Paper

Magnetically actuated cantilever with small resonator for scanning probe microscopy

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Magnetically actuated cantilever with a small resonator has been developed for application of scanning probe microscopy. The torsional resonator with a small mass is located at the end of the cantilever beam, and is driven near its resonance frequency by electromagnetic force. A force interaction between a tip and a sample cause the shift of the resonance frequency and it is detected by electromotive force generated through motion of resonator in a magnetic field. As a result, the resonator can be used as a force sensor. The same method is used for an actuation of the cantilever, which is adjusted for constant force during scanning operation. The smaller resonator has the higher resonance frequency, and is insensitive to thermo-mechanical noise.

Keywords: SPM; AFM; Non-contact; Electromagnetic force; Actuator

1. Introduction

Scanning probe microscopy (SPM) has been widely studied in the field of surface science, high-density data storage and manipulation in atomic scale. Generally, topographic image in the SPM system is mapped by measuring a force interaction between a sharp tip and a sample surface [1, 2]. The forces cause the deflection of the cantilever that can be measured by the force sensor. Most SPM designs on the market are based on optical methods for detection of the cantilever deflection (e.g., optical interferometry, laser beam deflection). However, all of these methods require a sensing element external to the cantilever. This external sensing element should be eliminated for miniaturization of the SPM system. Furthermore, integration of force sensor on the cantilever is represented a figure of merit for individual operation in a probe array. Recently, cantilevers with integrated force sensor for detection the cantilever deflection such as, piezo-resistive [3, 4], capacitive [5], electromotive force [6] and piezoelectric materials [7] have been presented. Among these methods, the piezo-resistive type is now available as a commercial product.

In constant force mode, the scanning speed of conventional SPM is limited by a low resonance frequency of a piezoelectric tube scanner [8]. To increase the scanning speed, the resonance frequency of the actuator should be increased. And parallel operation of cantilever array along the z-axis is highly desired. Cantilevers with an integrated actuator for a high scanning speed have been developed by several groups [9, 10, 11]. These cantilevers are successfully deflected in the vertical direction.

In this work, we propose a new structure of a resonator integrated cantilever for high-speed imaging and high sensitivity. The resonator integrated cantilever (RICA) can be actuated and vibrated by electromagnetic force (as called Lorentz force) in the vertical direction. For detection of small force (10^{-12} N) in non-contact mode, the frequency modulation (FM) detection method based on self-oscillation can be used [12].

2. Device design and operation principles

The fabricated RICA consists of two parts: the torsional resonator supported by two torsion beams for a high sensitive force sensing and the cantilever for keeping a constant interaction force between a sample and the tip during the operation. Designed structure of RICA and AFM system are shown in Fig. 1. Typical cantilever beam dimensions are 34 μm width, 150 μm length and 0.5 - 1 μm thickness. The torsional resonator has a paddle with a width of 8 μm and a length of 21 μm, torsional beam has a length of 2.5 μm and width of 1-2 μm.

External magnetic field is applied along the length of RICA. By flowing an ac current to a small metal line, the small torsional resonator can be vibrated near its resonance frequency. Estimated inductance of the metal loop on the resonator is about 6×10^{-12} H. The motion of the torsional resonator in the magnetic field induces the electromotive force (EMF) on another metal loop. Force between the tip of the torsional resonator and a sample can be directly measured by the shift of the resonance frequency, which is obtained from the EMF. Resonance frequency of the small torsional resonator is designed, as it is higher than that of the cantilever. As a result, the cantilever motion doesn‘t disturb the resonator when the cantilever is actuated under feedback control operation. Any other information has been described in detail elsewhere [6].

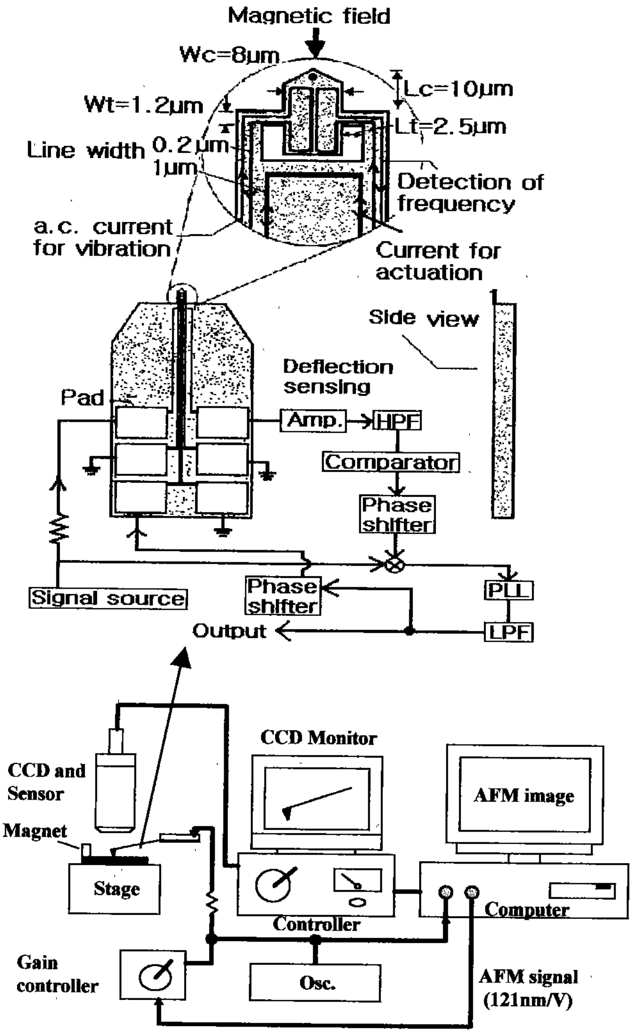


Fig. 1. Schematic diagram of basic structure and AFM system with RICA

The known physical properties of the RICA allow us to obtain the resonance frequency and vibration mode by simulation. The resonance frequency corresponding to each vibration mode is obtained by using finite element method (FEM) where ANSYS® is used. We used the fundamental mode (as known twist vibration) of the torsional resonator for the force sensing. The spring constant of the cantilever and the torsional resonator are designed about 0.2 N/m and 60 N/m, respectively.

3. Fabrication

3. 1. Fabrication flows of the RICA

The fabrication flow of cantilever with the small resonator for application of SPM is illustrated in Fig. 2. The (100) oriented p-type silicon-on-insulator (SOI) with a sheet resistance of 7-17 Ω·cm is used. The thickness of the top silicon layer, the intermidiate oxide layer and the substrate are 2.5 μm, 1 μm and 525 μm, respectively (Fig. 2-1). The intermediate buried oxide layer of the SOI wafer serves as an etch stop during backside etching and allows us to achieve a homogeneous cantilever thickness.

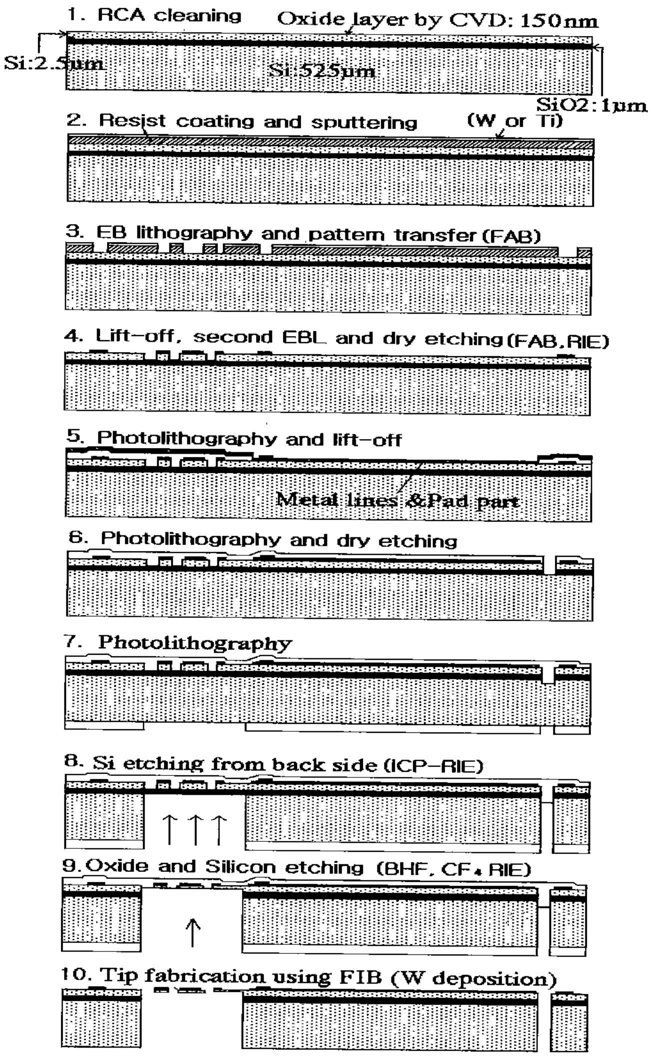


Fig. 2. A cross sectional views of the fabrication process

First, 150 nm thick oxide is deposited on the wafer using TEOS-PECVD to electrically isolate the metal line from the silicon substrate (Fig. 2-1). The metal lines on the small resonator and alignment marks for next EB (electron beam) lithography are patterned using EB lithography and then metals (Au/Cr) are deposited for lift-off (Fig. 2-3, 2-4). The detail of this process is described in 3. 2. Using the small alignment mark with a width of 0.2 μm, the small resonator shape is exactly defined by second EB lithography and fast atom beam (FAB) etching (Fig. 2-4). After etching of the oxide layer, topside silicon is etched using SF_6 RIE. The second EB lithography step requires fine alignment within ± 0.2 μm. The bonding pads and metal lines for the connection to the small metal line fabricated using the EB lithography are made by thick Au/Cr (Fig. 2-5), which is also defined by liftoff process. The body of the cantilever is defined by photo-lithography and then the patterned SiO_2 and silicon is etched using FAB and RIE (reaction ion etching) (Fig. 2-6).

Subsequently, deep RIE for etching of thick bottom silicon is performed. For this deep RIE step, we used advanced silicon etching (ASE, deep RIE) program of surface technology system (STS), Gwent, UK. The photoresist of 10 μm thick (Shiply, AZ4903) is used to protect the bottom silicon with 525 μm thick (Fig. 2-7). The top silicon of the wafer is also protected by a photo-resist of 3 μm thick (Tokyo Oukakogyou Co., OFPR 200) (Fig. 2-7), which provides a physical combination to the fragile cantilevers. The ASE program of STS provides an excellent etching profiles with nearly vertical side walls and virtually no undercut. After the deep RIE, the intermediate buried oxide of SOI is wet etched in bufferd-HF at 40 °C for 15 min (Fig. 2-9). The cantilever thickness is controlled by CF_4 plasma etching (Fig. 2-9). Finally, the RICA structure is released using O_2 plasma and then tip is fabricated by FIB (Fig. 2-10). A great advantage of the deep RIE with vertical sidewalls is that it permits a considerably high density of devices on the wafer.

3.2. High aspect ratio structure by EB lithography and FAB etching

Small resistance of the metal lines are required for large electromagnetic force. Narrow but high metal lines are fabricated using resist with high aspect ratio structure (HARS) as a mold. To fabricate the HARS on the resonator, pattern transfer method is used as shown in Fig. 2-2, 2-3 and 2-4. At first, the sample is coated with resist (Tokyo Oukakogyou Co., OFPR 800), then hard bake is performed at 200 °C for 2 hr. After baking, metal (Ti or W) is sputtered on the resist layer and then EB resist is coat-

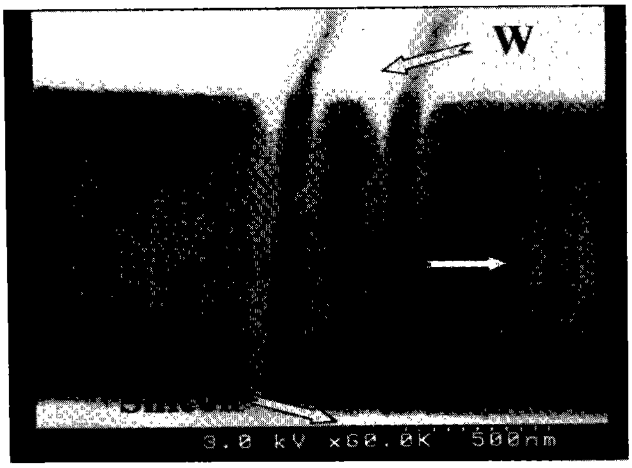
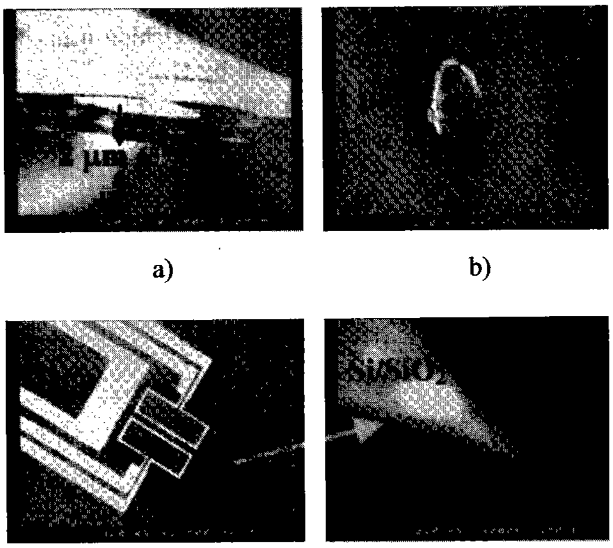


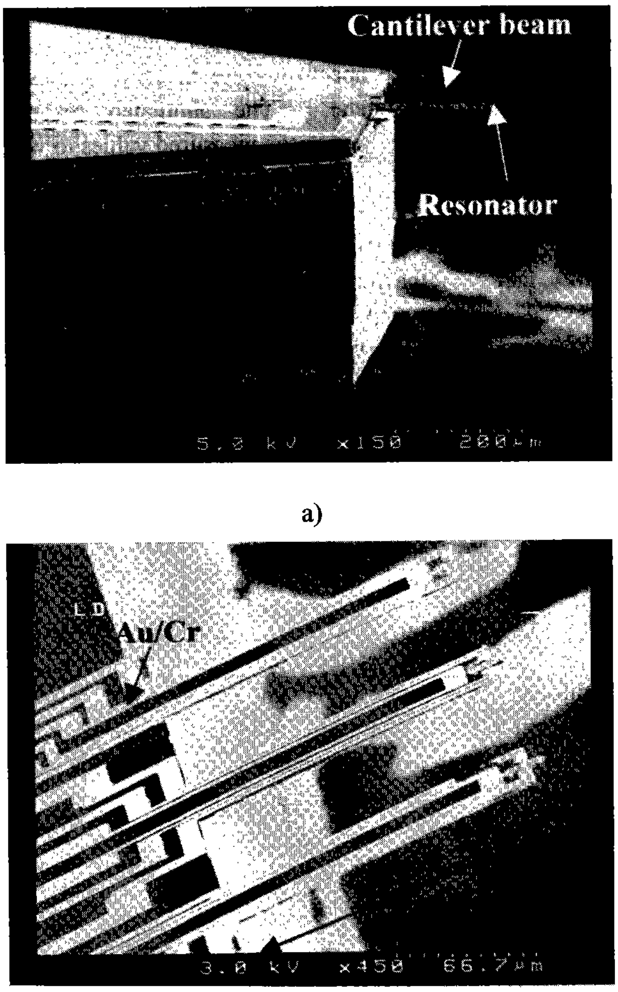
Fig. 3. A SEM view of the resist mold with high aspect ratio structure



a) b)

c) d)

Fig. 4. SEM views of fabricated tip by a) FIB, b) Lift-off, c) EB-lithography and RIE and d) A close-up view of c)



a)

b)

Fig. 5. SEM views of a) the fabricated RICA, b) the fabricated parallel RICA.

ed. The EB lithography conditions are optimized to produce fine resist pattern. After dry etching using FAB (metal etched by SF_6, resist etched by O_2), the resist mold with HARS is obtained on the substrate. Figure 3 shows the SEM image of the resist mold with HARS.

3.3 The fabrication of the tip

Many groups have reported the fabrication methods of sharp tip with various shape formed from silicon [13, 14], SiO_2, Si_3N_4, diamond and tungsten. Here, several nano-fabrication methods for constructing sharp stylus tip have been demonstrated. These fabrication methods are as following: W sharp tip by FIB assisted CVD (foused ion beam assisted chemical vapor deposition), Pt/Ti sharp tip by lift-off process and Si/SiO_2 sharp corner tip by the combination of EB lithography and reactive ion etching (RIE). Figure 4 shows the fabricated tips by these methods. SEM images of the fabricated RICA and the parallel RICA are shown in Fig. 5.

4. Results and discussion

In order to characterize the fabricated RICA, the mechanical resonance spectrums are measured using the laser doppler vibrometer. The simulated resonance frequency usually agrees with the measured values to within about 15% in error. The fabricated cantilever beam and torsional resonator had a fundamental vibration mode at 49.3 kHz and 3.4 MHz, respectively. The mechanical quality factor of the torsional resonator are 1360 (in 0.1 Torr), 203 (in air), respectively. The measured resonance spectrum of the torsional resonator is shown in Fig. 6.

By using different metal (Au/Cr) of the wires and HARS wires, the resistance (47Ω) of wires can be reduced in conparison with the previous cantilever beam (Pt/Ti, 1KΩ) [4]. The static deflection of the RICA is measured using deflection sensor of the AFM in atmosphere as shown Fig 9.

By flowing the dc current to metal loop on the cantilever, the cantilever is deflected by electromagnetic force and undesirable bimetallic effect. Figure 7 shows the deflection characteristics of cantilever beam as a function of supplied current and it is compared with the FEM simulation result. The static deflection of the fabricated RICA agrees with FEM simulation result in the low current below 15 mA. In a certain current over the 15 mA, the deflection curve of the RICA is different from that obtained by the simulation results. In order to large deflections, high currents are necessary which may cause thermally induced bending of the cantilever.

The amplitude of the thermally induced vibration at the end of the resonator can be calculated from the resonance frequency of torsional resonator. For a spring constant of 60 N/m, we measured the thermal noise vibration amplitude of fabricated torsional resonator at room temperature (300 K), corresponding to 8.3×10^{-15} m. The oscillation amplitude of the resonator is 28 nm when an a.c. current of 4 mA is applied to the metal loop on resonator and magnetic fields of 2000 gauss are applied from a front of the cantilever. Vibration velocity of the resonator in a constant magnetic field is a few hundred mm/sec, which is calculated from the vibrating frequency and maximum amplitude of the vibration. Induced EMF (electromotive force) of the another coil on the resonator can be estimated using these parameters. The induced EMF is a few hendered nano-voltages. The minimum detectable force gradient of fabricated cantilever beam with torsional resonator at room temperature, is expected about 1.8×10^{-5} N/m. The minimum datectable force is also calculated using the van der Waals forces, which is dominate the interaction force in non-contact region. Suppose that the distance (s) of the tip to the sample is 10 nm, the minimum force gradient of $F' = 1.8 \times 10^{-5}$ N/m would therefore correspond to a force of 1.8×10^{-13} N. Bandwidth of 1 kHz is for calculating the minimum detacable force.

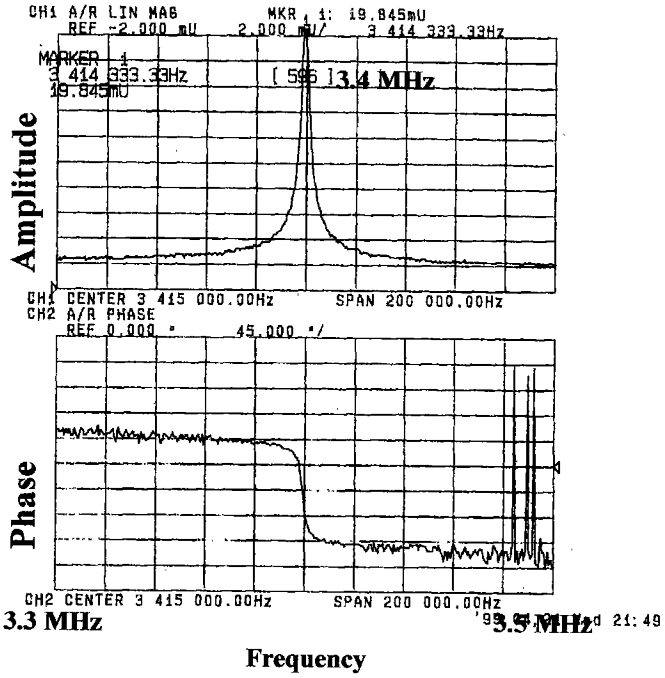


Fig. 6. The measured mechanical spectrum of the small torsional resonator

For operational testing of the fabricated RICA is mounted on the AFM system in air. The AFM image has been successfully demonstrated in contact mode as shown in Fig. 8. a. When operating in constant force mode, the signal generated by the cantilever deflection is detected by optical sensor of an AFM (atomic force microscope) and the output of the feedback signal through gain controller is connected to the metal line on the cantilever. The output signal of the gain controller, which adjusts the vertical z po-

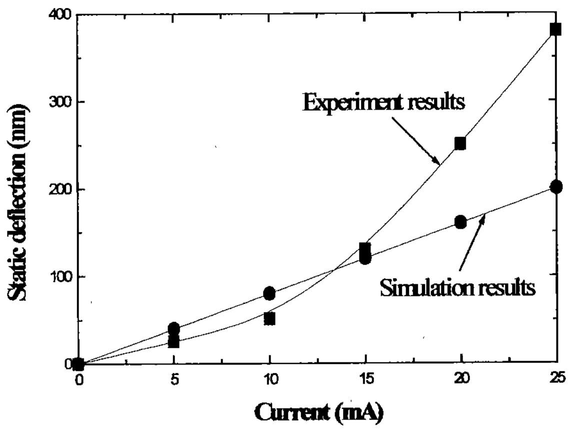
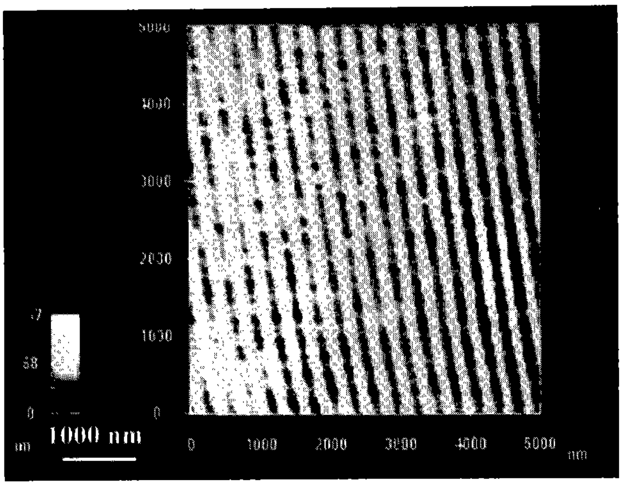
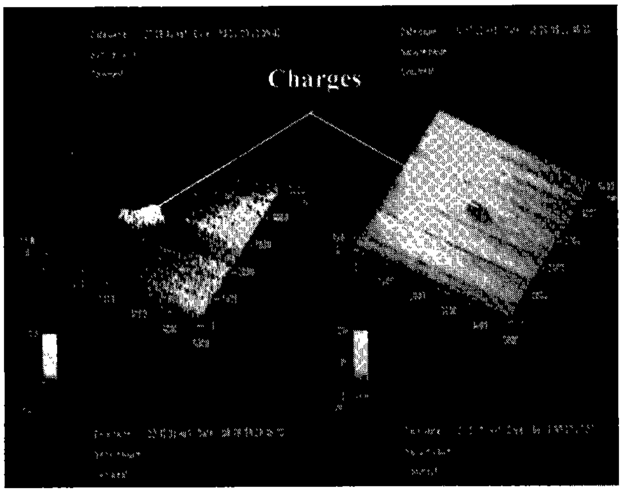


Fig. 7. The static deflection characteristics of the cantilever



a)



b)

Fig. 8. a) Surface image using RICA in contact mode, b) surface image of electrostatic force in non-contact DC mode.

sition to achieve a constant cantilever deflection, can be recorded as a fungtion of the x-y plane which are determined by the corresponding voltages Vx and Vy applied to the x and y piezoelectric scanner. Finally, the obtained signal is translated into the topograph of the computer.

When the cantilever beam biased a certain voltage touchs a thin oxide layer on the sample surface, contact electrification occures in the oxide layer. After the contact electrification around 1 min, electrified region is rescanned using non-contact DC mode. Applying a positive bias on the tip will induce the repulsive force on the sample surface. On the other hand, applying a negative bias on the tip will induce the attrative force on the sample surface as shown in Fig. 8. b., which is indicated the dependence of charges.

5. Summary

We have demonstrated the fabrication and operation of the RICA for application of SPM. The torsional resonator for electromagnetic excitation and detection is successfully fabricated using EB lithography and micromachining technology. The fabricated torsional resonator in a vacuum has the resonance frequency of 3.4 MHz and the cantilever is successfully deflected by electromagnetic force in vertical direction. By using DC non-contact mode, deposited charges were observed by the electrostatic force between silicon surface and conductive tip. The fabricated RICA with a high resonance frequency is expected to have extremely potential capability for a quick response and a high speed SPM operation.

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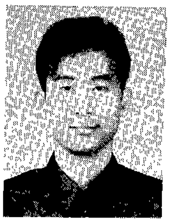

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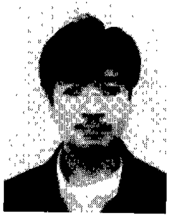

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