1-1-1992

Force Measurement with a Piezoelectric Cantilever in a Scanning Force Microscope

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ultramicroscopy

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Detection of surface forces between a tip and sample has been demonstrated with a piezoelectric cantilever in a scanning force microscope (SFM). The use of piezoelectric force sensing is particularly advantageous in semiconductor applications where stray light from conventional optical force-sensing methods can significantly modify the local carrier density. Additionally, the piezoelectric sensors are simple, provide good sensitivity to force, and can be batch fabricated. Our piezoelectric force sensors will be described, the theoretical sensitivity and performance of piezoelectric sensors will be discussed and experimental measurements of sensitivity and imaging results will be presented.

1. Introduction

The scanning force microscope (SFM) is based upon the sensing of ultrasmall forces between a nanometer scale tip and a sample surface. The typical arrangement is to have the tip attached to a cantilever which has a compliance in the range of 0.1 to 10 N/m. The force sensing can be achieved in several ways [1–6]. The most extensively used methods involve the use of a laser beam to measure the displacement of the cantilever by beam deflection or interferometry. These methods provide a high sensitivity to force, but require precise alignment of the optical beam with the cantilever. When imaging photosensitive materials, like semiconductors, the stray light from the illumination of the cantilever can strongly perturb the sample surface properties being measured. For these reasons, alternative force-sensing methods are attractive. Recently, Tortonese [7] demonstrated the use of piezoresistive sensing in an AFM cantilever. Previous work in this area includes a patent by Pohl [8] who described the use of an oscillating quartz force detection method, but no experimental work was

reported. More recently Takata [9] demonstrated a microscope based upon the detection of AC tip/sample forces with a piezoelectric sensor at the back side of the sample. Guthner [10] has also piezoelectrically sensed the interaction between a tip and sample with a high-Q quartz-tuning fork resonator. Here we describe the use of a piezoelectric bimorph cantilever for force detection, and present experimental results based upon this approach.

2. Theory and experiment

Fig. 1 contains a schematic representation of a piezoelectric force sensor in the form of a bimorph. The minimum detectable force of any cantilever is always limited by thermal motion of the cantilever. Thus the sensor used to detect force becomes unimportant if the force sensitivity is dominated by the thermal fluctuations. We will now evaluate the conditions under which a piezoelectric bimorph can be thermal noise limited as a force detector. The piezoelectric voltage produced by a bimorph of length l, width w, thick-
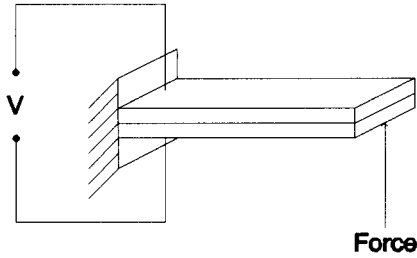
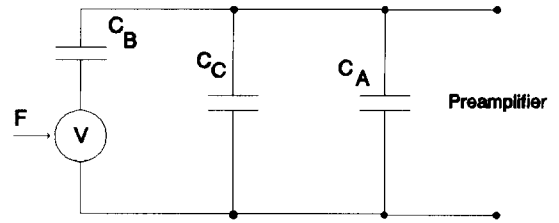Fig. 1. Schematic illustration of a piezoelectric bimorph cantilever.

Fig. 2. Equivalent circuit for the detection of forces by a piezoelectric bimorph.

ness t and piezoelectric stress constant g_{31} is given by

$$V = \tfrac{3}{2}\left(\frac{g_{31}l}{wt}\right)F, \tag{1}$$

where F is the applied force below the resonance frequency. For a cantilever of rectangular cross section, the resonance frequency is given by

$$f = 0.161\frac{t}{l^2}\sqrt{\frac{Y}{\rho}}, \tag{2}$$

where Y is Young's modulus and ρ is the density. The spring constant of the cantilever is given by

$$k = \frac{Ywt^2}{4l^3}. \tag{3}$$

The smallest measurable force, as limited by thermal exitation of the cantilever, is given by [11]

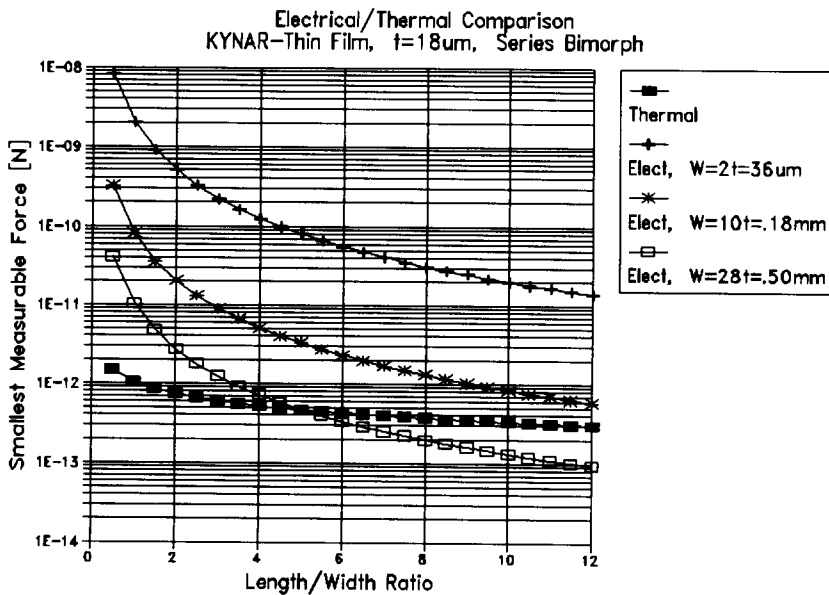$$F_{min} = \sqrt{\frac{6.18k_B T\sqrt{Y\rho}\,Bwt^2}{ql}}, \tag{4}$$

Fig. 3. Comparison of the performance of several preamplifier-noise-limited bimorphs with a thermal-vibration-noise-limited cantilever.

where k_B is Boltman's constant, T is the temperature, Q is the mechanical quality factor, and B is the detection bandwidth.

To experimentally demonstrate the capabilities of the piezo sensors, a piezoelectric polymer PVDF was chosen. This polymer is produced commercially [12] and is available in thicknesses ranging from 9–500 μm. The Young's modulus for PVDF is approximately 2×10^9 N/m, and the density is 1800 kg/m^3. The piezoelectric stress constant is 0.23 Vm/N.

The equivalent circuit for the piezo and preamplifier is shown in fig. 2. Here, C_B is the bimorph capacitance, C_C is the cable capacitance and C_A is the front-end amplifier capacitance. Since the voltage produced by the deflection of the piezo must pass through the series capacitance, ideally, the front end impedance of the preamplifier should be larger than the impedance of the piezo capacitance at the operating frequency.

Fig. 3 plots the amplifier-limited performance of several bimorph sensors built using PVDF films, and compares them with the thermal motion limited force sensitivity. The assumptions made in this calculation were that the capacitance of the cable was 40 pF and the front-end capacitance of the preamplifier was 15 pF. The force sensitivity is significantly improved if smaller cable and amplifier capacitances are used, since the piezo capacitances used in the calculations are of the order of 2 pF.

In these calculations, a PVDF bimorph of thickness 18 μm was evaluated. For the case of a piezo of width 0.5 mm (open boxed curve in fig. 3), the bimorph is limited only by the thermal vibration of the cantilever for a length-to-width ratio greater than 5. In this case, the spring constant of the cantilever is 0.1 N/m and the resonance frequency is 460 Hz. The amplifier noise for these curves is assumed to be 5 nV/Hz$^{1/2}$ which is typical for reasonably good preamplifiers.

The bimorphs we built were composed of two 28 μm thick piezo films with thin-film metal electrodes on either side. The as-purchased piezo films were glued together by applying a very small amount of epoxy to a 3 $\times$ 1 cm sheet of PVDF. A

second sheet was then compressed against the first sheet with a vise with rubber jaws. The epoxy was then allowed to cure. The resultant series bimorph was then carefully cut out of the two-layer sheet with an unused razor blade.

The cantilever used to determine the force sensitivity was triangularly shaped, the tip being the smaller end. The full length was approximately 2 mm and the base was approximately 0.5 mm. The cantilever resonance frequency and thickness (including epoxy) were measured to be 25 kHz and 75 μm, respectively. The triangular cantilever was held in a clamp with a free length of approximately 0.8 mm. Since the direct measurement of the spring constant is difficult, we estimate it here. The spring constant of a triangular bimorph can be estimated using the measured values of length and width with eq. (2). This equation can be used for our triangular cantilever by substituting $l/4$ for w, since the width at any point along the cantilever is just $l/4$ of the distance from the tip. The effect of the epoxy cannot be determined exactly, but it is reasonable to assume that the material properties of the epoxy are not drastically different than the PVDF. If this assumption is made, the spring constant is calculated to be 109 N/m.

The bimorph was used without any tip attached to it, and the shape and size of the tip were not measured; but as will be seen, the resolution achieved is consistent with a tip radius below 500 Å. Fig. 4 contains the measured frequency response of the PVDF bimorph, indicating that the Q was approximately 7.

The sensitivity of the bimorph was calibrated by bringing the tip close to a surface vibrating at the resonance frequency of the cantilever. The cantilever was pressed against the vibrating surface so that the tip displacement was equal to that of the surface. The minimum amplitude of vibration detectable was measured to be 0.5 Å in a 2.6 kHz bandwidth. With a spring constant of 109 N/m, this corresponds to a force sensitivity of 5.4 nN in a 2.6 kHz detection bandwidth. The noise spectral density at this frequency is independent of frequency and the minimum force detectable improves as the square root of the detection bandwidth. In a 1 Hz detection band-
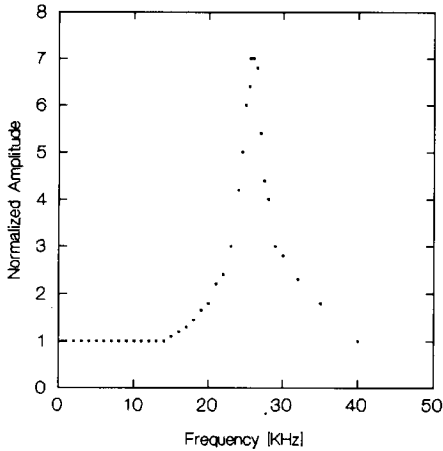
Fig. 4. Plot of the mechanical displacement amplitude of the piezoelectric bimorph as a function of frequency.

width, this minimum force corresponds to 105 pN.

This sensitivity can be significantly improved. The capacitance of the cantilever in this experi-ment was measured to be approximately 2 pF, while the capacitance of the leads and front end of the preamplifier was measured to be approximately 100 pF. This means that the measured force sensitivity was 50 times less than under the ideal condition where the lead and front-end capacitance is small compared to that of the bimorph. In practice, this ideal condition is extremely difficult to achieve, however, increasing sensitivity by a factor of 10 should be achievable by proper design of the detection system.

The experimental set-up for imaging is described in fig. 5. Since the voltage produced by a static deflection of the cantilever cannot be maintained by the piezo, an AC force detection was used in our SFM. The sample was vibrated at the resonance frequency of the bimorph. The signal from the bimorph was sent to a lock-in amplifier, where it was filtered and rectified to produce a dc output proportional to the magnitude of the AC force. This signal was then sent to a conventional integrating feedback control box. The out-
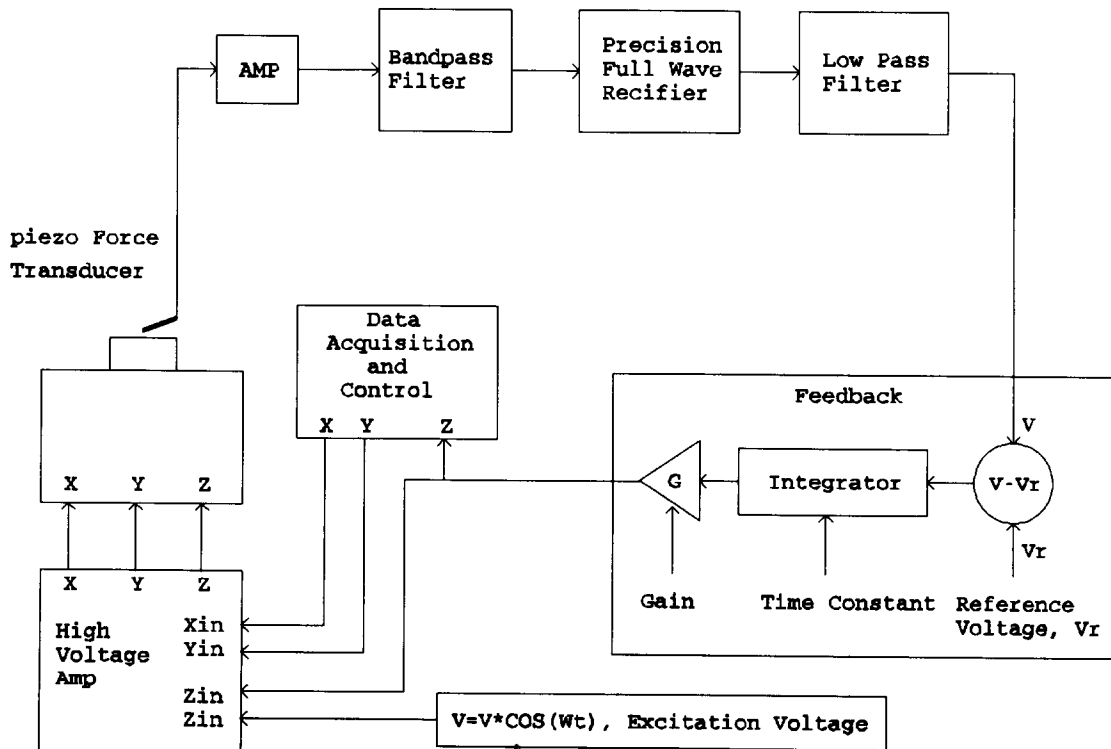

Fig. 5. Schematic illustration of the detection and feedback system for surface profiling.

put of the integrator was amplified and sent to the z input of the piezo tube.

The piezo cantilever was used to image two different surface structures. The first was a thin-film gold/palladium film (200 Å) on a glass microscope slide. Fig. 6 shows the topography of a 4000×4000 Å region of the surface. The image shows a later resolution on the 300 Å scale, and a vertical noise on the 1 Å scale. The large feature on the left has a vertical height of 30 Å. The image was taken with a vertical vibration of the sample of 30 Å, and the image was acquired in approximately 90 s.

The second surface imaged by the piezo sensor was a 1 μm period glass grating covered with 300 Å of gold. Fig. 7 contains the constant-force image of the grating structure. Due to the size of the tip, the vertical variation seen in the topographic image (300 Å) is smaller than the grating depth.

These results indicate that piezoelectric detection of surface force is a viable alternative to present force detection methods. Both the calculations and the experimental work described here were performed under conditions where the capacitance of the piezo was very small compared to the load capacitances. Substantial improvement in performance will be achieved when those capacitances are reduced. Furthermore, improvement in force sensitivity should also be possible
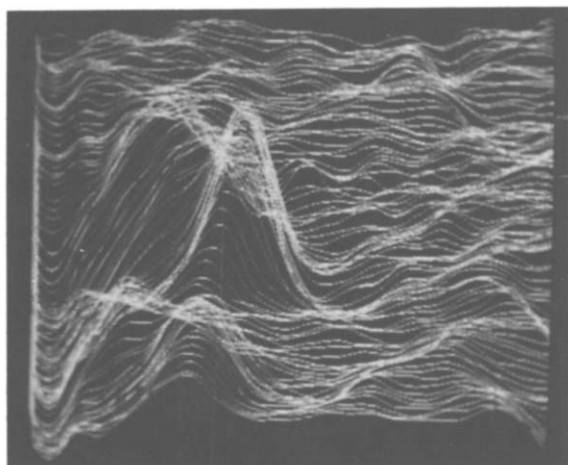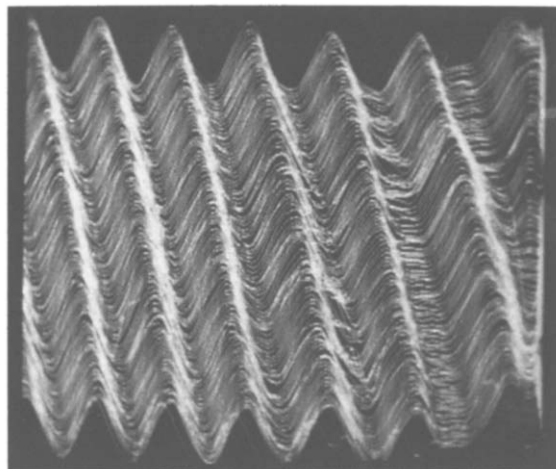

Fig. 7. Topographic image of a 1 μm period grating. The vertical height variation is 300 Å, limited by the size of the cantilever tip.

by going to thinner piezoelectric films. This can be achieved by deposition of films, rather than using prefabricated piezo sheets to construct the force sensors.

3. Conclusions

We have demonstrated the use of piezoelectric bimorphs as force sensors. The sensors have demonstrated a force sensitivity of 105 pN/Hz$^{1/2}$ under less than ideal conditions. The advantages of piezoelectric cantilever force detection include simplicity, good sensitivity, and possibility for batch fabrication. They also eliminate the need for optical force detection methods, which are prohibited when imaging photosensitive materials like semiconductors. We have not explored the use of charge amplifiers with the piezo sensors yet. This approach should provide the means to look at quasi-static forces, which will broaden the application of the sensors.

Acknowledgement

Fig. 6. A 4000×4000 Å image of a glass surface covered with 200 Å of gold. The tallest feature is 30 Å in height.

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