2015 International Symposium on Nonlinear Theory and its Applications
NOLTA2015, Kowloon, Hong Kong, China, December 1-4, 2015

Development of multi-probe atomic force microscope and probe interaction

Nobuo Satoh†

†Department of Elec. & Comput. Engineering, Chiba Institute of Technology
2-17-1 Tsudanuma, Narashino, Chiba, 275-0016 Japan
Email: satoh.nobuo@it-chiba.ac.jp

Abstract—We developed a multi-probe atomic force microscopy (MP-AFM) systems using piezoelectric cantilevers and piezoresistive ones. The use of self-sensing cantilevers with deflection sensors as probes markedly reduced complexity in the MP-AFM setup. Simultaneous observation images can be acquired by the MP-AFM under frequency modulation (FM) detection operations. The minimum distance between these probes was 6.9 μm when it used the piezoresistive cantilevers. We found that the nanoscale interaction between the probes was detected by determining the change in the amplitude of each cantilever. It was clarified that the interaction effect depended on the vibration amplitude of the cantilever-probe.

1. Introduction

Multi-probe atomic force microscopy (MP-AFM) development is in strong demand as an evaluation system on the nanometer scale [1]. Most of the present AFMs, the optical beam deflection method is ordinarily used [2, 3]. With this technique, high-resolution evaluation MP-AFM have also been reported [4]. However, one of the difficulties in development of multi-probe AFM is that the sensing method of the cantilever deflection is quite complicated.

On the other hand, it is indispensable to simplify the scheme that detects the position of the AFM cantilever to attempt a high performance in MP-AFM. The use of a self-sensing cantilever, in which a deflection sensor is integrated, extremely reduces the complexity of the setup [5], achieves the image observation with high resolution, accomplishes the practicable application in the nanoscale.

In this study, we chose piezoelectric cantilevers and piezoresistive ones. The deflection signal is detected as the current from the piezoelectric effect or piezoresistive effect of the cantilever without a complex optical system. The basic performance of the developed MP-AFM, the image data obtained by the instrument, and interaction worked distance of between cantilever-probes are described.

2. Using piezoelectric cantilever

2.1. Instrumentation

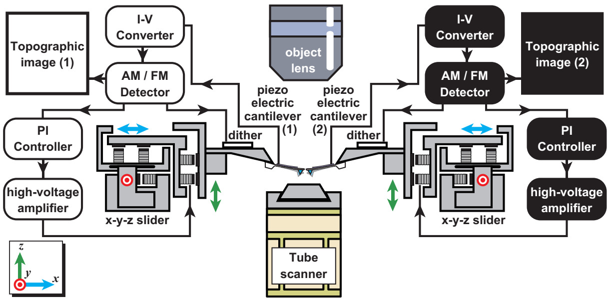

Figure 1: Schematic of multi-probe AFM system.

Figure 1 shows a schematic diagram of the multi-probe AFM system [6]. The position of each probe (PZT cantilever) [7] is monitored using the microscope objective located right above the probes. Each PZT cantilever working as a probe in the dynamic mode AFM (DFM) is at each probe stage, which is an inertial slider. All the experiments were carried out at room temperature in an atmospheric condition.

Figure 2 shows an optical micrograph of the two PZT cantilevers both of which were brought near each other by each slider. Here, we described how to approach the opposing cantilever-probe each other by two different modes of operation. Firstly, a single step motion of 100 - 1,000 nm is made by a stick-slip movement (SS-mode) of the slider. Secondary, the slider produces continuous motion that can be controlled by applying an external DC voltage (DC-mode). The DC-mode is used for positioning the tips in the z-direction, which is the main feedback control in the AFM operation. The sample was scanned by a tube scanner using an SPM controller (CNT-1000, RHK Technology).

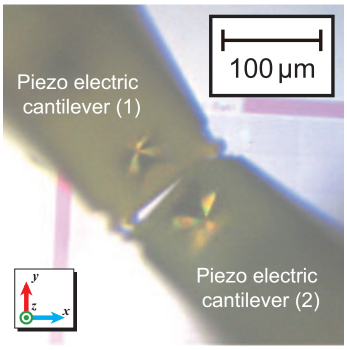

Figure 2: Top-view optical micrograph of two piezoelectric cantilevers positioned in close proximity to each other.

2.2. Simultaneous observation

Two PZT cantilevers were brought closer to each other by the inertial slider using the SS-mode while the distance between the two levers was monitored using an optical microscope so as not to avoid the contact. Then, each PZT cantilever was independently brought in closer near proximity to the surface of the address-patterned sample [6].

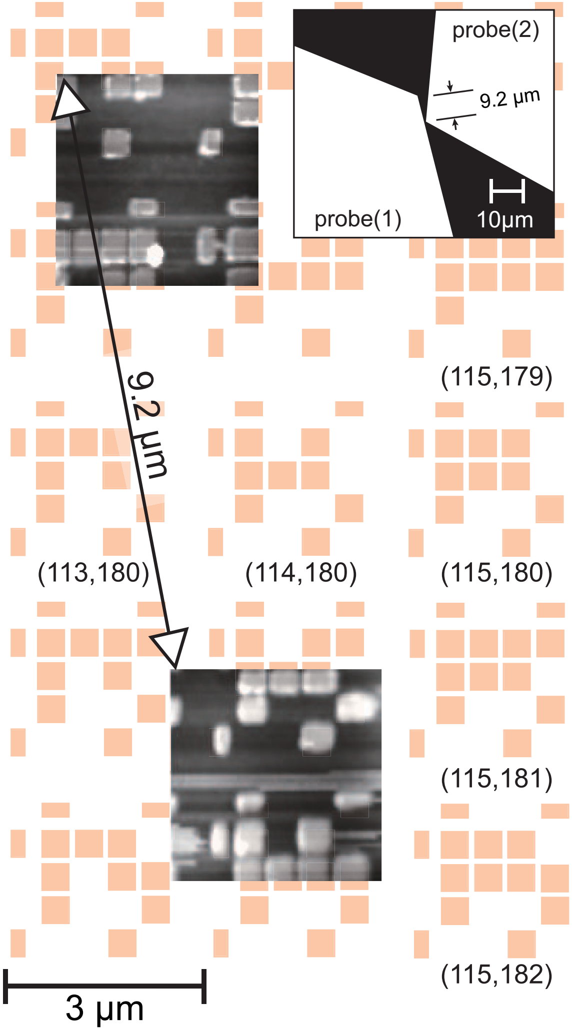

Figure 3: Absolute position identification of images obtained using address pattern. Inset: estimated configuration of tips from the result.

There are still some difficulties in making the distance between the probes shorter. The tip of the PZT cantilever (1) was estimated to be almost in contact with the side of PZT cantilever (2) in this experiment, as shown in the inset of Fig. 3, the minimum distance between the tips was actually limited to 9.2 μm. Another problem is the fabrication accuracy in the focused ion beam (FIB) process that limits the actual sharpness of a fabricated tip apex [6].

2.3. Probe-to-probe interaction

When the two vibrating cantilever-probes are located sufficiently close to each other, both vibration amplitudes can be interfered because of the interaction forces acting on each other. We found that each amplitude was reduced depending on the distance between the probes, which can be utilized for controlling distance.

These cantilevers were vibrated independently by the piezoelectric plates mounted to the lever holders and were brought close to each other by the DC-mode. Both PZT cantilevers were vibrated at their resonance frequencies. The vibration amplitude of PZT cantilever (1) was recorded while it approached PZT cantilever (2), which was fixed in a certain position.

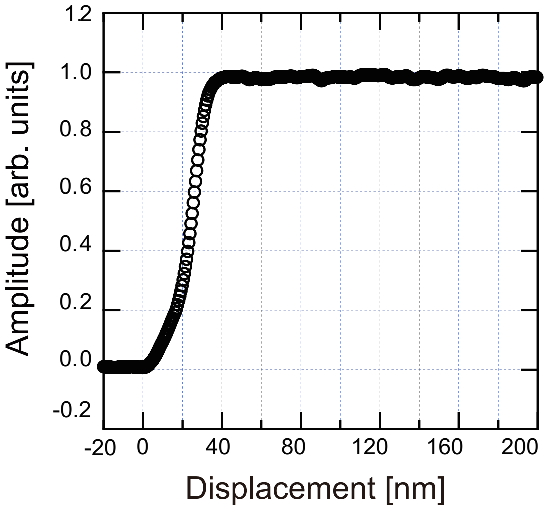

Figure 4: Distance dependence of cantilever oscillation amplitude signal [PZT cantilever (1)].

The measured relationship between the vibration amplitude and the relative cantilever distance is shown in Fig. 4. The vertical-axis is a normalized vibration amplitude of PZT cantilever (1). When the distance was decreased to a value smaller than about 40 nm, the amplitude sharply dropped to zero, which indicated that there might be strong interaction forces. When the amplitude vanished, the cantilevers have been actually in contact with each other. The possible origins of the interaction forces are viscous resistance of air, friction forces between the probes, surface tension on water at the probe edge, and atomic forces. Although we monitored the approach of the cantilevers with the optical microscope, it was impossible to confirm the movement of each PZT cantilever because of a displacement much smaller than the optical wavelength. The obtained distance dependence of the amplitude is promising for controlling the gap distance between the probes on a nanometer scale. Since the origins of the interaction forces are not understood, the reliability and reproducibility of the dependence have to be verified experimentally.

3. Using piezoresistive cantilever

3.1. Instrumentation

Figure 5 shows the instrument schematic of the developed MP-AFM using piezoresistive cantilevers [8]. The variation of the piezo-resistance of this cantilever is detected with a difference amplifier based on a homemade Wheatstone bridge circuit. The cantilever had a three-axis control slider, and each cantilever-probe could be independently driven. Dynamic mode AFM observation by each cantilever is achieved with this construction. Also, the observation by MP-AFM and evaluation of interaction of cantilever-probes were carried out at room temperature in an atmospheric condition.

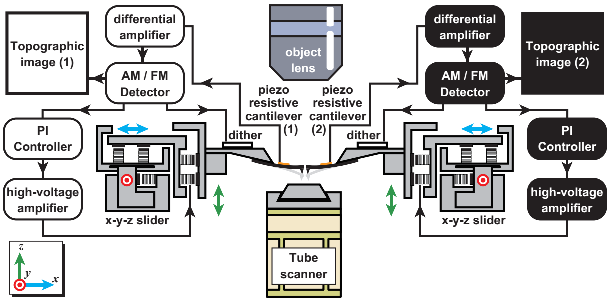

Figure 5: Schematic diagram of multi-probe atomic force microscope using piezoresistive cantilevers.

Figure 6 shows an optical micrograph of two piezoresistive cantilevers, both of which were brought closer to each other by setting each slider. We can visually confirm by optical microscope that the two cantilevers have not contacted physically. Thereafter, piezoresistive cantilever (1) and (2) are carefully brought close to the surface of the sample.

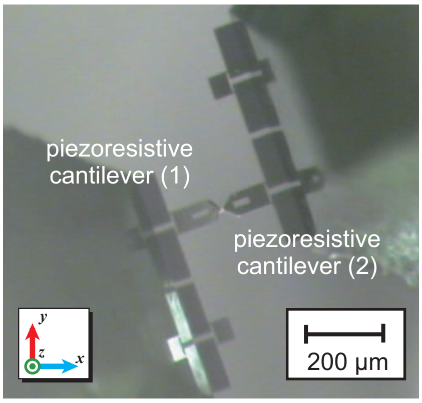

Figure 6: Optical microscope image set up on two piezoresistive cantilevers.

3.2. Simultaneous observation

A simultaneous observation result by MP-AFM using the piezoresistive cantilever (1) and the piezoresistive cantilever (2) under the FM detection operations are shown to be comprehensible in the pattern diagram of the address, and a schematic diagram of probe arrangement is shown in the inset of Fig. 7. It was confirmed respectively that the probe tip of the piezoresistive cantilever (1) is in the (131, 149) neighborhood, and it is in the (130, 151) neighborhood the probe tip of the piezoresistive cantilever (2). It could be calculated that the distance between probe-tips were 6.9 μm by comparison between these AFM simultaneous observation image and address patterns.

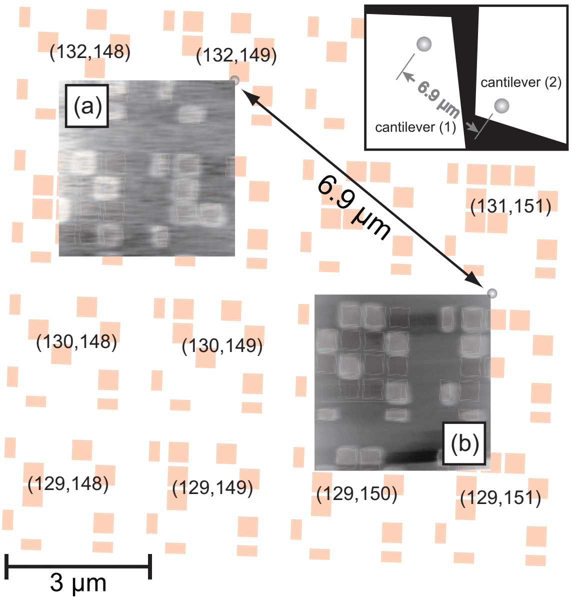

Figure 7: AFM images taken simultaneously using two independent probes. The upper-right image (a) was taken using cantilever (1), whereas cantilever (2) was used for (b). Absolute position identification of images obtained using address pattern.

3.3. Probe-to-probe interaction

We have aimed at the application to a single molecular measurement, and are verifying the principle to develop the technique for controlling the probe spacing on the nanoscale. When the vibrating piezoelectric-cantilevers were located close enough, vibration amplitudes can be interfered with because of the interaction forces acting on each other. In the case where the distance between piezoelectric cantilevers approaches 40 nm, we found the vibration amplitude signal of the cantilever decreases because there is mutual interference.

The method of making two opposed cantilevers approach each other is described. First, to evaluate only the interaction between two cantilevers, the effect of the sample surface is removed by giving enough separation between the sample and each cantilever. Second, piezoresistive cantilever (1) was vibrated at its resonant frequency. Also, piezoresistive cantilever (2) was in a fixed position, without excitation vibration. Subsequently, this probe was made to approach roughly by the SS-mode during visual confirmation with the optical microscope. Finally, it was made to approach most by the DC-mode, and contact state was performed.

The graph shown in Fig. 8 is plotted by the excitation signal intensity of moving piezoresistive cantilever (1) as the vertical axis, and by the distance between opposing cantilevers as the horizontal axis. Here, it is assumed to be the contact point (0 nm) at which the amplitude vibration disappeared. To evaluate and perform the attenuation distance dependency by the vibration amplitude of the cantilever, the amount of vibration amplitude measured 100 mV$_{p-p}$, 200 mV$_{p-p}$, and 300 mV$_{p-p}$, respectively.

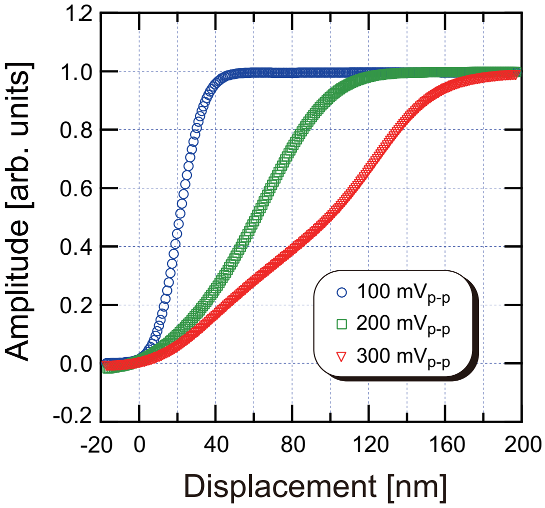

Figure 8: Distance dependence of cantilever oscillation amplitude signal of cantilever (1). The blue circle, the green square and red triangle correspond to 100 mV$_{p-p}$, 200 mV$_{p-p}$, and 300 mV$_{p-p}$, respectively.

First of all, it was confirmed that the interaction worked between probes of the piezoresistive cantilever because the vibration amplitude decreased. It was confirmed that a decrease in the vibration amplitude began from about 40 nm when the vibration amplitude was 100 mV$_{p-p}$. That is, it did as well as when the piezoelectric cantilever was used in our previous result. In a word, by the comparison with our previous study, it was experimentally clarified that the interaction was not the phenomenon that depended on the structure and the material of the cantilever.

Moreover, when the distance at which the attenuation was started was great, it was confirmed by an increase in the vibration of the piezo-resistive cantilever. It is suggested that the vibration of air by the cantilever causes some kind of interaction between the probes that reduces the vibration. Other possible explanations include the presence of water on the probe tip, which may cause shear force [9].

4. Conclusions

We developed a multi-probe AFM system using piezoelectric cantilevers and piezoresistive ones that markedly reduce the complexity of an ordinary AFM system. Each cantilever was three dimensionally positioned by inertial sliders, both cantilever tips were brought in close proximity to each other. The absolute distance between the probes was evaluated using the address-patterned sample. The minimum distance between the tips of two piezoelectric cantilevers and piezoresistive ones were 9.2 μm, 6.9 μm, respectively. Whereas the distance between the cantilevers (probably the tip and some area of the side of the cantilevers) was much shorter.

We found that the interaction forces between the cantilevers were detected by determining the change in the amplitude of each cantilever. The amplitude strongly depends on the relative distance. The measured interaction range was less than 50 nm. This strong distance dependence of the amplitude can be used for the distance control of the probes on a nanometer scale.

References

[1] T. Nakayama, O. Kubo, Y. Shingaya, S. Higuchi, T. Hasegawa, CS. Jiang, T. Okuda, Y. Kuwahara, K. Takami, M. Aono, *Adv Mater.* **24** 1675 (2012).

[2] S. Alexander, L. Hellemans, O. Marti, J. Schneir, V. Elings, P. K. Hansma, *J. Appl. Phys.* **65** 164 (1987).

[3] G. Meyer, N. M. Amer, *Appl. Phys. Lett.*, **53** 1045 (1988).

[4] E. Tsunemi, K. Kobayashi, K. Matsushige, and H. Yamada, *Rev. Sci. Instrum.* **82** 033708 (2011).

[5] C. Lee, T. Itoh and T. Suga, *Sensors and Actuators A*, **72** 179 (1999).

[6] N. Satoh, E. Tsunemi, Y. Miyato, K. Kobayashi, S. Watanabe, T. Fujii, K. Matsushige and H. Yamada, *Jpn. J. Appl. Phys.*, **46** 5543 (2007).

[7] T. Fujii and S. Watanabe, *Appl. Phys. Lett.* **68** 467 (1996).

[8] N. Satoh, E. Tsunemi, K. Kobayashi, K. Matsushige, and H. Yamada, *e-J. Surf. Sci. Nanotech.*, **11** 13 (2013).

[9] E. Betzig, P. L. Finn, J. S. Weiner, *Appl. Phys. Lett.*, **60** 2484 (1992).