Quartz tuning-fork type AFM probe operated in Anti-phase Vibration Mode

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Abstract:

This paper presents that quartz tuning fork shows excellent properties as Atomic Force Microscopy (AFM) probe. We used Focused Ion Beam (FIB) system to monolithically form a sharp tip at the side end of one beam. The fabricated probe can vibrate and detect the deformation itself because of piezoelectric property of crystal quartz. We evaluated the vibration characteristic and the self-detection ability of tuning fork. The tuning fork probe is actuated in two different vibration mode; in-phase and anti-phase mode, and clarified that high Q-factor of 5247 was obtained in anti-phase mode. We further applied this mode for AFM observation and images were successfully with dynamic AFM system.

1. INTRODUCTION

Micro-electro-mechanical systems (MEMS) technologies have developed rapidly, and now MEMS devices are used in various fields (optics, biochemistry, information engineering, etc). In the fabrication process of MEMS devices, atomic force microscopy (AFM) systems are very effective appliances. For example, we can evaluate the surface characteristics of materials and observe the profile of products in nano-scale by using AFM systems.

AFM probes have cantilever structures with sharp tips. In dynamic AFM systems, which are called as cyclic-contact and non-contact AFM modes, the probes are vibrated by piezoelectric oscillator and approached to the objects by scanning piezoelectric device under the feedback control. Non-contact AFM mode especially has a great advantage that any samples can be observed, even if the samples are the insulating and soft materials like DNA, because the probes don't damage the sample surfaces at all in principle.

We can obtain the images of the surface profile by measuring the changes of vibration (amplitude, phase, resonant frequency) caused by interaction force between the probe and the objects. Therefore, an external oscillation device and a sensing mechanism to measure the change of probe vibration are needed for conventional AFM systems.

However, there are several issues for the non-contact AFM probes. The minimum detection force of non-contact AFM mode depends on the resonant frequency, the spring constant, and Q-factor of the probe. The spring constant of the conventional probe is designed as a low value to improve the force sensitivity because it can be easily achieved. On the other hand, the reduction of spring constant leads to the probe contact to the sample easily because of the interfacial tension caused by the water on the sample surface. It causes the destruction of the sample and the errors in observation.

In addition, the resonant frequency is proportional to the square root of the spring constant. It means that reducing the spring constant doesn't necessarily bring the improvement of the AFM resolution.

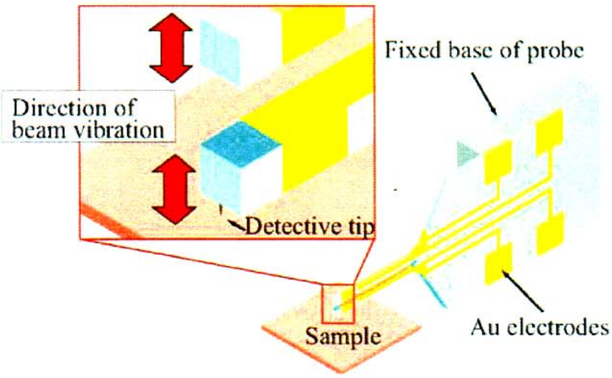

Figure 1 : Schematic view of the fabricated tuning fork probe.

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To solve these issues, we designed and fabricated the quartz-based tuning fork as an AFM probe. Figure 1 shows the schematic view of the fabricated tuning fork probe. We fabricated the tuning fork with integrated tip structure by using quartz micromachining technology and focused ion beam (FIB) system. The tip is monolithically integrated at the end of one beam. The electrode patterns for oscillating the tuning fork and detecting probe deformation are formed on four sides of the beam structure shown as Fig.1, and the tuning fork is vertically vibrated to the sample surface by exploiting the piezoelectric property of crystal quartz.

Some researchers have already reported that they applied the commercial quartz tuning fork to AFM probe[1-3]. However, in those cases, they had to bond the tip structure onto the tuning forks. It caused the increase of the vibration energy consumption (the decrease of Q-factor) and the decline of AFM resolution by the imbalance of tuning fork structure. In addition, there is a limitation of the mechanical properties for available quartz tuning forks, especially resonant frequency and spring constant.

2. DESIGN AND FABRICATION

2.1 Probe design

We designed the quartz-based tuning fork structure to achieve high resolution in NC-AFM systems. The minimum detection force, F_{min} of NC-AFM is given by [4]

$$F_{\min} = C\sqrt{\frac{k}{f_0 Q}}, \quad C = \sqrt{\frac{4k_b TB}{2\pi}} \quad (1)$$

where k is the spring constant, f_0 is the resonant frequency, Q is the quality (Q-) factor, d is the distance from the tip to the sample surface, n is an integer (3–6), A is the amplitude of the driven cantilever vibration, kb is the Boltzmann constant, T is the temperature, and B is the measurement bandwidth. The minimum detection force depends the mechanical properties of probe, i.e. the spring constant, the resonant frequency, the Q-factor. Reducing the spring constant, and increasing the resonant frequency and Q-factor of the probe structure allow the high resolution of AFM system. The theoretical spring constant and resonant frequency are given by Eqs. 1 and 2, respectively.

$$k = \frac{Ebh^3}{4l^3} \quad (1)$$

$$f_0 = \frac{(1.875)^2}{2\pi}\sqrt{\frac{E}{12\rho}}\frac{h}{l^2} \quad (2)$$

where E is Young's modulus, b, h, and l are the width, thickness, and length of one beam of the tuning fork, and ρ is the density.

We can improve the AFM resolution by increasing the Q-factor or by reducing the size of the beam structure. However, the beam probe is pulled in the adsorption layer on sample surface when the spring constant is low. We determined the spring constant of the tuning fork dimensions to avoid probe adsorption to the sample surface. The theoretical spring constant and resonant frequency of fabricated tuning forks are 578 N/m and 38.9 kHz, respectively. We used the Young's modulus of quartz, E = 78 GPa, and the density of quartz, ρ= 2650 kg/m^3, in the calculation.

2.2 Fabrication process

We fabricated the crystal quartz tuning fork with photolithographic technique and anisotropic wet etching. The fabrication process is shown as Fig.2. We used z-cut crystal quartz wafer with a thickness of 100 μm. The etching rate of the z axis was from ten to one hundred times as high as that of parallel crystal plane to the z axis. Therefore, we could etch the wafer vertically, and this resulted in straight and smooth beam sidewalls in a short time. The fabrication process is as follows.

(a) Chrome and gold are evaporated to both surfaces of wafer as etching mask.
(b) A photoresist is applied and formed the shape of etching mask by using photolithographic technique.
(c) Chrome and gold are etched and the photoresist is removed.

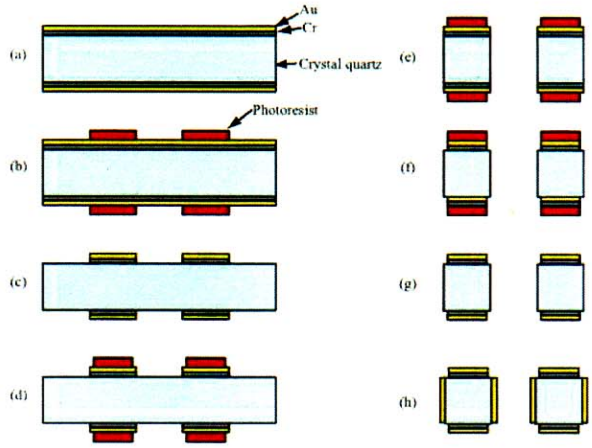


Figure 2: Fabrication process of quartz tuning fork.

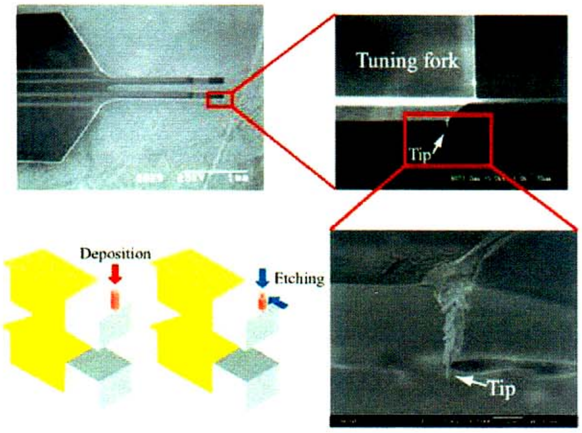


Figure 3: Fabricated tuning fork and tip structure.

(d) The photoresist is newly applied to the gold surface to form the shape of electrodes for beam vibration and self-detection.

(e) The crystal quartz is etched by a NH_4HF_2 saturated solution.

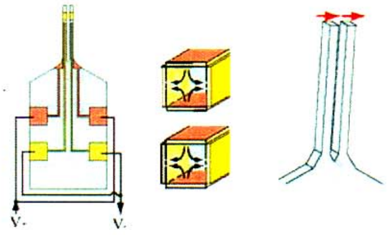
(f) The Chrome and gold are etched.

(g) The photoresist is removed.

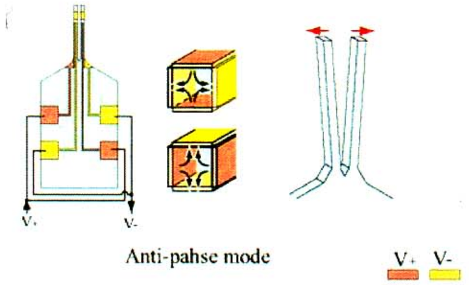
(h) The gold electrodes are evaporated from oblique directions.

2.3 Tip formation by using FIB system

The tip characteristic is one of the most important factors to decide AFM resolution. We have already reported that the integrated tip structure with tuning fork by designing compensation mask pattern [5]. This time, we used FIB system to monolithically form a sharp tip at the side edge of the one beam. This system is able to deposit and remove materials with nano-meter sized accuracy. Fig.3 shows the SEM images of the fabricated tip structure. The tip is approximately 500 nm in diameter, 5 µm in height, and the curvature radius of the tip apex is 40 nm. Firstly, tungsten is deposited to form tip profile, and then applied etching mode to sharpen the apex in the FIB process. The fabricated tip is sharp enough to take high resolution AFM images, and the symmetrical property of tuning fork hardly changes caused by tip formation, because the volume of the tip is too tiny compared to that of beam.



In-phase mode



Anti-pahse mode

Figure 4: Relationship between applied voltage and vibration mode of tuning fork.

3. PROPERTIES OF THE QUARTZ TUNING FORK PROBE

3.1 Vibration characteristic

We evaluated the vibration properties of the quartz tuning fork. The tuning fork structure has mainly tow different driving modes, which are in-phase and anti-phase vibration modes. As shown in Fig. 3, the phase mode is controlled by applied voltage conditions. Theoretically, the Q-factor of anti-phase is much higher than that of in-phase, because of lower vibration energy consumption, because the base part between the two tines becomes a node at anti-phase mode, and decreases vibrational energy dissipation. We experimentally investigated that the relationship between the Q-factor

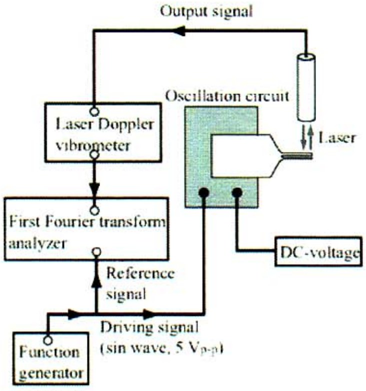


Figure 5: Experimental setup for evaluation of vibration characteristic.

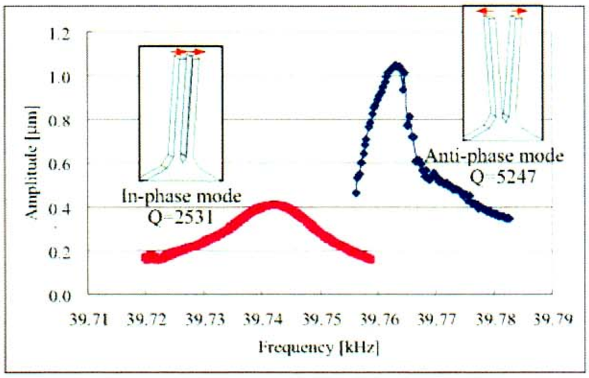


Figure 6: Frequency response curves of vibration amplitude.

and vibration mode by using optical sensing system, as shown in Fig. 4. The obtained Q-factors of in-phase and anti-phase were 2531 and 5247, respectively. The Q-factor at anti-phase is roughly one order of lager than that of single cantilever type probe, which is conventionally used in AFM system. From these results, we confirmed that we are able to realize high Q-factor by vibrating tuning fork probe at anti-phase mode (Figure 5).

3.2 Self-detection property

We further evaluated the self-detection ability of fabricated tuning fork. Fig xx shows the experimental setup for measuring electrical property of tuning fork. The resonant frequency, phase, and voltage amplitude of tuning fork are measured by using a lock-in amplifier. The one beam of tuning fork can be used for probe vibration, and the other beam can act as detection of the beam deformation in this experimental. The changes of the amplitude and the phase are shown as figure xx. The resonant frequency and Q-factors of tuning fork are 36.43 kHz and 2801, respectively. The Q-factor is roughly one order of larger than that of conventionally used AFM cantilever probe. This result means that the tuning fork probe can improve the AFM image resolution by applying self-detection.

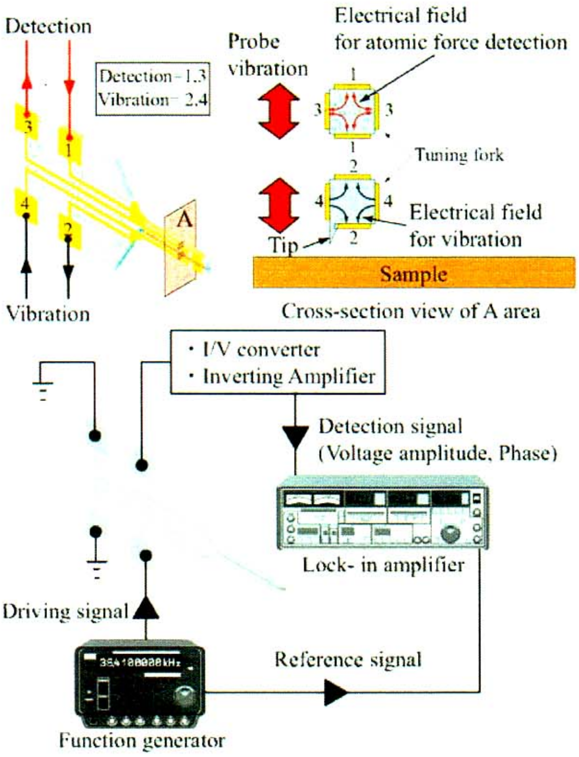


Figure 7: Experimental setup for evaluation of self-detection ability.

Probe application to AFM system

The fabricated tuning fork probe was applied to the commercially AFM system on the standard test (Fig.7). The tuning fork probe was vibrated in anti-phase vibration mode by self-excitation of crystal quartz, and the probe deformation was detected by using an optical-detection mechanism of AFM system in this experiment. In this case, the gold electrodes formed on the beam structure work as reflection surface in detecting the probe deflection. We used the silicon wafer with a 100 nm step as measurement sample. As shown in Fig.9 we confirmed that the tuning fork probe is able to clearly measure 100 nm step in anti-phase mode.

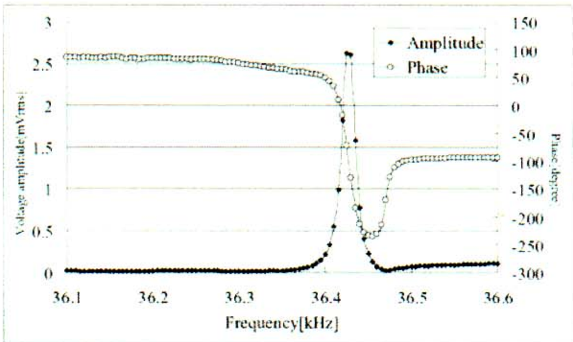


Figure 7: Frequency response curves of voltage amplitude and phase.

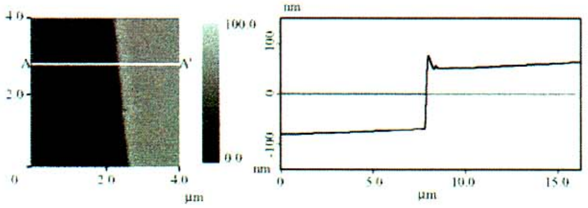


Figure9:AFMimage in cyclic contact mode.

CONCLUSION

The quartz tuning fork is fabricated as dynamic AFM probe with monolithically tip formed by quartz etching technology and FIB system. We evaluated the vibration characteristic and the self-detection ability of tuning fork probe and clarified the high Q-factor of fabricated probe. The tuning fork is applied to AFM observation in anti-phase mode and images were successfully with dynamic AFM system.

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