Silicon depletion layer actuators

J. H. T. Ransley, A. Aziz, C. Durkan, and A. A. Seshia

Nanoscience Centre, University of Cambridge, 11 JJ Thomson Avenue, Cambridge
CB3 0FF, United Kingdom

(Received 14 March 2008; accepted 16 April 2008; published online 9 May 2008)

The uncompensated donor or acceptor atoms present within the depletion layer of a diode can be employed as an electrostatic actuator, which utilizes the force between opposing charges on either side of the semiconductor junction. We describe the theory of this actuator and demonstrate its application for the case of a diode on the top surface of a silicon cantilever. The Schottky diodes fabricated on the top surface of cantilevers were used to drive them into resonance. As the actuator driving voltages are varied, the amplitude of vibration of the cantilevers changes, which is in agreement with the theoretical predictions. © 2008 American Institute of Physics. [DOI: 10.1063/1.2920440]

Semiconductor junctions in piezoelectric III-V and II-VI semiconductors have been employed as actuators for a number of years and there has recently been renewed interest in their application as actuators for nanomechanical resonators. Although silicon diodes are highly sensitive to both hydrostatic and anisotropic stresses (leading to applications of semiconductor junctions in stress sensors), silicon does not exhibit a significant piezoelectric effect and the use of silicon diodes as actuators has not been reported to date. However, diodes in silicon can be employed as actuators although the physical mechanism by which the actuator operates is different from that of piezoelectric semiconductors. Actuation results from the forces on the oppositely charged regions in the depletion layer rather than the interaction of this electric field with the material in the insulating carrier depleted region. In contrast to the conventional capacitive gap actuators widely employed in the microelectromechanical systems industry, such actuators are internal to the structure itself. There has recently been a significant interest on the use of internal actuators based on dielectric filled capacitors as a method to enhance the voltage-force transduction factor. The use of semiconductor junctions instead of these capacitors opens the possibility of fabricating higher quality resonators due to high crystallinity and low number of defects in the silicon wafer and the absence of additional acoustically mismatched materials in its construction. The actuator technology also has good compatibility with integrated circuit processing. In this letter, we present results obtained from using these actuators to drive atomic force microscopy (AFM) cantilevers which validate a model we have previously proposed.

The carrier depleted layer present in reverse-biased Schottky diodes and p-n junctions acts as the dielectric in widely employed variable capacitor or varactor devices. In contrast to a conventional capacitor with a distinct insulating dielectric layer, the charge is stored over the whole volume of the insulating region in the form of uncompensated donors or acceptors embedded within the lattice. For the case of abrupt junctions, the electric field linearly varies across the depletion region and, consequently, a linearly varying force acts on the charged dopants within the depletion layer [see Fig. 1(a)]. These forces produce a net compression of the depletion layer. This compression can be modulated by the application of an ac voltage $V_{ac}$ with a dc offset $V_{dc}$ (to maintain a reverse bias) across the junction. If the diode is placed on the top surface of a cantilever, this compression in the direction normal to the cantilever surface produces an extension parallel to the surface via Poisson’s ratio and results in the bending of the cantilever. We have shown that if a cantilever is driven at resonance by a diode actuator on its top surface, its amplitude of vibration is given by

$$a_{res} = \frac{1.890L^2Q\nu_a[N_d\epsilon e(V_{dc} + V_{bi})]^{1/2}V_{ac}}{h^2E},$$

where $L$ is the length of the cantilever, $h$ is its thickness, $\nu_a$ is Poisson’s ratio of silicon, $E$ is Young’s Modulus of the silicon, $N_d$ is the dopant density, $\epsilon$ is the electron charge, $e$ is the dielectric constant of carrier depleted silicon, $V_{bi}$ is the turn on voltage of the diode, and $Q$ is the quality factor of the resonance.

Gold-silicon Schottky diodes were prepared on uncoated μMasch AFM cantilevers. Three cantilevers were studied, cantilevers 1 and 2 being on the same substrate. Initially chrome-gold counterelectrodes of several square millimeters were evaporated onto the sample (10 nm Cr, 30 nm Au) through a shadow mask. The cantilever’s native oxide layer was then removed by a HF etch. The sample was rinsed in water and rapidly transferred to a vacuum system for the deposition of gold—ensuring that oxide regrowth was minimal. 30 nm of gold was evaporated through a second shadow mask—ensuring a small junction area compared to that of the counter electrode. A gap between these two sets of electrodes results in a significant resistance in series with the diode (see below). Electrical connections were made to the gold by using silver loaded epoxy and gold wire. Figure 1(b) shows a scanning electron micrograph of cantilevers 1 and 2. The dimensions and physical properties of the three cantilevers used in this study are given in Table I along with the other parameters used in the modeling of the devices.

---

aAlso at Department of Materials Science and Metallurgy, University of Cambridge, Cambridge, CB2 3QZ, United Kingdom.

bAuthor to whom correspondence should be addressed. Electronic mail: aas41@cam.ac.uk.
in contact with a surface mounted on a piezoelectric stage. Figure 3 shows the response of the three devices as the reference frequency was swept from 5 to 30 kHz.

Figure 4 shows the variation of each cantilever’s vibration amplitude with applied ac bias, at a dc reverse bias of 1 V. Figure 5 shows how the vibration amplitude varies with applied dc reverse bias, with a fixed ac bias of amplitude 85 mV. For this measurement, the ac voltage was held at a fixed frequency as the dc bias was varied. The lock-in output was measured with a data acquisition card. The dc and ac dependence of the observed amplitude are in good agreement with the expression in Eq. (1) (shown as a thin line in the figures). Note that it was not possible to measure the dopant level in these samples in a straightforward manner and the values were assumed based on fits to the data in Figs. 4 and 5 (these values are given in Table I). The dopant density was the only free parameter used in the fitting of the data—all the

<table>
<thead>
<tr>
<th>Property</th>
<th>Cantilever 1</th>
<th>Cantilever 2</th>
<th>Cantilever 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>w/µm</td>
<td>34 ± 1</td>
<td>35 ± 1</td>
<td>35 ± 1</td>
</tr>
<tr>
<td>L/µm</td>
<td>285 ± 1</td>
<td>335 ± 1</td>
<td>250 ± 1</td>
</tr>
<tr>
<td>h/µm</td>
<td>1.9 ± 0.1</td>
<td>1.9 ± 0.1</td>
<td>1.4</td>
</tr>
<tr>
<td>N_A/10^17 cm^-3</td>
<td>1.5</td>
<td>1.5</td>
<td>2.0</td>
</tr>
<tr>
<td>Q</td>
<td>101</td>
<td>101</td>
<td>98</td>
</tr>
<tr>
<td>f_res/kHz</td>
<td>24.85</td>
<td>21.15</td>
<td>24.84</td>
</tr>
<tr>
<td>f_pred/kHz</td>
<td>28 ± 2</td>
<td>20 ± 1</td>
<td>···</td>
</tr>
</tbody>
</table>

Figure 2 shows the current-voltage characteristic of the devices. Both diodes have a turn on voltage of approximately 300 mV. The forward characteristics are limited by the series resistances of 125 Ω (cantilever 3)–250 Ω (cantilevers 1 and 2). These values are reasonable considering the device layer doping level of (1–5) × 10^17 cm^-3, which leads to a resistance per square of 330–865 Ω. At biases between 0 and 2 V, the leakage resistance of the diodes is greater than 5 kΩ and its capacitance is estimated to be of order 1 nF (which corresponds to an impedance of order 10 kΩ at resonant frequencies of order 20 kHz). This means that both dc and ac voltages will be primarily dropped over the diode provided that the reverse bias across the device is less than 2 V.

The deflection of each cantilever with various applied dc and ac voltages was measured by using an AFM optical beam-deflection setup and a lock-in amplifier. The lock-in’s internal oscillator generated the ac signal applied to the Cr–Au counterelectrode, while a dc reverse bias was applied to the gold on the junction itself. After the measurements were completed, the measured deflection was calibrated by bending the cantilever by a known amount after bringing it to a net compression of the depletion layer. As a result of Poisson’s ratio of the Si, this compression in the z direction produces extension in the direction parallel to the surface of the cantilever and bending of the cantilever as shown in the figure.

Note that it was not possible to measure the dopant level in these samples in a straightforward manner and the values were assumed based on fits to the data in Figs. 4 and 5 (these values are given in Table I). The dopant density was the only free parameter used in the fitting of the data—all the...
other parameters were directly measured. A log-log plot of the data in Fig. 4 (not shown) gives gradients of 0.4 (cantilevers 1 and 2) to 0.6 (cantilever 3) in reasonable agreement of the predicted power dependence of 0.5.

In summary, we have presented a model for the response of clamped-free silicon cantilevers as they are driven into resonance by a diode actuator. A good agreement between this model and the response of devices fabricated from silicon AFM cantilevers has been obtained. Diode actuators based on $pn$ junctions offer the potential to drive high-$Q$ resonators in silicon without narrow gaps or the added complexity of dielectric layers.