Real-time atomic force microscopy using mechanical resonator type scanner

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The real-time atomic force microscope for biological sample is a challenging research field. We have demonstrated a real-time atomic force microscope by implementing a mechanical resonator type scanner called by “microscanner” The microscanner was designed to have a resonance frequency in the range of 5–10 kHz and an amplitude of 1–3 μm. The resonant vibration of the microscanner was served as a fast-scan directional motion, and an image acquisition rate of 30 frames/s with 256 × 256 pixels per frame was achieved. Time-varying sequential images of a poly(ethylene-oxide) sample were taken as a demonstration of potential for excellence in real-time imaging a moving nano-object. © 2008 American Institute of Physics. [DOI: 10.1063/1.2999579]

I. INTRODUCTION

As atomic force microscopy (AFM) has been used for many biological research fields, it becomes a critical issue in development of the AFM to increase the imaging speed. For tapping mode or noncontact (NC) mode AFM (NC-AFM), one can use small cantilevers (l ≈ 10 μm) with high resonance frequencies (f0 ≈ 1 MHz) to improve the mechanical response time of the cantilever.1,2 Ando et al. developed a high-speed scanner with resonance frequency up to 60 kHz. They used a small cantilever with 500 kHz resonance frequency in water and 0.2 N/m spring constant.3 Additionally, an optical deflection detection using an objective lens and wideband electronics were adapted, and an imaging time of 80 ms with 100 × 100 pixels was achieved.

On the other hand, when the cantilever has a high quality factor, the time constants of the amplitude (or phase) shift of cantilever motion become increased. A phase-locked-loop scheme can be used for frequency detection method to overcome the delayed response of the amplitude or phase.4 Up until now, the imaging rate of ~10 frame/s with ~100 pixels has been achieved in NC-AFM.5

The scanning speed of a typical contact mode AFM (C-AFM) is much faster than that of NC-AFM. While the resonance frequency determines the response time of the cantilever mainly in NC-AFM, the mass of the cantilever is the most dominant factor determining the scanning speed in C-AFM.6 The imaging rate of the C-AFM is not related with the resonance frequency but with the velocity change in the cantilever proportional to the interacting force divided by the mass. Another limitation of the scanning speed for C-AFM is the velocity of the scanner. The velocity of the scanner is determined by the mass, driving power, and the feedback bandwidth (if it is controlled by a closed-loop system). Because conventional scanners have a piezoelectric hysteresis behavior between the driving voltage and actual motion, the closed-loop control is inevitable. Meanwhile, high-speed AFMs based on a mechanical resonant scanner, which vibrates sinusoidally with its resonance frequency, were reported by Humphris et al.6 and Picco et al.7

According to their report, the high-speed AFM using a quartz crystal resonator showed real-time imaging capability. The quartz crystal resonator so-called tuning fork was served as a fast-scan axis scanner with its resonance frequency of 20–100 kHz. By using a resonance behavior that provides a sinusoidal motion of the resonator, the accurate positioning of the fast-scan axis scanning motion was obtained. Unfortunately, for the practical purpose, there are critical drawbacks in tuning fork based scanner. It is very difficult to attach a cantilever to the tuning fork. Because the tuning fork is quite small, the cantilever needs to be cut from the Si chip and a glue or epoxy should be applied to attach it. Otherwise, one needs to mount a sample on the tuning fork. However, in this case, the area of sample should be smaller than ~1 × 1 mm2 due to the small dimension of the tuning fork, which limits its usage to particular samples.

In order to overcome those drawbacks, we have developed a mechanical resonator which is called “microscanner” having a long vibrating bar and an exciting lead zirconate titanate (PZT) to replace the tuning fork. Our mechanical resonator has resonance frequency in the range of 5–10 kHz and a vibration amplitude of a few microns. The Si chip of which typical dimension is ~5 × 2 × 1 mm3, supporting the cantilever is mounted on the resonator directly, with no need to cut the cantilever from the Si chip.

II. EXPERIMENTALS

As shown in Fig. 1, the microscanner has a long shear vibrating bar, side wings, and its holding structure. The vibrating bar has dimension of length l=13 mm, thickness t=2 mm, and width w=4 mm. Its spring constant is given by $k=0.25Ew(t/l)^3=1400$ N/m, where Young’s modulus $E$
of brass metal is \( \approx 100 \) GPa. The resonance frequency \( f_0 \) is given by \( \frac{1.02}{2\pi}E\rho / t^2 \), where mass density of brass is \( \rho = 8400 \) kg/m\(^3\). The calculated frequency \( f_0 = 6.5 \) kHz is very close to the measured value of 6.7 kHz. The piezoelectric actuator is a PZT plate with \( 4 \times 4 \times 1 \) mm\(^3\) dimension which has a vibration amplitude of a few nanometer scale with driving voltage of 10 V. The vibration amplitude at the end of the vibrating bar is amplified due to its resonant behavior.

On resonance, the vibration amplitude is increased by the factor of 100, equal to its quality factor. The vibration with a few microns amplitude makes a beep sound, but it causes no problem on the high-speed imaging performance.

We have prepared a homemade AFM system for the normal scanning mode operation, and its schematic is shown in Fig. 2. The microscanner was installed at the head part of the AFM, where the cantilever was attached with a glue. A tube scanner was used for a slow scan axis motion and normal operation of the AFM.

Two different types of cantilevers were used for the high-speed scanning. One was a Si cantilever with 0.1 N/m stiffness designed for a C-AFM. The other was a SiN cantilever (biolever, Olympus) with 0.006 N/m stiffness and the resonance frequency of 13 kHz.

In a coarse approach process, the sample was moved up to make a contact to the tip by a piezomotor (Picomotor, New focus Inc.). Once contact was made, the microscanner was turned on and a broadband position-sensitive photodiode (PSPD) signal stream was fed into an analog-digital converter with 20 MHz sampling rate. While the cantilever was vibrated horizontally by the microscanner, the laser beam and its optics were not vibrated following the cantilever. Because the laser beam spot size was larger than 5 \( \mu \)m in diameter, the small vibration of the cantilever did not cause noticeable misalignment of the laser beam path. When the cantilever was vibrated horizontally at the position far from the sample, the PSPD signal showed a sinusoidal background noise, which might be caused by slight tilting of the cantilever. The background noise was eliminated by digital correction process in personal computer.
III. RESULTS AND DISCUSSION

A thick film of poly(ethylene-oxide) (PEO) was prepared by solving the PEO powder into chloroform, and the liquid was cast on a mica substrate. The (PEO) liquid became viscous as the solvent was being evaporated due to the air exposure. The snapshot images were taken with 0.5 s time interval since after the PEO liquid was exposed in air for an hour, as shown in Fig. 3. The scan size was $1 \times 1 \ \mu m^2$, and each image with $256 \times 256$ pixels was taken for 30 ms. For this image the SiN cantilever was used, and it was found that the Si cantilever had tendency to make scratches on the sample. It shows that small structures in upper part of images were disappearing in a solvent-drying process. The chemical analysis of the process is beyond the scope of this article. It is noticeable that this gel-like soft sample was imaged with reasonably good quality even in this fast-scanning contact AFM. This effect can be attributed to the super lubricity effect associated with the liquid layer on the gel structures.

For the measurement of vertical response time of the cantilever, a standard sample of silicon oxide grating was scanned with a conventional AFM (a) and the high-speed AFM (b), as shown in Fig. 4. Along the red line in the image (a), topographic line profile is shown in Fig. 4(c). The conventional AFM image (a) was taken with a constant-force feedback control, while the high-speed image (b) was done in constant-height mode. From the periodicity of the corrugation, the scan size of the high-speed AFM with 10 V_{ac} excitation was determined to be 1 $\mu$m. The fast-scan axis direction in the image (b) was from left to right. The corrugation of the sample is 80 nm and the high-speed image shows that the motion of the tip was fast enough to follow the surface with 80 nm corrugation in 8 $\mu$s. In consequence, the horizontal speed of the tip in our high-speed AFM was 1.2 cm/s, and the vertical speed was 1.0 cm/s.

IV. CONCLUSIONS

In summary, a real-time, high-speed AFM system was developed by implementing a small-sized mechanical resonator made of brass. The fast imaging capability of 30 frames/s with $256 \times 256$ pixels was demonstrated with vertical motion velocity of 1 cm/s. Because the cantilever chip can be attached at the end of the microscanner without cutting the cantilever, the cantilever can be replaced easily by users. Due to the compactness of the microscanner, it can be inserted into conventional AFMs, and it makes possible to monitor the real-time image of small area and navigate the larger area by using the scanner provided by the conventional AFM.

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