DEVELOPMENT OF SELF-VIBRATION AND -DETECTION AFM PROBE BY USING QUARTZ TUNING FORK

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ABSTRACT: We developed a novel type of quartz tuning-fork probe that vibrates and detects its own probe deformation, for application to atomic force microscopy (AFM). This tuning-fork probe improves the AFM image resolution because of its high Q (quality) factor value. The tuning-fork probe has a sharp tip that was fabricated using anisotropic wet etching and a focused ion beam system. We evaluated the vibration properties of the tuning-fork in both the in-phase and anti-phase driving mode, and measured a Q factor value of 2808 in the anti-phase mode. We also confirmed that the tuning-fork probe is able to measure a 100 nm-step on a silicon surface by self-vibration and self-detection, without using external vibration and optical-detection mechanisms.

Keywords: Atomic Force Microscopy (AFM), Quartz tuning-fork, Piezoelectric

1. INTRODUCTION

Atomic force microscopy (AFM) systems have been used in many scientific fields, for example, surface physics, bio-medicine and information science. Conventional AFM systems involve using a Si-based cantilever with a sharp tip as a probe for surface topography detection. The cantilever probe is resonated by an external piezoelectric oscillator, and the surface topography is measured by detecting changes in resonant behavior (amplitude, phase, and resonant frequency) with an optical displacement sensing system. AFM image resolution is generally determined by the spring constant, the resonant frequency, and Q-factor of the probe structures in the cyclic-contact and non-contact dynamic detection modes in the AFM system. Conventional AFM systems have two drawbacks. One is that it is difficult to improve the image resolution because of the low Q-factor value of the Si-based cantilever probe structure, and the other is that they require external excitation and a detection mechanism.

To overcome these two problems, we previously proposed an AFM probe that consisted of a quartz-based tuning-fork structure [1]. The quartz tuning-fork probe has the following advantages.

(1) High Q-factor
The tuning-fork probe structure is able to increase the Q-factor value to over 1,000. This is because the bottom edge of the two beams in the tuning-fork becomes a vibration node when both beams are vibrated in anti-phase mode.

(2) Self-excitation and -detection
Quartz is an inherently piezoelectric material. Therefore, the quartz probe can be made to vibrate and detect its own deformation by controlling the electrical field inside the probe.

We previously developed a fabrication process of the quartz tuning-fork probe with a sharp tip by micro-electro-mechanical-systems technologies [1]. We describe the vibration performance and the capabilities of the self-excitation and -detection functions of the quartz tuning-fork probe.

2. QUARTZ TUNING-FORK PROBE FOR AFM SYSTEM

A schematic view of the quartz tuning-fork probe is shown in Fig. 1. The detection tip is on the edge of one of the beams. The tuning-fork is

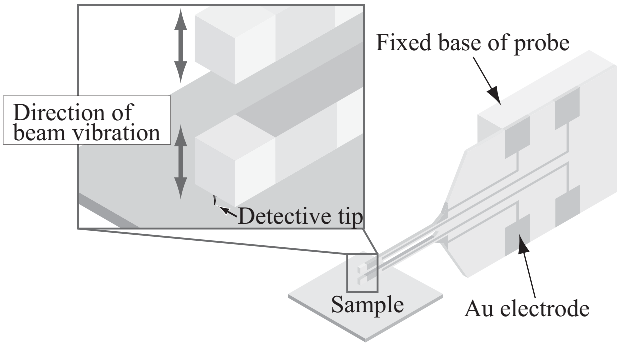
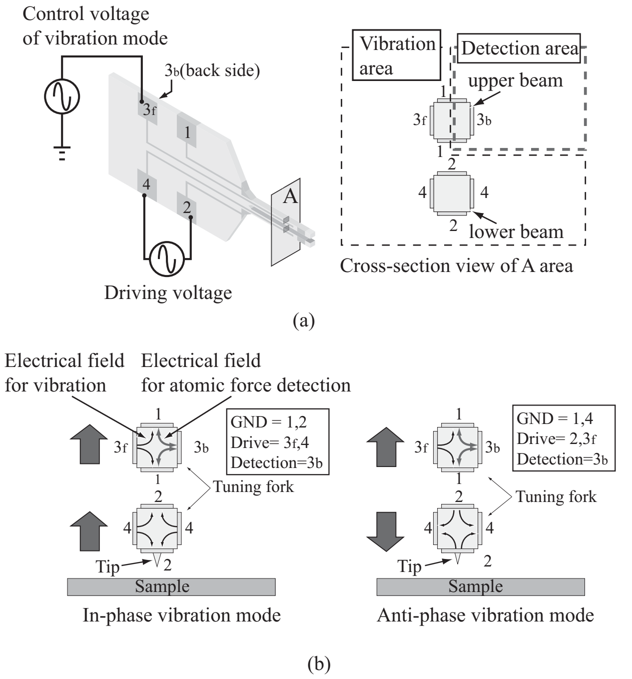


Figure 1: Schematic view of the quartz tuning fork AFM probe.



(a)

(b)

Figure 2: Vibration and detection operations. (a) Vibration and detection areas on tuning fork probe. Vibration area: lower beam, left-side of the upper beam. Detection area: right-side of the upper beam. (b) Relationship between the vibration mode and applied voltage condition.

vertically vibrated above the sample surface and it detects the atomic force by using the piezoelectric properties of quartz. Isolated electrode patterns are formed on each side of the beam structures for the purpose of both vibrating the beams and detecting the beams' deformation.

Figure 2(a) illustrates in detail the electrode patterns on the tuning-fork probe. The inside of the upper beam is electrically divided into two sections. The left-side of the upper beam and the lower beam are used for beam excitation. The vibration mode (in-phase or anti-phase mode) is controlled by changing the applied voltage polarity to these electrodes, as shown in Fig. 2(b). The right-side of the upper beam is used to detect the deformation of the beams. As described above, we were able to vibrate the tuning-fork probe in the anti-phase mode and detect the atomic force at the same time by electrically dividing the inside of one beam into two sections.

The probe structure was fabricated using anisotropic wet etching technology. The length, thickness, and width of one beam were 1500, 100, and 100 μm, and the theoretical spring constant and resonant frequency were 568 N/m and 38.9 kHz. We used Young's modulus, E = 78 GPa, and the density ρ = 2650 kg/m^3, in the calculation.

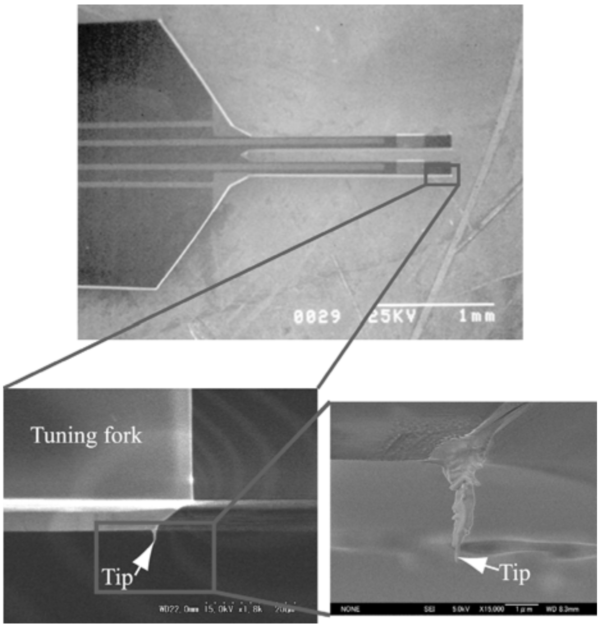


Figure 3: Fabricated quartz tuning fork probe and the tip.

The detection tip has to be sharp to ensure a high AFM image resolution. We therefore used a focused ion beam (FIB) system produced by Seiko Instruments, to form a sharp tip at the end surface of one beam. First, tungsten is deposited on the side of one beam to form the tip outline, and then it is etched to make it sharp. Figure 3 shows SEM images of the fabricated tuning-fork's tip structure. The fabricated tip structure is approximately 500 nm in diameter and 5 μm in height. The curvature radius of the apex and the ratio of the diameter to height are 40 nm and 12.5. This tiny tip hardly changes the symmetrical properties of the tuning-fork because it is so small, and we believe that the fabricated tip is of sufficient quality to obtain high-resolution AFM images.

3. SELF-VIBRATION AND -DETECTION PERFORMANCE

3.1 Q-FACTOR

We evaluated the vibration properties of the fabricated quartz tuning-fork in both in-phase and anti-phase vibration modes. Figure 4 shows the changes in the amplitude and the phase, as functions of the frequency. We controlled the

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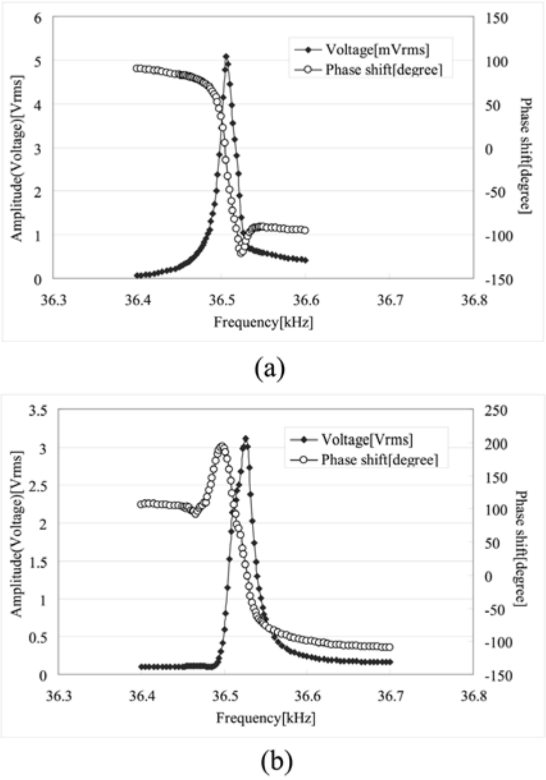

Vibration mode	Resonant frequency[kHz]	Q-factor
In-phase	36.53	1660
Anti-phase	36.51	2808

Figure 4: Changes of amplitude and phase as a function of frequency.
(a) In-phase mode (b) Anti-phase mode.

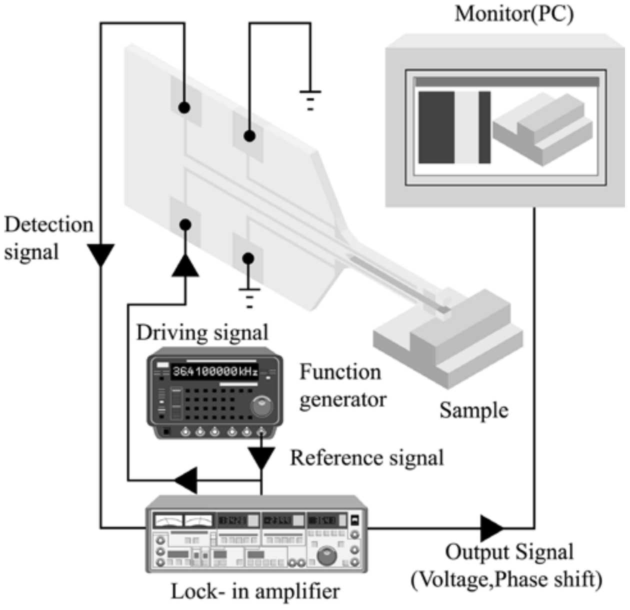

Figure 5: Experimental setup for AFM observation using self-vibration and –detection properties of quartz tuning fork probe.

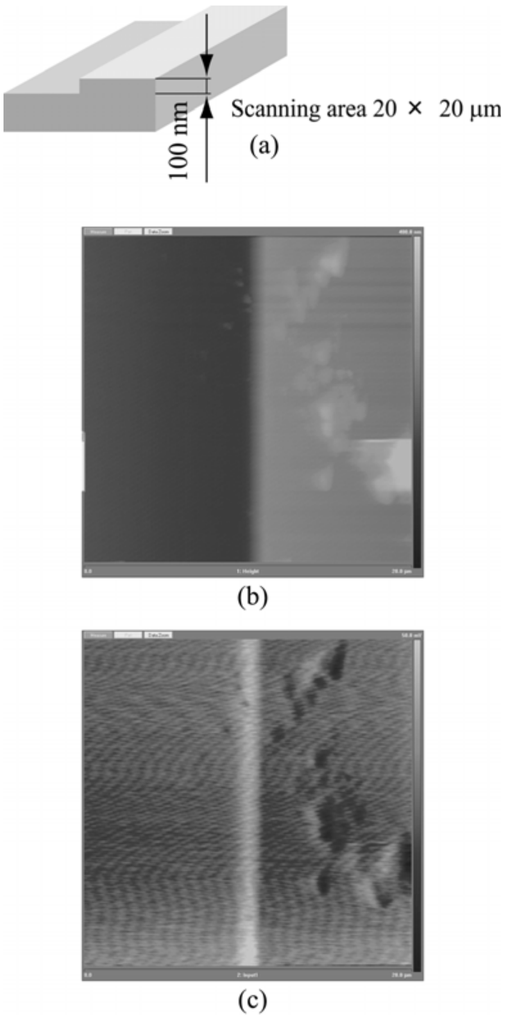

Figure 6: AFM images obtained by tuning fork probes.
(a) Schematic view of the sample. (b) AFM image taken by optical-sensing mechanism. (c) AFM Image taken by self-detection of tuning fork.

vibration modes by changing the polarity of the voltage applied to the electrodes, and detected the amplitude and phase signals from the right-side of the upper beam. The measured Q-factors of the in-phase and the anti-phase were 1660 and 2808. The Q-factor of the anti-phase was greater than that of the in-phase, because of the anti-phase's lower energy consumption (the bottom edges of the two beams become a node in the anti-phase, which decreases vibration energy dissipation). The measured Q-factor of 2808 in anti-phase mode was roughly one order of magnitude greater than that of a conventional AFM cantilever probe. This result means that using the tuning-fork probe improves AFM image resolution.

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3.2 AFM OBSERVATION

We measured a 100 nm step on a silicon surface using self-vibration and self-detection of the tuning-fork probe. The experimental setup is shown in Fig. 5. In this experiment, we operated the probe in the cyclic contact AFM mode, and used phase information to take a 2D AFM image. Figures 6 (b) and (c) show AFM images taken using a conventional optical-detection mechanism, and self-detection of the tuning-fork probe, respectively. The tuning fork probe measured 100 nm-step of the sample, and also clearly detected dust with a thickness of 10-20 nm on the surface, without using any external vibration or optical-detection mechanisms.

4. CONCLUSION

We developed a quartz tuning-fork probe that can be made to vibrate and detect its own probe deformation, for application to atomic force microscopy (AFM). The results we obtained from our tests of this device are summarized in the following.

(1) The tuning-fork probe with a sharp tip was fabricated using anisotropic wet etching and a focused ion beam system. The fabricated tip's structure is approximately 500 nm in diameter and 5 µm in height. The curvature radius of the apex and the ratio of the diameter to height are 40 nm and 12.5, respectively.

(2) We evaluated the vibration properties of the tuning-fork in both in-phase and anti-phase driving modes. The Q-factors of the in-phase and the anti-phase modes were 1660 and 2808. These values are roughly one order of magnitude greater than those of a conventional AFM cantilever probe.

(3) The tuning-fork probe measured a 100 nm-step of the sample, and also clearly detected dust with a thickness of 10-20 nm on the surface, without using any external vibration or optical-detection mechanisms.

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