High-sensitivity piezoresistive cantilevers under 1000 Å thick

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Ultrathin, high-sensitivity piezoresistive cantilevers were constructed using vapor-phase epitaxy to grow the conducting layer. A fourfold reduction in thickness was achieved over the thinnest implanted piezoresistive cantilevers, allowing improved force or displacement sensitivity and increased bandwidth. In cantilevers 890 Å thick, the dopant is well confined to the surface, and the sensitivity is 70% of the theoretical maximum. A cantilever fabricated for high force resolution has a minimum detectable force of 8.6 fN/$\sqrt{\text{Hz}}$ in air. Additionally, the $1/f$ noise is shown to follow the relation proposed by Hooge [Phys. Lett A **29**, 139 (1969)], increasing in inverse proportion to the number of carriers. © *1999 American Institute of Physics.* [S0003-6951(99)01728-3]

Piezoresistive cantilevers are typically used in force microscopy applications where difficulties in laser alignment make optical detection inconvenient. Applications include atomic data storage systems,[1] cantilever arrays,[2] high-vacuum atomic force microscope (AFM) measurements,[3] and portable cantilever-based sensors.[4,5] The convenience of the integrated sensor has thus far always come at the expense of resolution, when compared to optically detected cantilevers. In principle, reducing the thickness of piezoresistive cantilevers can increase the sensitivity to overcome this drawback.

The other principal situation where piezoresistive cantilevers are useful is for high bandwidth measurements, such as high-speed atomic data storage, or high temporal resolution force measurements. The bandwidth of a cantilever is limited by its resonant frequency, usually in the tens of kilohertz for commercial AFM cantilevers. To increase resonance without increasing cantilever stiffness requires a reduction in mass, hence there is a trend towards smaller beams.[6] Typical AFM laser spot sizes are about 30 μm, however, and it is difficult to get an adequate optical signal from a cantilever which is only a few microns long and wide, and under 1000 Å thick. An integrated sensor can overcome this problem.

The sensitivity of a piezoresistor at the base of a rectangular cantilever is given by

$$\frac{\Delta R}{R} = \beta \frac{6 l \pi_L}{w t^2} \Delta F = \beta \frac{3 E t \pi_L}{2 l^2} \Delta x, \tag{1}$$

where R is the resistance; l, w, and t are the length, width, and thickness; π_L is the piezoresistive coefficient; E is the young's modulus; and ΔF is the applied load. β is a coefficient between 0 and 1 representing the efficiency compared to an ideal doping profile restricted exclusively to the surface of the beam.[7] The displacement sensitivity Δx is computed by substituting $F = kx$ where for a rectangular beam $k = Ewt^3/4l^3$. Since the force sensitivity varies as t^{-2}, it can be most effectively maximized by reducing the beam thickness. For maximum displacement sensitivity, the length of the cantilever dominates, but to reduce length without increasing the spring constant requires that the thickness be reduced commensurately. In both cases, if the thickness is reduced, the sensitivity gains can be made without sacrificing bandwidth.

The difficulty in reducing the cantilever thickness relates to the β coefficient. For thin cantilevers it is increasingly difficult to confine the doped sensing region to the surface of the beam. If the doped region is evenly spread both above and below the neutral axis of the beam, the stresses will average out to a zero net signal. Chui *et al.*[8] reduced piezoresistive cantilevers to 1 μm thick by first growing a passivating oxide, and then implanting though it, thereby avoiding the diffusion of the implant during the growth of the oxide. Ried *et al.*[1] made 0.34-μm-thick piezoresistive cantilevers by lowering the implant energy to 10 keV, and using a low-temperature oxide for passivation.

The depth of an implanted junction cannot be reduced much further, however, since the implanted ions have greatly enhanced diffusivity until they are activated. Since activation is achieved by annealing, the dopant diffusion is unavoidable. Even for rapid thermal anneals used by Chui *et al.* and Ried *et al.*, the diffusion coefficient for the implanted boron is 10^3 times greater that the intrinsic value.[9]

For reduction of the doped region thickness beyond the capabilities of conventional implantation, we have used vapor-phase epitaxial growth. The boron atoms are incorporated into the lattice during the epitaxy, so an activating anneal is unnecessary. Furthermore, since there is no damage-enhanced mobility, some high-temperature steps can be tolerated.

Using epitaxially grown piezoresistors, 870–900-Å-thick cantilevers were fabricated in lengths ranging from 10 to 350 μm, with widths from 2 to 44 μm. Scanning electron micrographs (SEMs) of four of these are shown in Fig. 1.

The fabrication procedure is similar to that outlined by Tortonese *et al.*.[10] A thermal oxide was grown and removed to thin the top 2000 Å of a 10 Ω cm p-type Simox silicon-on-insulator (SOI) wafer to 800 Å. After a 30 s HCl clean in the epichamber, which removed another 100 Å, 300 Å of $4 \times 10^{19}\,\text{cm}^{-3}$ boron-doped silicon was grown over the entire wafer. The cantilevers were then patterned and plasma

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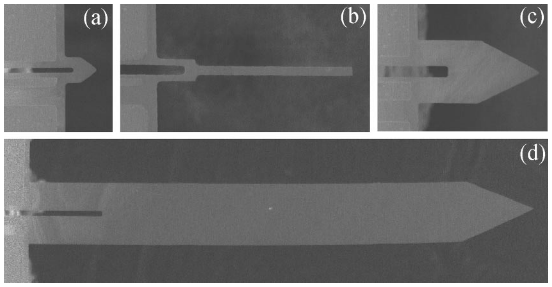

FIG. 1. SEMs of 0.087–0.090-μm-thick piezoresistive cantilevers. (a) 10 μm×8 μm. (b) 60 μm×4 μm. (c) 40 μm×20 μm. (d) 350 μm×44 μm. Note that image (d) is at 0.45% scale from the others.

etched. Boron for the contacts was implanted at 1×10^{15} cm^{-2}, 30 keV, followed by a 200 Å growth of passivating thermal oxide during a 3 h anneal at 700 °C.

Aluminum for the contacts was then deposited, and annealed in a forming gas at 400 °C for 1 h. A release mask was subsequently patterned on the back of the wafer, and a Bosch deep silicon etch used to release the cantilevers and partially dice the wafer in a single step. The buried oxide, which stopped the silicon etch, was then removed with a 6:1 buffered oxide etch (BOE), using a photoresist adhered support wafer to protect the cantilevers. The cantilevers were then dried using the critical-point method.[11]

Using a wet etch to clear the buried oxide at the bottom of the backside etch holes was problematic, since the surface tension of the BOE prevented it from entering the small holes. As a result, when the support wafer was removed, the cantilevers were still embedded in the buried SOI oxide. To release some cantilevers while preserving the aluminum leads, part of the wafer was immersed in a pad etch for 10 min, removing both the buried oxide and the passivating layer from most of the chips. A comparison between released and unreleased cantilevers showed negligible differences in the noise levels, suggesting that the passivating oxide is not critical for low-noise devices. Removal of the passivating oxide also eliminates the cantilever curvature which would arise from stress in the oxide layer.

The sensitivity data were taken on the longest cantilever, which exhibits the best force resolution. The fractional resistance change of the 350-μm-long cantilever is 50 ppm per micron deflection. The response to deflections in an AFM is shown in Fig. 2.

Sensitivity measurements like those shown in Fig. 2 were not consistently repeatable for the 350 μm cantilever, since the cantilever is too flexible for the tip to slide on the surface and twisting can arise during the z deflection in our AFM. The piezoresistor can self-detect its thermomechanical noise when the resonance quality is greater than 5, so we were able to get reliable sensitivity measurements by observing the amplitude of the thermomechanical noise at resonance in a moderate vacuum (20 mTorr) with both the piezoresistor and a laser vibrometer. The quoted sensitivity was measured by this method, and is consistent with the measurement shown in Fig. 2.

TSUPREM-4 simulations of the epitaxially grown doped layer before and after the 700 °C anneal are shown in Fig. 3. From the postanneal profile, a theoretical value of β was computed to be 0.65. Using the measured sensitivity and Eq.

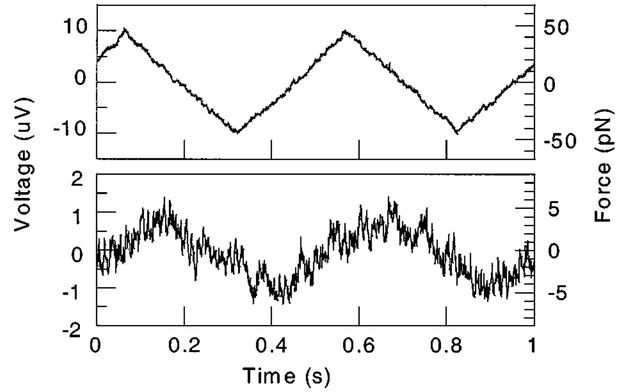

FIG. 2. Force sensitivity for 0.089 μm×44 μm×350 μm piezoresistive cantilever in a bandwidth from 1 Hz to 1.2 kHz. Upper trace shows response to ±1 μm displacement, lower trace to ±0.1 μm. The force sensitivity is calculated using the modeled spring constant of 3×10^{-5} N/m.

(1), with $\pi_L=4\times10^{-10}$ m^2/N for 4×10^{19} cm^{-3} boron-doped silicon,[12] the measured value for β is 0.7. This indicates that the simulated doping profile is valid and that the doping is well confined to the surface. Once the value of β for the doping is determined, the sensitivity of the shorter cantilevers can be computed directly from Eq. (1), and the capability for high-bandwidth, high-displacement-sensitivity cantilevers is also established.

The force sensitivity was computed from the displacement sensitivity using a calculated spring constant of 3×10^{-5} N/m. The thickness of 890 Å was measured with a reflectometer.

The noise spectrum for the same cantilever is shown as the lowest line in Fig. 4. The $1/f$ noise knee is at 1 kHz, at which point the noise flattens out to less than two times the Johnson noise limit. The total noise from 10 Hz to 1 kHz is 1.14 μV, giving a force resolution of 500 fN in this bandwidth. At 1 kHz, the force resolution is 8.6 fN/$\sqrt{\text{Hz}}$.

Although the sensitivity data all point to improved performance with reduced cantilever dimensions, it was observed that the $1/f$ noise was greater for the smaller cantilevers on the wafer. Increased $1/f$ noise for smaller cantilevers was also apparent in piezoresistive cantilevers from the literature.[8,10] As plotted in Fig. 5, the noise from these cantilevers fits the empirical model proposed by Hooge,[13] who observed that the $1/f$ noise in homogeneous materials varies inversely with the number of carriers. In volts squared per hertz, the noise density can be written as $S_V=(\alpha V^2)/(Nf)$. Here, V is the bias on the resistor, N is the number of carriers, f is the frequency, and α is a constant which appears to

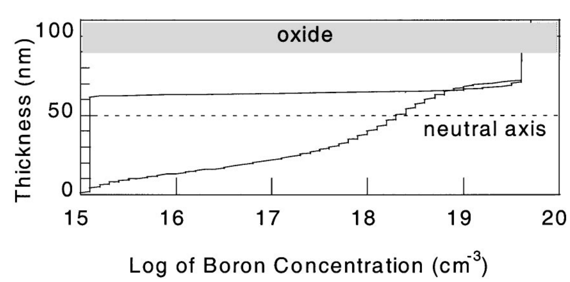

FIG. 3. SUPREM-IV simulation of dopant distribution after growth of 300 Å 4×10^{19} cm^{-3} boron-doped epitaxial silicon, and after a wet oxide growth for 3 h at 700 °C.

depend on the quality of the crystal lattice.[14] A 2-μm-thick cantilever made by Tortonese has a substantially lower α than the others, but it is the only case where a substantial anneal is done after the implant. Such anneals have been shown to improve the α parameter by up to three orders of magnitude.[14]

Where the current in the cantilever reverses its path at the end of the cantilever legs, the current density is no longer uniform, and not all carriers participate equally in the conduction. As a result, the total number of carriers in the cantilever is an inappropriate measure for the Hooge noise model. Finite-element models were made for the current distribution in each case, and the predicted noise density determined from the more generic Hooge noise formula[15]

$$S_V=\frac{\alpha\rho^2}{nI^2 f}\int\int\int (J\cdot J)^2 dx dy dz. \tag{2}$$

In this case, I is the total current, J is the current density, ρ is the resistivity of the material, n is the carrier density, and the integral is over the entire volume of the cantilever. The effective number of carriers plotted on the x axis in Fig. 5 was then determined by analogy to the case of a simple rectangular resistor.

With this relation for the $1/f$ noise and the number of carriers, both the Johnson noise and $1/f$ noise of a piezoresistive cantilever can be predicted from the doping and geometry, enabling the optimization of the cantilever design. The Hooge noise relation indicates that the performance gains from ever-smaller cantilevers are mitigated somewhat by an inevitable increase in $1/f$ noise. Since the noise is only increasing as the square root of the cantilever volume, however, the improved sensitivity still outweighs the noise, and maximum resolution is achieved with smaller structures.

It has been demonstrated that shallow doping profiles for piezoresistive cantilevers can be achieved using epitaxially grown layers. This has permitted the construction of piezoresistive cantilevers with femto-Newton force resolution in air. In addition, it has been shown that the $1/f$ noise of these cantilevers is inversely proportional to their volume.

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