Independent detection of vertical and lateral forces with a sidewall-implanted dual-axis piezoresistive cantilever

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A dual-axis atomic force microscope (AFM) cantilever with independent piezoresistive sensors has been developed for simultaneous detection of vertical and lateral forces. The cantilever consists of a flat, triangular probe connected to a base by four tall, narrow ribs. The vertically compliant triangular probe and the laterally compliant ribs incorporate separate piezoresistors for vertical and lateral force sensing. In the fabrication process, a special oblique ion implant technique is used to produce electrical elements on vertical sidewalls and horizontal surfaces of the cantilever structure at the same time. The dual-axis cantilever has been used to perform microfriction measurements as well as obtain simultaneous vertical-force and lateral-force AFM images. © 1998 American Institute of Physics. [S0003-6951(98)00811-0]

Some applications of atomic force microscopy (AFM) 1,2 such as nanotribology 3 rely on the detection of lateral forces 4 as well as vertical forces with micromachined cantilevers. An existing approach to lateral force detection based on conventional planar cantilevers makes use of the torsional bending mode to measure lateral forces at the tip, with deflection sensing being achieved through optical 5 or piezoresistive 6–8 means. However, because the same planar cantilever is also simultaneously used in the vertical bending mode for topographical imaging, mechanical crosstalk and signal mixing may occur between the two modes, leading to difficulties in data analysis and interpretation. Another design requirement arises from the need to balance the lateral stiffness of a cantilever against its vertical stiffness. This tends to constrain the shape and relative dimensions of the cantilever. 5–7,9

This letter describes a novel AFM cantilever with two orthogonal directions of compliance based on a dual-axis mechanical configuration. Associated with each direction of compliance is an independent set of piezoresistive deflection sensors. This design makes it possible for vertical and lateral forces to be measured without complex signal-separation circuitry, and allows the cantilever geometry and stiffness to be separately optimized for each sensing direction. The cantilever is made up of two distinct mechanical sections corresponding to the vertical force sensor and the lateral force sensor (Fig. 1). The vertical force sensor is in the form of a flat, triangular probe with a piezoresistive boron layer, similar in design to typical existing devices. 2,8,10 Instead of being connected directly to the base, however, the triangular probe is suspended at the end of four parallel high-aspect-ratio “ribs” which give the structure lateral compliance. The two inner ribs have sidewall-embedded piezoresistors, forming a lateral force sensor. During imaging, forces at the cantilever tip are mechanically resolved into vertical and lateral components which are separately detected by the corresponding deflection sensors, giving rise to synchronized vertical-force and lateral-force output signals. To our knowledge, this represents the first use of piezoresistive sensors fabricated on horizontal and vertical surfaces of a micromachined structure to achieve simultaneous force sensing in orthogonal directions.

The shaded areas of Fig. 1 show the electrical path along the two separate force sensing circuits. For the vertical force sensing circuit, the sidewalls of the two outer ribs are heavily boron doped (i.e., p doped) to provide high conductivity, allowing current to flow from the base via the ribs to and from the triangular probe with its leg-mounted piezoresistors. For the lateral force sensing circuit, current flows from the base onto one of the two inner ribs with its sidewall-mounted piezoresistor, then doubles back at the crossbar and returns via the other inner rib. To prevent electrical crosstalk between the vertical and the lateral force sensing circuits, back-to-back p-n diodes are fabricated on the crossbar as shown in Fig. 1.

The dual-axis cantilever is fabricated out of a 10-μm
thick top silicon layer of a silicon-on-insulator (SOI) wafer. First, an oxide mask is used to define the position of the ribs, while a photoresist dot is used to define that of the tip. An anisotropic Cl2/HBr plasma etch\textsuperscript{11} is then used to form the ribs and the tip in one step. Protected by the oxide mask, the ribs are etched to a rectangular profile. However, the silicon underneath the less resilient photoresist dot is etched to a tapering conical profile. The etch chemistry produces a self-sharpening effect as well, giving a tip radius as small as 200 Å without oxidation sharpening. The plasma etch is stopped when a thin layer of top-side silicon remains, and the triangular probe is then formed from this layer. A 1000 Å surface oxide layer is grown for electrical passivation, and a series of oblique low-energy boron implants is performed at approximately 45° to the normal, enabling electrical elements such as piezoresistors to be simultaneously formed on vertical sidewalls and horizontal surfaces of the cantilever, and ensuring electrical continuity at the interfaces. Oblique ion implantation is an extension of an existing technique for producing thin, planar cantilevers with shallow piezoresistive layers.\textsuperscript{8,10,14}

The oblique ion implant technique described here represents a novel approach to fabricating electrical elements on high-aspect-ratio micromachined structures. This approach is motivated by the fact that electrical paths on the dual-axis cantilever need to follow a vertical plane in some parts of the structure and in a horizontal plane in others. One way of fabricating such paths is to implant dopant ions at ∼45° to the normal, enabling electrical elements such as piezoresistors to be simultaneously formed on vertical sidewalls and horizontal surfaces of the cantilever, and ensuring electrical continuity at the interfaces. Oblique ion implantation is an extension of an existing technique for producing thin, planar cantilevers with shallow piezoresistive layers.\textsuperscript{8,10,14}

Figure 2 shows a scanning electron micrograph of a fabricated single-crystalline silicon cantilever. The triangular probe is 1.3 μm thick and 90 μm long with each leg being 8 μm wide, while the ribs are 1.3 μm wide, 10 μm tall, and 110 μm long. One of the advantages of the present design is that the stiffness and piezoresistive sensitivity of the triangu-

FIG. 2. Scanning electron micrograph of a dual-axis cantilever, with a closeup of the tip. The device shown has a 1.3 μm thick triangular probe connected to the base by four 1.3 μm×10 μm×110 μm ribs.
lar probe and the ribs can be independently adjusted by changing their dimensions, unlike the case of the simple planar cantilever. The calculated mechanical stiffness of the triangular probe is 2 N/m vertically and 470 N/m laterally, while the stiffness of the four ribs combined is 11 N/m laterally and 5000 N/m vertically.

The performance of the piezoresistive deflection sensors was measured with Wheatstone bridge circuits based on low-noise Burr–Brown INA103 instrumentation amplifiers configured with a gain of 100. The bridge voltage was 5 V (i.e., 2.5 V across each resistor). The vertical and lateral deflection sensors on the cantilever exhibited piezoresistive sensitivities $\Delta R/R$ of 0.25 ppm and 1.0 ppm per Å, respectively. The piezoresistors were approximately 10 kΩ in resistance. The measured noise floor for a typical device was within 20% of the theoretical Johnson noise floor, with a 1/f knee around 500 Hz.

Dual-channel AFM imaging capability has been demonstrated with the dual-axis cantilever. Figure 3 shows vertical and lateral force AFM images obtained in parallel. The imaging was performed in air in constant-loading-force mode, using two separate bridge-amplifier circuits. The substrate was a silicon sample with a grid of ridges 1600 Å in height, 2 µm in width, and 10 µm in pitch. The bright y-oriented bands in the lateral force image correspond to an increase in lateral tip displacement. These bands coincide with the left edges of the y-oriented ridges in the vertical force image, suggesting that the tip (scanned from left to right) was tripped at the leading step edge before climbing it. Figure 3 can be compared against a pair of line scans (Fig. 4), in which the tripping of the tip at the leading step edge is visible as a large positive spike in the lateral deflection signal.

Experiments have also been performed with the dual-axis cantilever to measure microscale friction. In one experiment, the silicon tip of the cantilever was scanned in air across a polycarbonate substrate at various tip velocities and loading forces, progressing from low to high loading forces. The lateral deflection of the cantilever was measured and the results are shown in Fig. 5. It was observed that lateral deflection of the cantilever, which is an indication of the frictional force experienced by the tip, increased roughly linearly with loading force for a given tip velocity within the limited range of loading forces studied. The coefficient of friction (represented by the slope of the best-fit lines) ranged from 0.4 at low tip velocities to 0.6 at high tip velocities. The entire set of measurements was repeated multiple times with essentially similar results, indicating that no apparent tip-sample wear occurred that changed the coefficient of friction. An AFM image of the sample taken afterwards also showed no signs of wear.

In conclusion, we have described a dual-axis AFM cantilever that allows simultaneous, independent detection of vertical and lateral forces as well as individual optimization of its mechanical characteristics in the two orthogonal directions. A special ion implant process using a large oblique angle of incidence was developed for producing electrically conductive elements (including piezoresistive elements) on vertical sidewalls and horizontal surfaces of high-aspect-ratio micromachined structures. This fabrication approach is not limited to AFM cantilevers and can in fact be applied to other lateral force sensors such as accelerometers, fluidic sensors, and magnetic sensors. The dual-axis cantilever has potential utility in nanotribology (for frictional analysis), tip-based data storage (for concurrent servocontrol and data readback) and magnetic imaging for simultaneous imaging of vertical and lateral fields at domain walls.

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