Multi-Probe Atomic Force Microscopy Using Piezo-Resistive Cantilevers and Interaction between Probes

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We developed a multi-probe atomic force microscopy (MP-AFM) system using piezo-resistive cantilevers. The use of piezo-resistive self-sensing cantilevers with deflection sensors as probes markedly reduced complexity in the ordinary 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 using the piezo-resistive cantilevers fabricated by a focused ion beam. Furthermore, 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.

Keywords: Multi-probe; Atomic force microscopy; Piezo-resistive cantilever

I. INTRODUCTION

Multi-probe atomic force microscopy (MP-AFM) development is in strong demand as an evaluation system on the micrometer and nanometer scales on insulator surfaces [1]. As is well known, in most of the present AFMs, the optical beam deflection method is ordinarily used [2, 3]. With this technique, high-resolution evaluation MP-AFM has also been reported [4, 5]. 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 high performance in multi-probe AFM. The use of a self-sensing cantilever, in which a deflection sensor is integrated, extremely reduces the complexity of the setup [6], achieves the image observation with high resolution [7], accomplishes the practicable application in the nanoscale [8]. We developed and reported an MP-AFM [9] using piezoelectric cantilevers [10] that is unique among such self-sensing cantilevers, which allowed us to not require any complex optical elements [11, 12]. The use of other self-sensing cantilever, MP-AFM can have the multifunctionality. For instance, the functionality expansion in the MP-AFM is that operation mode enables not only the dynamic mode but also the static one. Therefore, the advancement of generality by the instrumental improvement is required.

In this study, we chose a piezo-resistive cantilever [13] where the cantilever deflection was measured by using a piezo-resistive sensor with a Wheatstone bridge circuit. The deflection signal is detected as the current from the piezo-resistive effect of the cantilever without a complex optical system. The basic performance of the developed MP-AFM, the estimation of detection sensitivity of the piezo-resistive cantilever, the image data obtained by the instrument, and interaction worked distance of between cantilever-probes depending on vibration amplitude of the cantilever are described.

II. EXPERIMENTAL SETUP

A. FIB fabricated cantilevers

In the displacement detection method of the piezo-resistive cantilever that is the self-sensing cantilever, it is a cardinal principle that the swerve stress held in the
base of the cantilever by generating small displacement is detected as a resistance variation. We purchased and used the cantilever PRC120 (resonant frequency 250 to 300 kHz, spring constant 30 to 40 N/m, and sensitivity 120 mV/nm) from SII NanoTechnology Inc.

In the MP-AFM, one of the important factors is how closely probes can approach each other under a controlled environment. As one solution example, the cantilever of the figuration that has the feature can be commercially purchased [5]. In the case to adopt the piezo-resistive cantilever, the shortest achievable distance between piezo-resistive cantilever-probes is required. However, there is no probe-tip in a top-end position in the structure of the piezo-resistive cantilever. Therefore, the micro fabrication of the cantilever tip was conquered by focused ion beam (FIB) equipment according to the cut-line (orange dot line) shown in Fig. 1(a). Even after the cutting process, the cut part was still attached due to some electrostatic interactions. The appearance of the probe tip after it is constructed is shown in Fig. 1(b). Because the length was shortened by the cantilever previously being minutely processed by FIB, it was confirmed that the resonant frequency increased slightly. In addition, given the transformation of the cantilever by the FIB processing and damage with gallium ion, when this cantilever was used, we confirmed there was no effect on the displacement sensing.

\section*{B. MP-AFM instrumentation}

The instrument schematic of the developed MP-AFM using piezo-resistive cantilevers is shown in Fig. 2. The variation of the piezo-resistance of this cantilever is detected with a difference amplifier based on a homemade Wheatstone bridge circuit. This equipment was constructed under an optical microscope. An object lens was arranged on the probes; the position of each probe could be confirmed visually. 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.

The frequency modulation (FM) detection method [14], where the frequency shift of the cantilever resonance detected by a PLL (phase locked loop) circuit was used [15], was employed in the feedback control of the distance between the probe and the sample surface. The FM detection method has several advantages in terms of the force sensitivity and response time, which is limited by the quality factor in the amplitude modulation (AM) detection method. In addition, we have succeeded in manufacturing the electric circuit to which the AM/FM detection technique is easily switched. In this study, we used the FM detection method that achieves high sensitivity when topography is observed and the AM detection method in evaluation of the interaction between cantilevers.

In the MP-AFM, three-dimensional position control of the cantilever-probe is essential. We used a three-axis inertial slider (UMP-1000, Unisoku Corp.) for both coarse and fine positioning of each probe as shown in Fig. 2. This slider had two kinds of move-modes, and was used properly according to the distance. First, a single step motion of 100-1,000 nm is made by a stick-slip movement (SS mode) of the slider. The amount of displacement can be adjusted by the waveform of the driving signal. Second, the slider also produces continuous motion that can be controlled by applying an external DC voltage (DC mode). From the above-mentioned, such two sliders for twin-probes were basically prepared. These were same sliders that had been introduced in our previous study [9].

The sample was scanned by the tube scanner using an SPM controller (RHK Technology Ltd.: SPM-1000). Each topographic image is acquired in taking the signal output corresponding to the cantilever displacement from each FM detector. It is operated by the controller where the error signal from the FM detector had P-Gain and I-Gain, amplified with the high-voltage amplifier unit (Messe-tek Corp.: M-2629B) for the distance control between the probe and the sample, and applied to the piezo-electric element of the slider. The DC mode is used for positioning of the tips in the z-direction, which is the main feedback control in the AFM operation. Using these units in our previous study [9], we had already evaluated in terms of practicality for both the scanning control of the tube scanner and distance control of the cantilever-probe.
FIG. 3: Frequency spectrum of the piezo-resistive cantilever in Brownian motion ($Q = 511, f_0 = 293.2 \text{kHz}, k = 40 \text{N/m}$).

## III. RESULTS AND DISCUSSION

### A. The piezo-resistive cantilever in Brownian motion

Figure 3 shows the frequency spectrum of the piezo-resistive cantilever in Brownian motion. The points present experimentally measured values and blue-solid line is fitted with them. Moreover, the red-dotted line indicates theoretically calculated values [16]. The resonance-peak found in the spectrum corresponds to Brownian vibration at the cantilever with the background thermal-noise. The quality factor ($Q$) and the resonant frequency ($f_0$) of the cantilever calculated from the fitting curve were 511 and 293.2 kHz, respectively. The spring constant ($k$) of the cantilever applied to the calculation was assumed to be 40 N/m. The result revealed that the deflection noise density arising from the cantilever deflection measurement was 150 fm/√Hz at the room temperature in the atmospheric condition.

We compared the measurement value with the theoretical deflection noise density. The Johnson noise of the piezo-resistance in the cantilever was 3.15 nV/√Hz and the converted input-voltage noise in the differential amplifier was approximately 4 nV/√Hz. By considering these characteristics, a theoretical deflection noise density was calculated with approximately 120 fm/√Hz. It was confirmed that the measurement was roughly corresponding to the theoretically value. The displacement sensitivity as the change-ratio of the piezo-resistance was converted to the theoretically value. The displacement sensitivity to be able to acquire high-resolution image by having implemented the piezo-resistive cantilever to the MP-AFM compared with our previous study [9].

In the performance evaluation of multi-probe AFM, it is essential to obtain the information of the absolute coordinate of each probe [17]. We have prepared an address-patterned sample with an array of different micro-fabricated platinum patterns, each corresponding to a combination of two binary codes. The patterns were made of platinum films with a thickness of 5 nm and deposited on an Si substrate. The left eight and right eight patterns correspond to x and y coordinates, respectively. In addition, four peripheral rectangles give us information about the bit pattern directions without causing confusion. The whole sample consists of 256 × 256 patterns separated with a spacing of 700 nm. The absolute position of the probe can be determined within an accuracy of 10 nm. Thus, the distance between the probes can be simply evaluated without microscopes. The performance comparison with the MP-AFM improvement was also facilitated by having used the address-patterned sample as our previous study [9].

Then, it can be visually confirmed by optical microscope that the two cantilevers have not contacted physically. Thereafter, piezo-resistive cantilever (1) and (2) are carefully brought close to the surface of the sample. Figure 4 shows an optical micrograph of two piezo-resistive cantilevers with the FIB fabricated, both of which were brought closer to each other by setting each slider.

A simultaneous observation result by MP-AFM using piezo-resistive cantilever (1) and piezo-resistive cantilever (2) under the FM detection operations are shown to be comprehensible in pattern diagram of the address, and a schematic diagram of probe arrangement is shown in the inset of Fig. 5. It was confirmed respectively that the absolute position of the probe can be determined within an accuracy of 10 nm. Thus, the distance between the probes can be simply evaluated without microscopes. The performance comparison with the MP-AFM improvement was also facilitated by having used the address-patterned sample as our previous study [9].

A simultaneous observation result by MP-AFM using piezo-resistive cantilever (1) and piezo-resistive cantilever (2) under the FM detection operations are shown to be comprehensible in pattern diagram of the address, and a schematic diagram of probe arrangement is shown in the inset of Fig. 5. It was confirmed respectively that the probe tip of piezo-resistive cantilever (1) is in the (131, 149) neighborhood, and it is in the (130, 151) neighborhood the probe tip of piezo-resistive cantilever (2) from Fig. 5. It could be calculated that the distance between probe-tips was 6.9 µm by comparison between these AFM simultaneous observation image and address patterns.
C. Interaction between cantilever-probes

In ordinary electrical probe systems and multi-probe STMs, the distance between the probes is controlled manually under another microscope. However, it is significantly difficult to avoid contact of the probes in a manual control condition and to stably make the probe spacing within several nanometers. 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, as with other kinds of self-detection type cantilevers, were located closely 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 30 nm, we found the vibration amplitude signal of the cantilever decreases because there is mutual interference.

Next, 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, piezo-electric cantilever (1) was vibrated at its resonant frequency, as with other kinds of self-detection type cantilevers, were located closely 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 30 nm, we found the vibration amplitude signal of the cantilever decreases because there is mutual interference.

First of all, it was confirmed that the interaction worked between probes of the piezo-resistive cantilever because the vibration amplitude decreased. It was confirmed that a decrease in the vibration amplitude began from about 40 nm when vibration amplitude was 100 mVpp. That is, it did as well as when the piezoelectric cantilever was used in our previous result [9]. 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 [18]. As future research, the phenomenon will be specified by using the difference of the condition in the liquid and/or vacuum besides the atmosphere while using the static mode operation, and the distance control between precise probes that aggressively use this effect will be achieved.

IV. CONCLUSION

Piezo-resistive cantilever probes that processed FIB and MP-AFM were developed. Distance between them
of 6.9 μm was confirmed by comparing the location information from the image acquired by each probe. Interaction was generated from the piezo-resistive cantilevers approaching each other on the nanoscale. The interaction between probes was not the phenomenon that depended on the structure of the cantilever or the material of the cantilever, it was experimentally shown. In addition, it was clarified that the strength of the interaction depended on the vibration amplitude of the cantilever-probe.

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