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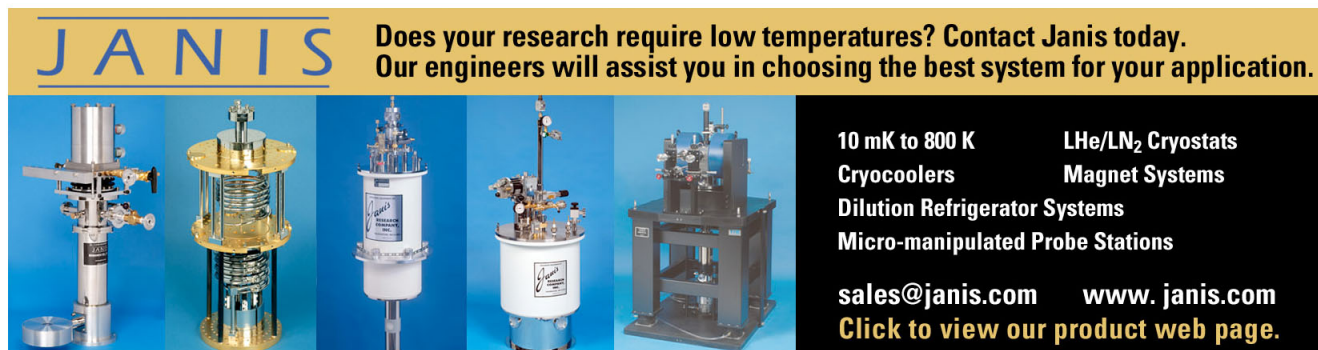
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High-speed atomic force microscopy using an integrated actuator and optical lever detection

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A new procedure for high-speed imaging with the atomic force microscope that combines an integrated ZnO piezoelectric actuator with an optical lever sensor has yielded an imaging bandwidth of 33 kHz. This bandwidth is primarily limited by a mechanical resonance of 77 kHz when the cantilever is placed in contact with a surface. Images scanned with a tip velocity of 1 cm/s have been obtained in the constant force mode by using the optical lever to measure the cantilever stress. This is accomplished by subtracting an unwanted deflection produced by the actuator from the net deflection measured by the photodiode using a linear correction circuit. We have verified that the tip/sample force is constant by monitoring the cantilever stress with an implanted piezoresistor.

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I. INTRODUCTION

Recently, there has been interest in increasing the throughput of scanning probe microscopy;¹⁻³ however, applications such as imaging and lithography often require that the probe maintains a constant force on the sample.⁴ The maximum scan rate at which this method of scanning can operate is limited by the bandwidth of the actuator responsible for providing constant force. Typically, the actuator consists of a macroscopic piezoelectric material in the form of a tube or stack which exhibits relatively low resonant frequencies (often less than 1 kHz). This can limit scanning speeds to less than a few hundred microns per second. As a result, it often takes minutes to produce a single image.

Previously, we found that the scan speed could be increased an order of magnitude by integrating a thin layer of ZnO on the base of a piezoresistive cantilever.⁵ The cantilever was bent to follow sample topography by applying a voltage across the ZnO while the sample force was detected by measuring the piezoresistor. In that study, both the imaging bandwidth (6 kHz) and the resolution (~ 60 Å) were limited by complications in measuring the piezoresistor. We expect that these results can be improved by optimizing the cantilever design and refining the detection electronics. However, the susceptibility to unwanted electrical interference of a detector consisting of an electrical loop can make it difficult to obtain large bandwidths with high resolution.

We report here the extension of high-speed imaging with an integrated actuator to include an optical lever sensor. Developed by Meyer and Amer⁶ and Alexander *et al.*,⁷ the optical lever is capable of subangstrom vertical resolution and is not influenced by electrical signals that control the integrated actuator. In a standard system, constant tip/sample force is achieved by translating either the cantilever or the sample with a servo loop that maintains a constant cantilever deflection. The optical lever is used to measure the deflection angle of the cantilever. In ordinary circumstances, this angle only changes when a force is acting on the tip; thus, the optical lever gives a true measure of the force. In a system

where the actuator is mounted on the cantilever, motion in the vertical direction is achieved by changing the angle of the cantilever⁸ and this is a problem that must be addressed when the optical lever is used for detection. This scheme is depicted in Fig. 1 for three cases where:

- (a) the tip/sample force is near zero;
- (b) the cantilever is strained by a topographical step; and
- (c) a voltage is applied to the ZnO to relieve the strain.

The angle of the reflected beam in (a) is different from the angle in (c) although the force is the same. As we discuss, the signal measured by the optical lever is a function of the ZnO bending in the absence of a force on the tip. It is a simple matter to construct a circuit that subtracts this unwanted signal from the servo loop. We have found that a first-order linear correction applied to a 720- μm -long cantilever yields a vertical range where constant force is possible. Using this correction procedure, we present a $100 \times 100 \mu\text{m}^2$ image scanned with a tip velocity of 1 cm/s, as well as a high-resolution image of the granular structure of gold scanned at 0.5 mm/s. In the case of the high-resolution image, the tip speed was limited by the scanning device.

II. EXPERIMENT

A schematic of our atomic force microscope (AFM) is shown in Fig. 2. The silicon cantilever can be displaced vertically up to 4 μm using a layer of ZnO located at the cantilever base.⁹ To maximize the displacement for a given applied voltage, the ZnO thickness is 3.5 μm and is equal in thickness to the silicon portion of the cantilever. Because the spring constant is proportional to the thickness cubed, and the base is twice as thick as the remainder of the cantilever, most of the bending will occur in the thinner portion when the tip is deflected. Therefore, we can effectively uncouple the deflection of the cantilever caused by applying a voltage across the ZnO and the deflection caused by physically displacing the tip with a sample. As a result, if the tip is in contact with a surface while the ZnO voltage is modulated, the deflection signal from the photodiode will consist of two angular components: the strain-induced angle [depicted in

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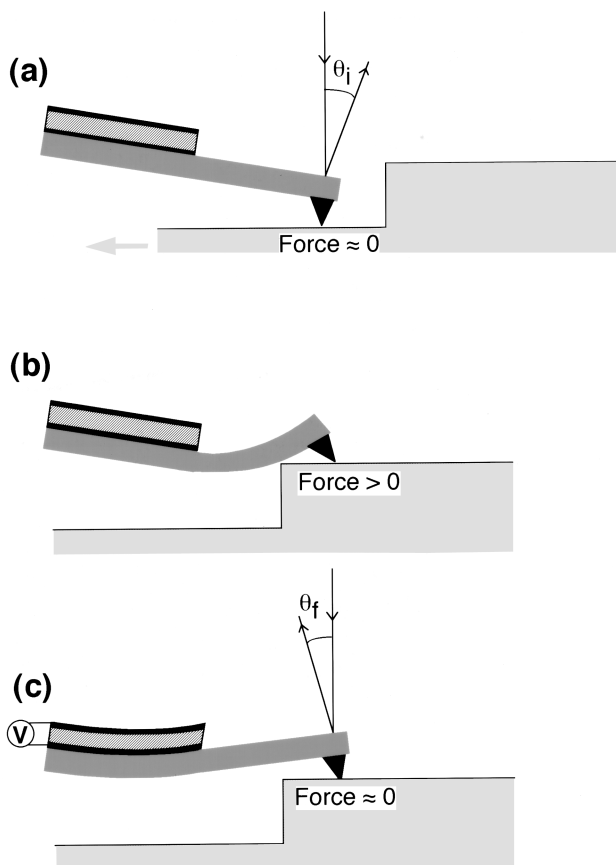


FIG. 1. Schematic drawing showing (a) the initial cantilever shape, (b) the shape after being scanned over a step, and (c) after an appropriate voltage is applied to the ZnO to return the cantilever stress to that shown in (a). Note that the cantilever exerts an equal force on the sample in (a) and (c) but the deflection angle of the laser beam is different. This difference (created by the actuator itself) can be subtracted from the photodiode signal so that only strain-induced bending of the cantilever is measured.

Fig. 1(b)], and the ZnO-induced angle [Fig. 1(c)]. To obtain constant force, the servo loop must detect only the strain-induced angle.

To eliminate the ZnO-induced angle, we sum the output of the photodiode with the signal that controls the ZnO (see Fig. 2). In order to calibrate the correction scheme, the ZnO is modulated while the tip end of the cantilever is free and

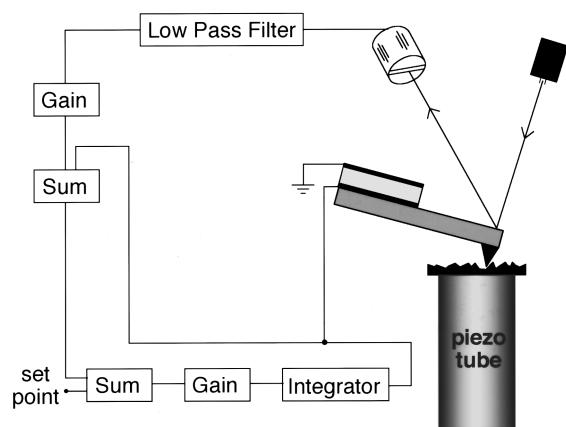


FIG. 2. Atomic force microscope (AFM) schematic including a linear correction of the photodiode used to remove the ZnO-induced bending.

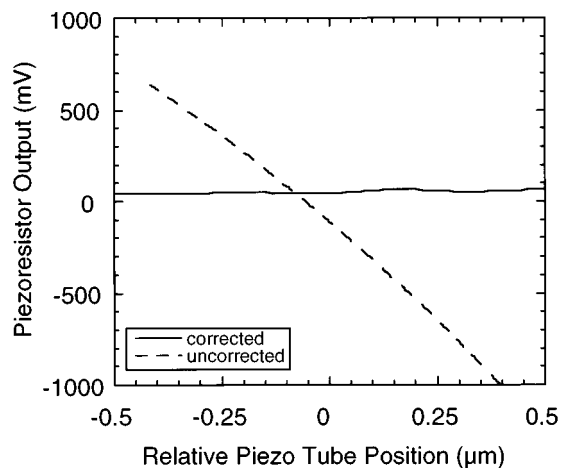


FIG. 3. Graph of the piezoresistor output vs vertical position of the piezo tube when the photodiode signal is corrected (solid) and uncorrected (dashed). The piezoresistive signal obtained with correction indicates that a constant tip/sample force is maintained over a $1 \mu\text{m}$ range of the piezo tube. The piezoresistor is implanted in the region of the cantilever that is not covered with ZnO and is a direct measure of the force applied at the tip.

the gain of the photodiode output is adjusted so that the corrected deflection is nulled. At this point, the servo loop cannot distinguish between the scenario depicted in Figs. 1(a) and 1(c). Since the cantilevers used in this experiment contain an integrated piezoresistor,¹⁰ constant force can be verified by modulating the sample in the vertical direction with the piezo tube while the ZnO actuator and corrected photodiode signal are in feedback.

The value of the piezoresistor represents strain in the cantilever and is a direct measure of the force at the tip. Our cantilever has been fabricated such that the geometry and doping profiles cause the piezoresistor to respond to forces on the tip, but not to the strain induced by ZnO movement.¹¹ This configuration provides an accurate measure of the tip/sample force regardless of the degree of ZnO actuation.

Figure 3 plots the output of the piezoresistor as a function of the relative piezo tube position when the photodiode signal is corrected (solid) and uncorrected (dashed). When the correction procedure is implemented, the piezoresistive signal is constant over a piezo tube range of $1 \mu\text{m}$, indicating that constant force is maintained. When the correction scheme is omitted from the servo loop, the piezoresistor varies with the tube position, indicating that the tip/sample force is not constant. For piezo tube positions greater than $1 \mu\text{m}$, the laser beam was deflected out of the linear range of our photodiode.

III. RESULTS AND DISCUSSION

The frequency response of the actuator, sensor, and servo loop is determined by modulating the setpoint while the tip is in contact with a surface (see Fig. 2). First, the integral gain and time constant of the servo loop are increased to just below the point where the system becomes unstable. The modulation frequency of the setpoint is then swept while the output of the integrator (ZnO signal) and input to the gain/integrator (error signal) are recorded. The amplitude and phase response of the ZnO are shown in Fig.

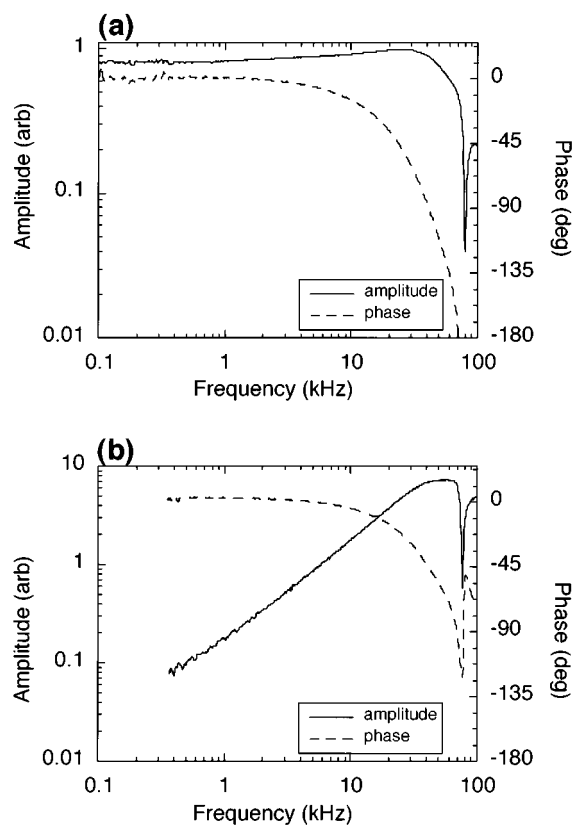


FIG. 4. Frequency response of the servo loop shown in Fig. 2. The input to the ZnO actuator is shown in (a) and the input to the gain/integrator stages (error signal) is shown in (b). The system is driven by modulating the setpoint with a variable frequency sine wave. With a 45° phase margin of the error signal, the imaging bandwidth is 33 kHz. Note the mechanical resonance at 77 kHz.

4(a), and the error signal is shown in Fig. 4(b) for a $570\text{-}\mu\text{m}$ -long cantilever. By adding a 12 dB low-pass filter at 100 kHz, we could increase the integral gain while still maintaining stability of the servo loop. The resulting bandwidth is 33 kHz for a 45° phase shift of the error signal. The mechanical resonance at 77 kHz (shown in Fig. 4) causes the system to oscillate if the integral gain is increased further.

Large scale imaging in the constant force mode with a tip velocity of 1 cm/s is demonstrated in Fig. 5. The sample was constructed by patterning circles on a $1000\text{-}\text{\AA}$ -thick gold film deposited on a Nb-doped SrTiO_3 substrate. Images were obtained by raster scanning the sample over an area of approximately $100 \times 100 \mu\text{m}^2$ using a 2-in.-long piezo tube with a fast scan rate of 50 Hz. A complete image consisting of 512 scan lines was acquired in under 15 s. In order to verify that constant force mode was being used, the cantilever stress was monitored with the piezoresistor at tip speeds up to $\sim 3 \text{ mm/s}$. Electrical interference between the piezoresistor and the ZnO actuator was eliminated by measuring the piezoresistor with a lock-in technique as described in Ref. 5. Limitations in our electronics prevented the use of this technique at higher speeds. To circumvent resonances in the tube, the fast scan direction was driven with a sine wave while the slow scan was ramped with a triangle wave. A video acquisition system¹² was used for the fast data acquisition. Given an x and y input, this system digitizes the z

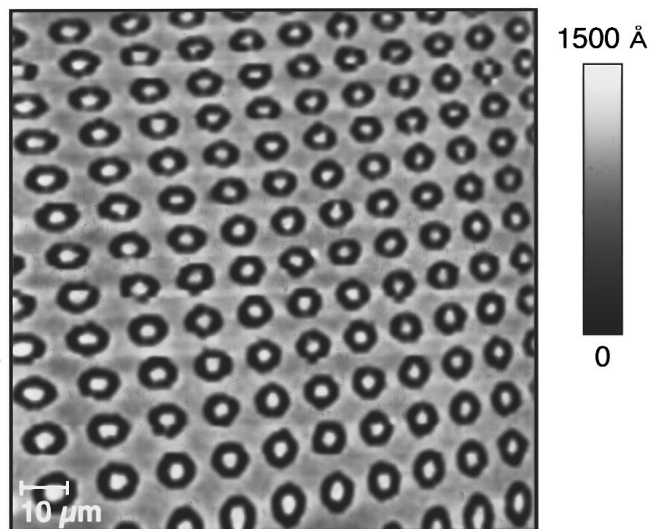


FIG. 5. Constant force image acquired with a scan speed of 1 cm/s. The sample is made by depositing and patterning gold on a Nb-doped SrTiO_3 substrate. The 512 scan line image is approximately $100 \times 100 \mu\text{m}^2$ and was produced in less than 15 s. The image is slightly distorted due to a nonlinear response of the piezo tube scanner.

input and converts it to a video signal so that the image can be displayed on a monitor in real time. The images are then captured on video tape and downloaded to a computer for analysis.

Using the same scanning system, we reduced the scan size to the micron scale and increased the scan rate to 200 Hz. Since many frames per second could be acquired at this rate, we were able to center and zoom in on a single feature with real time visual feedback. Figure 6 shows a section of a $1.25 \times 1.25 \mu\text{m}^2$ image revealing the granular structure of the gold taken at a tip velocity of 0.5 mm/s. Although our servo loop is capable of faster tip velocities, a mechanical resonance of our piezo tube just above 200 Hz limited the scan rate. Since tip speed is a function of both scan rate and scan

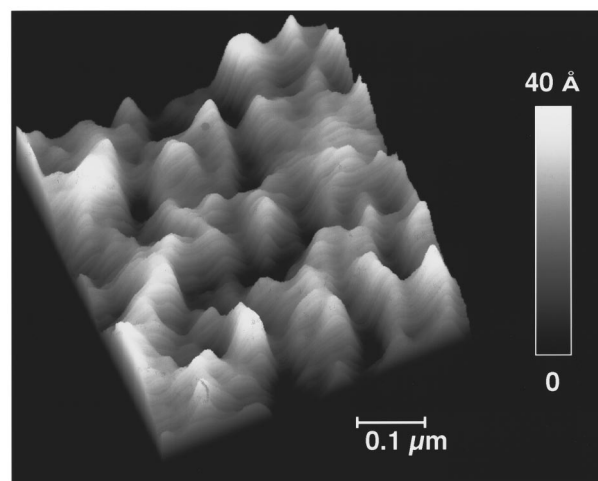


FIG. 6. The granular structure of the gold is revealed in this image, taken at a tip speed of 0.5 mm/s.

size, the tip speed was limited to roughly 0.5 mm/s for scan sizes on the order of $1 \mu\text{m}^2$. In a 10 kHz bandwidth the measured electrical noise of the system corresponds to a deflection of a few angstroms.

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