale output of 200 mV at 5 V$_{bias}$ is $>140$ dB.

These low noise results are promising for the design of piezoresistive devices for low frequency measurements.


<table>
<thead>
<tr>
<th>Implanted Geometry</th>
<th>Implant Dose (cm$^{-2}$)</th>
<th>Time</th>
<th>$\sqrt{D_t}$ (µs)</th>
<th>$N$</th>
<th>$R$ (kΩ)</th>
<th>$\alpha$ (nV/√Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A 1/4 active bridge test die</td>
<td>$1 \times 10^{14}$</td>
<td>162 min steam</td>
<td>1000</td>
<td>2.06</td>
<td>1.4 $\times 10^9$</td>
<td>28.2</td>
</tr>
<tr>
<td>B 1/4 active bridge test die</td>
<td>$5 \times 10^{15}$</td>
<td>5 min N$_2$</td>
<td>1000</td>
<td>0.71</td>
<td>1.8 $\times 10^{11}$</td>
<td>1.1</td>
</tr>
<tr>
<td>C cantilever</td>
<td>$5 \times 10^{16}$</td>
<td>5 min N$_2$</td>
<td>1100</td>
<td>4.76</td>
<td>7.0 $\times 10^{11}$</td>
<td>0.47</td>
</tr>
<tr>
<td>D Full-active bridge cantilever</td>
<td>$5 \times 10^{16}$</td>
<td>5 min N$_2$</td>
<td>1100</td>
<td>4.76</td>
<td>1.8 $\times 10^{11}$</td>
<td>1.8</td>
</tr>
</tbody>
</table>

Downloaded 13 Jul 2009 to 171.67.216.22. Redistribution subject to AIP license or copyright; see http://apl.aip.org/apl/copyright.jsp