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Micromachined Si cantilever arrays for parallel AFM operation

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Abstract

Silicon cantilever arrays with a very small pitch for parallel AFM operations were studied. We fabricated 1x104 in eight groups and 1x30 Si probe arrays and produced a smaller pitch (15 μm) between probe tips by using Si anisotropic etching with a vertical wall shaped oxide mask. The vertical controls of Si probes were able to operate individually or in a group by integrating electrostatic actuators into the cantilevers of the probes. The fabricated Si cantilever arrays showed reasonable dynamic characteristics for the probe cantilever and reliable parallel operation of AFM.

Keywords: Atomic force microscopy; Parallel AFM operations; Si cantilever array

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1. Introduction

Atomic force microscopy (AFM), in other words, scanning probe microscopy (SPM), is currently applied to high-density storage and nanolithography as well as nano-scale measurement of surface properties. However, the AFM is restricted in its throughput because of slow scanning speed. Therefore, the demand for improving its operation time is increasing. A parallel operation with a probe array has been studied for the advanced throughput of AFM [1-3]. SPM arrays for data storage with a wide pitch (> ~100μm) have also been reported [4,5]. A two-dimensional Si SPM array with a narrow range (≈10μm) has been fabricated for its application to nanolithography [6]. In addition, AFM metal probe arrays [7], glass probe arrays [8], and diamond probe arrays [9] have all recently been developed.

In this work, we developed Si cantilever arrays for parallel AFM application. In order to treat smaller objects, we made the distance of each probe tip as small as possible. In addition, the cantilevers of multi probes had electrostatic actuators that enabled individual or grouped probes to move vertically. This paper describes the fabrication and evaluation of two types of Si probe arrays.

2. Fabrication of Si probe cantilever

The proposed Si probe cantilever is schematically shown in Fig. 1(n). In order to have more flexibility in AFM operation, the probe of the array was designed to self-move in a vertical direction. Simple electrostatic actuators were integrated into the microstructure of the probe cantilever. Potential applications of the proposed AFM probe array include scanning probe nanolithography as well as the ability to observe the surface of a sample in nano resolution.

The main fabrication process is shown in Fig. 2. For the wafer, we used an SOI of (100)-oriented surface (Fig. 1(a)). First, the SOI wafer was thermal oxidized and then the top oxide film of the wafer was patterned (Fig. 1(b)). The region of the probe tip was made by wet-etching in TMAH (Fig. 1(c)). Leaving the tip area at the anisotropic etching process was needed because the following anisotropic etching process for the purpose of AFM tip fabrication also produced many other tips in the Si probe cantilever.

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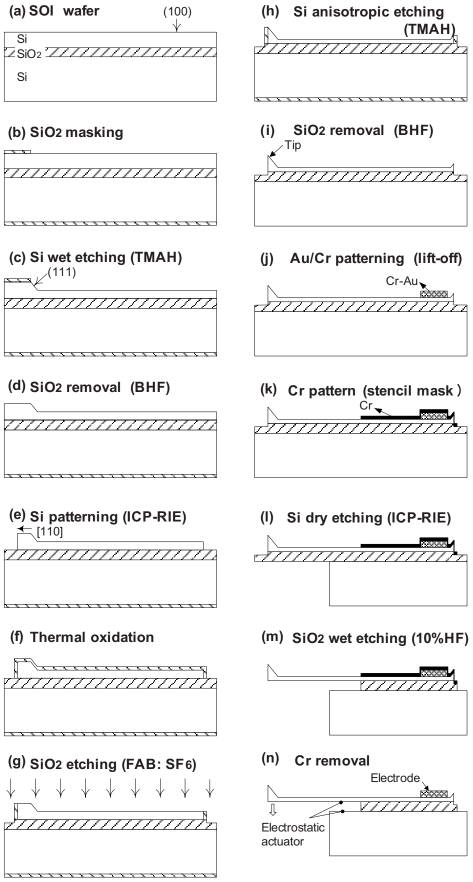
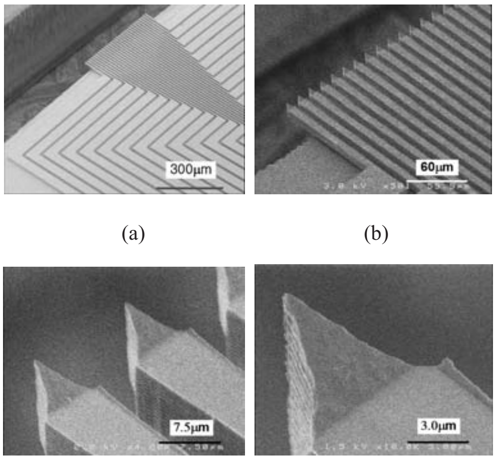


Fig. 1. Fabrication process of AFM Si probe.



(a) (b)

(c) (d)

Fig. 2. SEM images of 1x30 probe array: (a) array chip, (b) individual cantilevers, (c) multiprobes, and (d) probe tip.

Without making the probe tip much higher than other accompanying tips, there would be many undesirable incidents of contact between the specimen and the AFM probe by the accompanying tips. Then, the remaining top oxide film was removed (Fig. 1(d)).

For the shaping of the probe, the upper Si layer was patterned by dry isotropic etching of the ICP-RIE. In probe patterning, the fronts of the tips were aligned in the [110] direction, as shown in Fig. 1(e). The patterned Si layer was thermally oxidized with a thickness of ~100 nm (Fig. 1(f)). To remove the oxidized layer, we used a fast atom beam (FAB) with SF_6 gas. Since FAB is a directional isotropic etching process, only horizontal oxide film on the Si layer, not vertical oxide film beside the Si layer, was removed (Fig. 1(g)).

The Si layer with vertical oxide film was wet-etched in TMAH. As shown in Fig. 1(h), a sharp tip was produced because the single crystal silicon of the (100) surface was anisotropic wet-etched in the [110] direction with a mask. In general, SiO_2 film is used as a mask for the fabrication of the Si probe tips by using anisotropic wet-etching, and the horizontal surface mask produces a pyramidal tip [10]. The declined pyramid surfaces of the tip cause problems geometrically, making it difficult for the tips of the probe array to get close to each other. In our work, we used the vertical mask to make the tip so that the side surfaces of the tip were not only declined but also vertical. Hence, we could make the probe tips as close as possible to each other.

We eliminated the vertical oxide mask by wet-etching in Buffered-HF (BHF) (Fig. 1(i)). For fabricating the metal electrodes, Cr and Au were sputtered sequentially and patterned by a lift-off technique (Fig. 1(j)). A Cr mask film was sputtered by using a stencil mask of molybdenum (Fig. 1(k)). The Si of the back side of the wafer was isotropic dry-etched by ICP-RIE (Fig. 1(l)). Probe cantilevers were released by wet-etching the SiO_2 layer of SOI in BHF at room temperature (Fig. 1(m)). In the etching process of the SiO_2 layer, we also made an electrostatic actuator with Cr masking. Finally, Si SPM probes were completed by eliminating the Cr film by wet-etching (Fig. 1(n)).

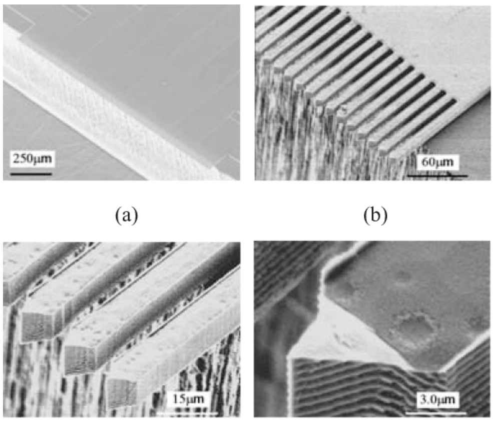
3. Evaluations of Si cantilever arrays

We fabricated two types of Si cantilever arrays with a pitch of 15 μm, which was smaller than any previous work. One of the array types was a 1x30 array, and each of the probe cantilevers of the array had its own electrode. Hence, independent actuation and detection for AFM operation were possible by applying actuator voltage and measuring the electric signal. The microfabricated 1x30 probe array is shown in Fig. 2. The other type was a 1x104 array, but 13 probes were grouped with one electrode. The 13 grouped probes were operated together for actuation and detection of AFM application. There were eight groups of probe cantilevers and eight electrodes in the 1x104 array chip. Eight probe groups were controlled independently. Fig. 3 shows magnified views of the fabricated 1x104 Si probe array. Figs. 2(d) and 3(d) show that sharp tips of ~3 μm in height were fabricated on Si micro probes. We can see in Figs. 2(c) and 3(c) that an undesirable Si tip or edge was produced on the probe cantilevers in the anisotropic etching process (Fig. 1(h)), but it was negligible in size compared to the probe tips.

The fabricated probe cantilever was vibrated by an excitation voltage of 80 V, and then amplitude and phase degree of cantilever vibration were optically measured by scanning probe microscopy (Olympus Co.). The Si cantilever had a width of 10 μm and a length of 105 μm. From the measurement of Fig. 4, the first natural frequency of the cantilever was found to be 10.9 kHz. The Si cantilever showed a relatively low natural frequency. However, the probe cantilever was somewhat stiff, because the thickness of the cantilever was comparatively thick at ~9 μm. The spring constant, k, was approximately calculated by using following equation:

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{1}$$

here, m is mass of the cantilever and f is the natural frequency. The density of silicon was assumed as 2.328 g/cm^3 and the spring constant was calculated as about 0.1 N/m.



(a) (b)

(c) (d)

Fig. 3. SEM images of 1x104 grouped probe array: (a) array chip, (b) grouped cantilevers (c) multiprobes, and (d) probe tip.

The atomic force microscope is an imaging tool, scanning the sample surface. Contact and non-contact imaging techniques are used. Generally, a soft cantilever, such as spring constant k is less than 1 N/m, is suitable for contact mode. In non-contact mode, the probe is vibrated near its resonant frequency, typically from 100 to 400 kHz. High natural frequency of the probe cantilever is desirable for the non-contact mode. The natural frequency of the fabricated cantilever is slightly low to be used for the non-contact mode. However, the spring constant of the fabricated cantilever is appropriate for the contact mode.

We tested parallel operation of the fabricated probe array. The fabricated probe array was installed in the scanning probe microscopy. In the contact mode of SPM, scanning probe nanolithography was tried on photo-resist thin film coated on gold surface. We did parallel patterning by scratching the photo-resist using the probe 1x30 array tips as in Fig. 5. Parallel imaging was tested employing the fabricated multi-probes. We could scan the surface of MEMS chip sample using the 1x104 (grouped) probe array as in Fig. 6. Parallel scanning was performed in the contact mode of SPM (Olympus Co). For further evaluation, scanning probe measurement and nanolithography are under additional study.

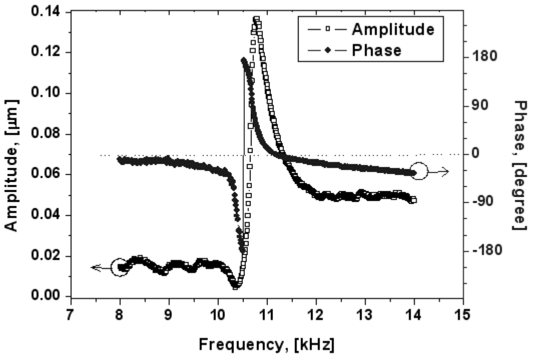
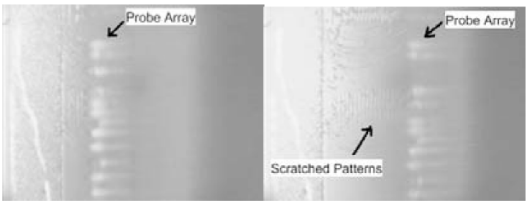
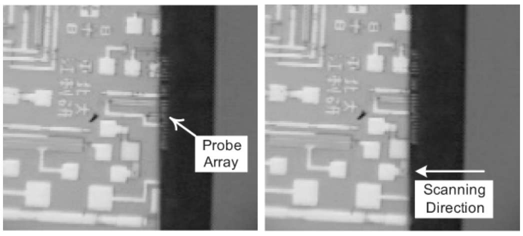


Fig. 4. Natural frequency curve of Si probe cantilever.



(a) (b)

Fig. 5. Sequential photographs, from (a) to (b), of parallel lithography of AFM 1x30 probe array.



(a) (b)

Fig. 6. Sequential photographs, from (a) to (b), of parallel scanning of AFM 1x104 grouped array.

4. Conclusions

Silicon cantilever arrays for parallel operation were developed to enhance the performance of AFM. We used a new fabrication process, anisotropic etching by vertical oxide mask, to make the probe tips so that the tips of the probe array could be situated as closely as possible to each other. We made 1x30 and 1x104 (grouped) probe arrays with a pitch of 15 μm. For independent AFM operation, the cantilevers of the probe arrays had their own electrostatic actuators that enabled individual or grouped probes to move vertically. The experiments showed reasonable dynamic characteristics of the probe cantilevers and reliable parallel operation. We expect that the developed Si probe arrays will be useful in parallel AFM applications in nanolithography and nano scale measurement of surface properties.

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