Noise reduction in atomic force microscopy: Resonance contact mode

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Noise reduction has been accomplished in atomic force microscopy by applying a high frequency, low amplitude vibration to the cantilever while it is in contact with a surface. The applied excitation (>200 kHz; ~ 1 nm) is acoustically coupled to the tip and dampens the resonance Q factors of the system. The applied frequency is well above the bandwidth of the acquisition system (50 kHz). We call this mode "resonance contact" mode. The nonlinear behavior of the tip–sample interaction allows the high frequency excitation to effectively broaden the frequency response of the system resonances. © *1996 American Institute of Physics.* [S0034-6748(96)02602-8]

I. INTRODUCTION

Noise reduction is of interest for any analytical instrument and is crucial in certain environments. Mechanical noise can induce unwanted signals in atomic force microscopy measurements, limiting the resolution and scan speed. In this report, a method for reducing mechanical noise in atomic force microscopy (AFM) is demonstrated; this technique is easy to implement with minimal instrumentation.

The use of AFM in a dynamic mode was first demonstrated by Martin *et al.* in 1987.[1] This "resonance noncontact" mode is implemented as follows: the cantilever is vibrated near its first resonance frequency (ω_0). As the tip approaches the sample, the tip–sample interaction produces a force gradient that shifts the resonance frequency of the cantilever:

$$m^* \omega_{\text{new}}^2 = k_{\text{new}} = k_0 - \frac{\partial F}{\partial z},$$

where k is the spring constant, m^* is the effective mass, ω is the resonance frequency, and z is the tip–sample separation. Since the driving frequency (ω_0) is not equal to the new resonance frequency of the cantilever (ω_{new}), the amplitude of the vibration is lowered and can be used as a feedback signal. This technique effectively eliminates the lateral force that is present in normal contact mode imaging. However, this strategy requires lock-in electronics and special cantilevers.

In modulated "noncontact" or "intermittent contact" scanning modes, the oscillation of the cantilever is damped in amplitude and phase by interaction with the sample. In air, these surface interactions are often dominated by the contamination layer that is present. Recently, other modulated modes have been demonstrated in water with cantilevers having relatively weak spring constants (0.5 N/m).[2–4] Also, ultrasonic detection has been used in conjunction with AFM to detect cantilever movements in the MHz regime.[5]

In this report, a simple method for reducing low frequency noise in dc AFM experiments is demonstrated. While the cantilever is in contact with the sample, the base of the cantilever is mechanically driven at a high frequency. At certain frequencies, the overall mechanical noise of the system is lowered. No special instrumentation is required for this mode other than a function generator to vibrate the cantilever at high frequency and a piezoceramic to couple the excitation into the cantilever–sample system. We refer to this technique as the resonance contact mode (RCM). A mechanism based on nonlinear coupling between the tip and sample is presented to explain this phenomenon.

II. EXPERIMENT

A Topometrix Discoverer AFM with in-house software was used for the experiments in this report.[6,7] This system uses an optical lever detection scheme to monitor the cantilever displacement. In order to determine the frequency characteristics of the cantilever motion, the output of the photodiode preamplifier was connected directly to a HP spectrum analyzer. Standard 200 μm, silicon nitride, thin arm triangular cantilevers were used for all of the experiments ($k=0.1$ N/m, $\omega_0 \sim 20$ kHz).

The software uses a proportional-integral-differential (PID) feedback algorithm to maintain constant cantilever deflection. The feedback parameters determine the response time of the instrument; higher values will produce shorter response times. However, if the gains are increased above a certain threshold, the feedback loop will oscillate. This threshold is one of the factors limiting the maximum scan speed.

In order to vibrate the cantilever, the tip mounting system was attached directly to a small piezoceramic (labeled RCM piezo A in Fig. 1). This base plate was initially designed to be used in resonance noncontact mode. For the liquid experiments, a piezoceramic was glued between the AFM head that houses the tip/detector and the base which houses the sample. Driving this piezo was also effective at coupling vibrations to the cantilever. This piezo will be referred to as RCM piezo B. A function generator was used to apply the driving signal.

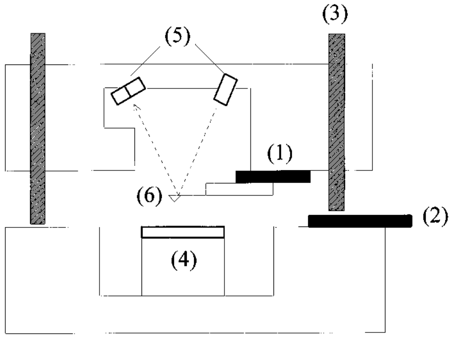

FIG. 1. Schematic of the RCM setup. Two piezos can drive the RCM frequency: (1) RCM piezo A or (2) RCM piezo B; (3) approach screws; (4) sample tube scanner; (5) feedback laser and photodiode; (6) cantilever.

Three imaging conditions were analyzed: clean samples in air, oily samples in air, and clean samples in water. The oily sample was studied in order to determine the meniscus effect when RCM was used in air. The sample was smeared with a small amount of vacuum pump oil; the oil was then wiped off with a Kimwipe before the tip was brought into contact.

III. RESULTS

A. Typical noise spectrum

Figure 2 is a noise spectrum when the cantilever is in contact with a compact disk (CD) that had been smeared with oil; the feedback is engaged but the tip is not scanning. Two specific noise peaks are present in this experiment: 4 and 14 kHz (and overtones). The 4 kHz noise changes amplitude as the feedback gains are altered but does not shift in frequency. A change in imaging conditions may shift this frequency slightly. For example, changing the meniscus from oil to water shifts this frequency to ~2.7 kHz. However, using a new cantilever, sample, or setpoint does not shift this frequency. There is also a mechanical resonance at 14 kHz; this noise varies in amplitude and frequency for different tips and samples. Also, the frequency shifts depending on the beam alignment and the angle of the AFM head relative to the sample. Therefore, this mechanical resonance is not necessarily related to the cantilever's first resonance mode.

In order to determine the sources of these peaks, the feedback parameters were altered. As the integral gain was

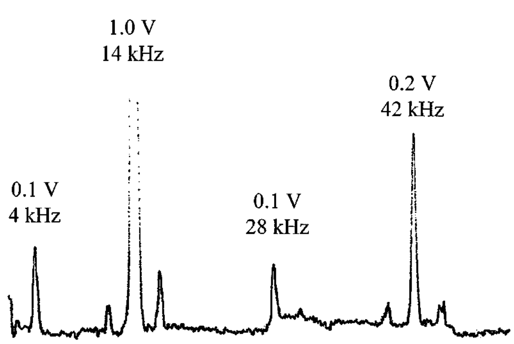

FIG. 2. Typical noise spectrum; the integral gain is set ~12 times higher than the optimal value; the 14 kHz noise is a mechanical resonance; the 28 kHz noise is probably an overtone of the 14 kHz; the values of the amplitudes are labeled in the graph. With the optical setup of this instrument, 1 V on the photodetector ~80 nm spatial movement at the tip.

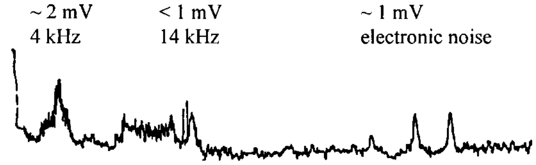

FIG. 3. Noise in Fig. 1 after RCM is initiated at 361 kHz; notice the new scale; the small peaks above 30 kHz are electronic noise.

increased, the 4 kHz signal increased in amplitude. As the setpoint was lowered (corresponding to less deflection of the cantilever, less tension), the higher frequency noise increased. The 4 kHz noise completely disappeared when the feedback was disengaged. Therefore, the high frequency noise is attributed to a mechanical resonance and the 4 kHz noise to a feedback loop resonance.

No particular sources of room noise are present between 1 and 20 kHz, within the detection limits of the system. Therefore, the large noise peaks that are observed when in contact must arise from structural modes with very large quality factors (Q).

The noise level in Fig. 2 is actually very high for this instrument; typical ambient noise is ~10 mV peak-to-peak total when viewed on the oscilliscope. However, to demonstrate the power of this technique, a particularly noisy tip–sample system is presented.

Very similar spectra have been obtained with numerous tips and samples. The feedback resonance does not shift appreciably. The mechanical noise shifts from 12 to 20 kHz, depending on the tip, sample, and scanner. Also, RCM is effective even when the initial noise is fairly low, e.g., 10 mV peak-to-peak noise prior to RCM can be lowered to the electronic white noise level ($\ll$1 mV).

B. Resonance contact mode

Figure 3 is a spectrum of the noise in Fig. 2 after RCM had been initiated at 361 kHz on RCM piezo A. The same results were obtainable when RCM piezo B was used at the same frequency. Notice the different vertical scales. The low frequency noise has been lowered three orders of magnitude. When the initial mechanical noise is less than in Fig. 2 (~10–100 mV initial noise), the noise can be totally eliminated (within the detection limits of the spectrum analyzer).

The effectiveness of RCM is extremely frequency dependent. Certain RCM frequencies have no effect on the noise. An interesting observation is that the noise frequencies can be selectively decoupled; for example when RCM was shifted from 361 to 342 kHz, the 14 kHz noise was totally eliminated, but the 4 kHz noise was not altered. Other RCM frequencies lower the amplitude of the high frequency noise while actually raising the amplitude of the low frequency noise.

The output of the photodiode was simultaneously monitored on an oscilloscope, since the spectrum analyzer was not capable of monitoring signals above 50 kHz. Effective RCM frequencies also produce a small ac signal at the same frequency. In Fig. 3, a 30 mV peak-to-peak signal at 361 kHz was present, corresponding to a 2.5 nm amplitude on the cantilever. As the RCM driving amplitude was lowered, so

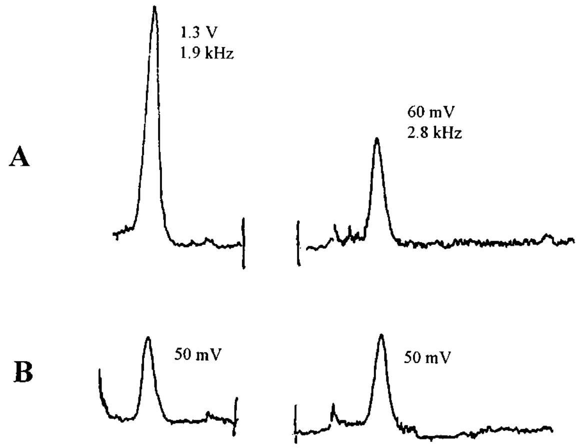

FIG. 4. RCM piezo B was driven with a function generator to mimic noise in the system. Two noise frequencies were chosen 1.9 kHz ($Q \sim 2$) and 2.8 kHz ($Q \sim 1$) (a) driven noise excitation prior to RCM, (b) after RCM was initiated at 335 kHz, both excitations were lowered to 50 mV.

was this 30 mV signal. Below a certain level, the 361 kHz signal remained (~10 mV or 0.8 nm), but the RCM effect no longer lowered the noise. It is unclear if the tip is actually moving up and down 2.5 nm relative to the sample. It is also possible that the cantilever arm is undergoing a higher mode vibration that produces warping to a small degree. The 2.5 nm value was determined by measuring the ac output on the photodiode at 361 kHz and calibrating that signal to the spatial sensitivity of the optical lever.

A RCM vibration amplitude of at least 1 nm is required to be effective; typically, 2–3 nm p-p is used. Larger amplitudes are also effective. RCM has been successfully implemented with numerous tips, samples, and scanners. The same trends were observed when the meniscus layer was altered from oil to water. RCM is also effective when imaging was done completely under water in a standard liquid cell.

C. Driven noise

In order to explore the mechanism responsible for RCM, noise was systematically introduced into the system. To simulate noise, RCM piezo B was vibrated at a low frequency; the tip–sample separation was modulated at that frequency, mimicking noise.

A function generator was connected to RCM piezo B; a small resonance ($Q \sim 2$) was found at 1.9 kHz. There was no apparent resonance at 2.8 kHz (i.e., the noise at 2.7, 2.8, 2.9, etc. was identical). RCM piezo A was then used to initiate RCM. Many different RCM frequencies were applied in order to attempt to dampen both applied noises. It was impossible to lower the noise at 2.8 kHz an appreciable amount (60–50 mV). However, the 1.9 kHz was lowered with a RCM of 335 kHz from 150 to 50 mV. No RCM frequency could lower the 1.9 kHz noise below 50 mV. Figure 4 is the superposition of the four spectra; the x axis is not to scale.

From these results, we conclude that the RCM piezo produced a driving vibration of 50 mV on the cantilever. Both the 1.9 and 2.8 kHz peaks could only be lowered to this value. Since the 1.9 kHz signal had a larger initial Q, it was lowered a larger amount. The 2.8 kHz noise had a very small Q and could only be lowered to the driving amplitude. Therefore, the RCM excitation broadens the frequency response of the structural modes of the system. It does not decouple vibrations. If RCM were decoupling vibrations, it should be possible to lower noise even if the Q were 1.

It was much more difficult to find an effective RCM frequency for these two driven excitations than in the situation where the normal structural modes were excited by the background noise (4 and 14 kHz in Fig. 2).

IV. IMAGING EXAMPLES

Figure 5 was taken with the integral gain set ~18 times higher than optimal. This high feedback gain allowed the image to be acquired very quickly, 12.5 lines per second and 250 pixels per line. The noise values prior to RCM were 60 mV at 3 kHz, 1.0 V at 15 kHz, and 300 mV at 90 kHz, with RCM on at 375 kHz there was only a 10 mV–3 kHz signal. RCM was initiated at the beginning and end of the scan and turned off in the middle. Notice the noisy signal between these two points. The line cuts show that the true features of the CD pit are not resolved without RCM. Low frequency noise (<1 kHz) has also been effectively eliminated while imaging.

Figure 6 is a high resolution image of a bare silicon wafer. Once RCM is initiated, smaller features become apparent. Also, streaking occurs in some images. This streaking has not been observed with RCM. The noise level was 2 orders of magnitude larger in the image prior to initiation of RCM.

V. DISCUSSION

The observed noise peaks are resonance frequencies of the system while the cantilever is in contact with the sample. These peaks have very large Q's. Even while in constant contact, the cantilever will be coupled to these vibrations.

If a vibration is excited in a completely harmonic system, the resulting motion will reflect the displacements characteristic of the normal mode which is excited. No coupling occurs between normal modes. However, the harmonic approximation is only valid for very small vibrational amplitudes. As these amplitudes increase, the nonlinear terms of the force equation will become significant and the system will behave anharmonically:

$$F = -kx - ax^2 - bx^3 - \cdots ,$$

where k is the spring constant, x is the displacement, and $a, b, \ldots$, are constants. The term k will actually be a function of both the cantilever spring constant and the tip–sample potential. As x becomes large, the higher order terms become significant.

When RCM is initiated, a finite amplitude (1–2 nm) is applied to the cantilever; this vibration causes anharmonic excitation of the system. This anharmonic excitation may allow coupling between the normal modes of the system, broadening the frequency characteristics and lowering the Q values at any particular resonance frequency. RCM requires that a finite amplitude be applied in order to probe the anharmonic regime of the potential. This assertion is observed experimentally.

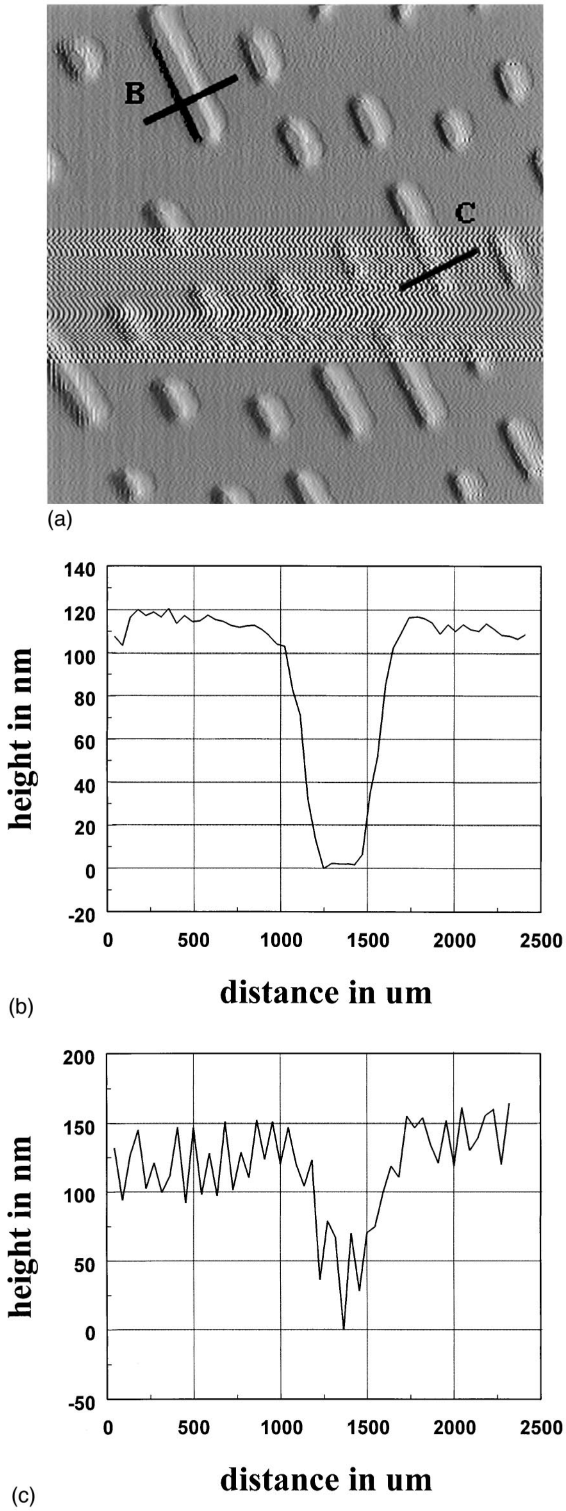

FIG. 5. (a) A 10×10 μm AFM image of a CD; RCM was initiated at the beginning and end of the scan. (b) When RCM is on, the CD pit shape is clearly resolvable. (c) The line cut of a similar pit when RCM is off.

Certain RCM frequencies have no effect since they do not effectively couple the vibration of the driving piezo into the cantilever. A RCM frequency is required that is a resonance of the system, so that the tip–sample system will have a sufficiently large amplitude to enter the anharmonic regime of the potential.

Another observation is that the RCM frequencies that are effective are in the range of natural resonances of the cantilever. Rabe and Arnold calculated and measured the resonance frequencies for a rectangular cantilever and found many structural resonances between 100 and 1000 kHz.[4] Similar values have also been calculated for triangular cantilevers.[8] These resonances will be shifted once the cantilever is in contact.

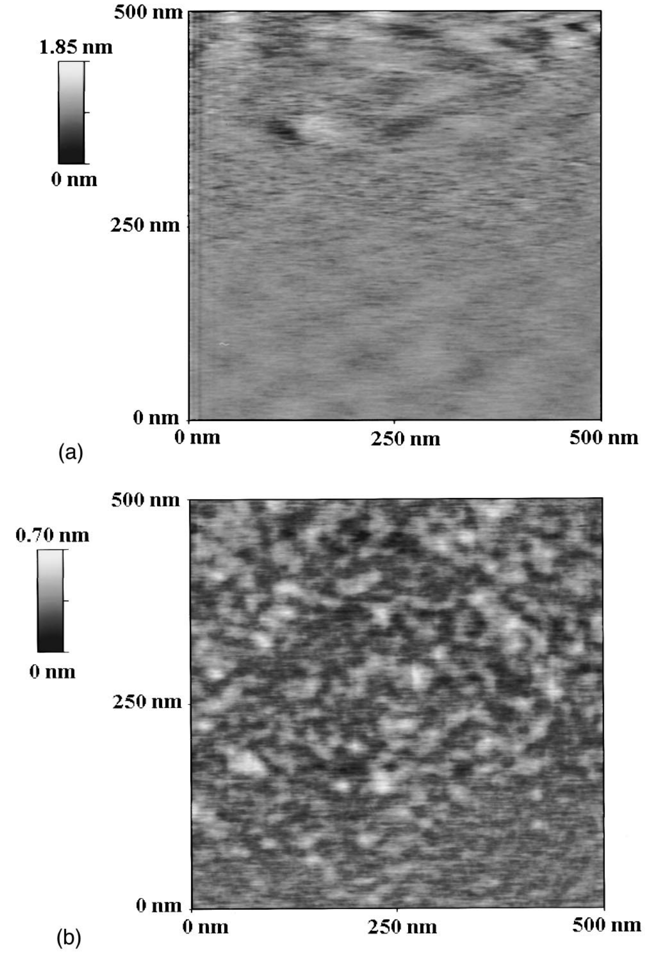

FIG. 6. Several 500×500 nm AFM images of a bare silicon wafer; (a) prior to RCM; (b) when RCM on.

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