研究速報

Characterization of Silicon Nanocantilevers

Kimitake FUKUSHIMA*, Daisuke SAYA*, Hiroshi TOSHIYOKI*,
Hiroyuki FUJITA* and Hideki KAWAKATSU*

1. Introduction

Atomic force microscope (AFM)[1], which was originally invented as a tactile surface profiler, has evolved into various kinds of scanning probe microscope (SPM). Non-contact mode atomic force microscopy (nc-AFM)[2] is a kind of SPM that measures the potential of atomic force (Lennard Jones potential) existing in the proximity of the sample surface.

In nc-AFM, a cantilever with a sharp tip on one end is used as a probe. When the mass and the spring constant of the cantilever is given by m and k respectively, the equation of motion is given as follows:

$$m\ddot{x} = -kx$$

When the tip approaches the sample and is caught in the potential, a force with a tip-sample distance dependency is applied to the tip. This kind of force can be modeled as an extra spring constant k_T and therefore the equation of motion is modified to:

$$m\ddot{x} = -(k + k_T)x$$

As a result, the resonance frequency f_0 of the cantilever changes from:

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

to

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k+k_T}{m}}$$

Thus, by monitoring the change in the resonance frequency of the cantilever, or by monitoring the change in the resonance amplitude of the cantilever, the force gradient acting on the tip can be known.

Since any kind of force gradient can have the same effect on tip, various types of scanning force microscopes (SFM) such as Kelvin force probe microscopy (KFPM)[3,4] or magnetic resonance force microscope (MRFM)[5-9] utilizing the same principle as nc-AFM have evolved. Also, since the mass change of the cantilever can have the same effect, chemical sensors with oscillating cantilevers are proposed.

The minimum detectable force (force resolution) of the nc-AFM method is limited by the thermal noise level of the cantilever[10]. When the cantilever is in equilibrium with the surroundings in terms of energy, the cantilever should have the vibration energy that matches the temperature of the surroundings. Therefore:

$$\frac{1}{2}kx_{rms}{}^2 = \frac{1}{2}k_BT$$

where, k_B: Boltzman's constant, T: Temperture of the surroundings

When the vibration energy is divided equally among the spectrum, the minimum detectable force F_{min} is written as follows:

$$F_{min} = \sqrt{\frac{2kk_BTB}{\pi Q f_0}}$$

where, Q: quality factor of the cantilever, B: Bandwidth of measurement

Therefore, to minimize F_{min}, a cantilever with low spring constant k, high quality factor Q, and high resonance frequency f_0 is needed.

The minimum force detection reported was attonewton order force measurement achieved by using a long ultra thin silicon cantilever.[11] Their technique was to minimize F_{min} by lowering k to the limit and maintaining Q at certain amount. Although this method is applicable against simple force measurement, spring constant k must be maintained above certain amount to avoid tip-sample contact (snap-in) in nc-AFM measurement.

To make a low noise cantilever for nc-AFM measurement, min-

*Center for International Research on Micro-Mechatronics, Institute of Industrial Science, The University of Tokyo.

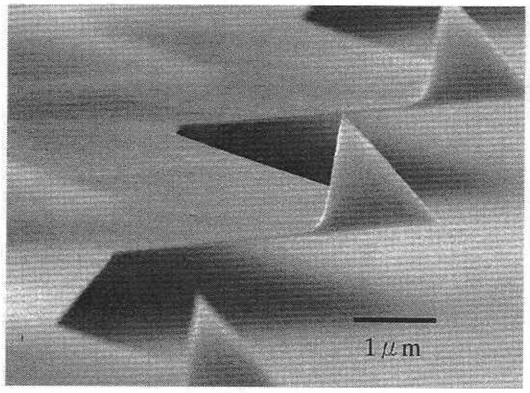

Fig. 1 A SEM image of single crystal silicon nano-cantilever

imizing the size is effective[12-15]. Since the mass of the cantilever decreases, high resonance frequency can be achieved while keeping the spring constant at certain amount. Also, high Q is achieved due to reduction in intrinsic loss. In this approach, we have developed a small single crystal silicon cantilever for use in nc-AFM as shown in Figure 1. The cantilever has a length of few microns and thickness of 40 to 80nm. In this paper, we present the results of the measurement of static and dynamic mechanical characteristics of these cantilevers.

2. Measurement of static mechanical characteristics

For measurement of static characteristics, we have used an atomic force microscope situated inside scanning electron microscope (SEM-AFM)[16]. First, we measured the cantilever's tolerance against strong stress. The cantilever was pressed hard by a tungsten needle usually used as a tip for scanning tunneling microscopy (STM). As shown in Figure 2, the cantilever could survive stress without any apparent indication of plastic deformation even after the cantilever is bent into S figure. Since the gap between the cantilever and the base is 1μm, elasticity was confirmed for at least 1um of bending. The curvature at the edge of the tetrahedral shown in Figure 3 is preventing stress concentration and thus increasing the structural strength. When we pressed the cantilever to a further extent, the cantilever eventually broke at the rim of the SiO_2 column supporting the cantilever as shown in Figure 4.

We have also measured the spring constant of the cantilever by SEM-AFM. By measuring the force curve (sample stage deflection vs. cantilever deflection) at the base and the end of the cantilever and comparing the gradient, we can obtain the ratio between the spring constant of the cantilever used to press and the nano-cantilever. By taking for granted the spring constant of the AFM

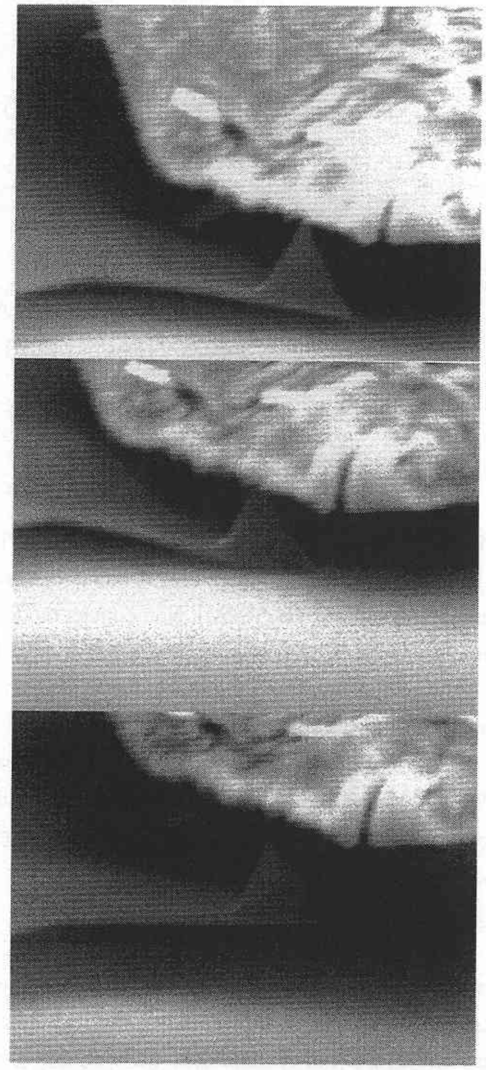

Fig. 2 Continuous images of nano-cantilever being pressed by tungsten needle. The cantilever was seen to survive stress without any apparent indication of plastic deformation even after the cantilever is bent into S figure.

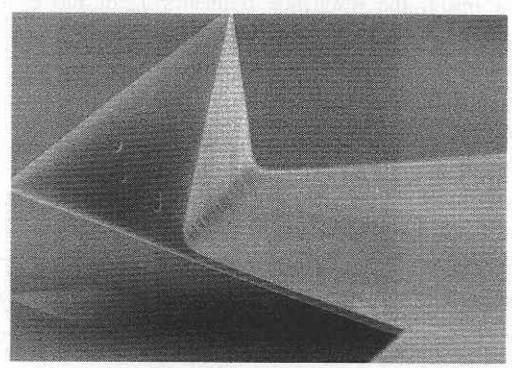

Fig. 3 Close-up view of the nano-cantilever. A curvature can be seen on the edge of the tetrahedral.

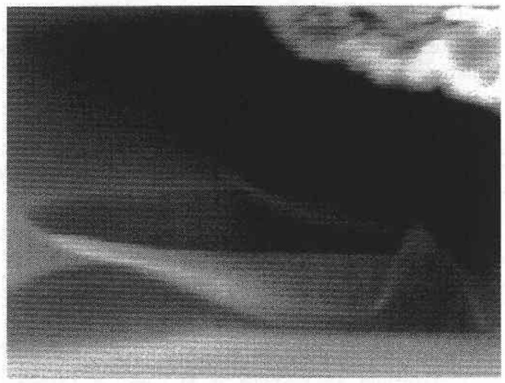

Fig. 4　SEM image of a nano-cantilever after fracture. The point of fracture was at the edge of SiO_2 column.

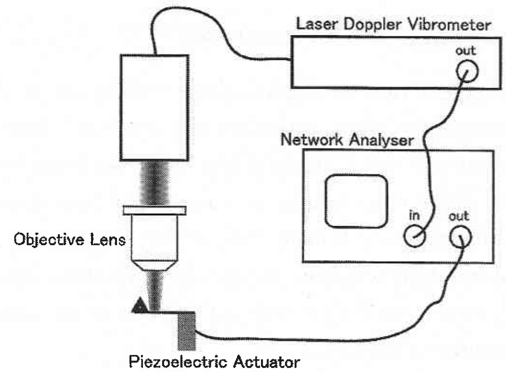

Fig. 5　Schematic figure of the experimental setup for measurement of dynamic characteristics. A laser Doppler vibrometer and a network analyzer was combined to obtain vibration amplitude spectrum of the cantilever.

cantilever, we can obtain the spring constant of the nano-cantilever. For a nano-cantilever with a length of 8μm and a thickness of 60nm, the spring constant was measured to be 3 to 5 N/m.

3. Measurement of dynamic mechanical characteristics

For measurement of dynamic mechanical characteristics, we have used a commercially available laser Doppler vibrometer and a network analyzer. The setup of the experiment is shown in Figure 5. The output of the network analyzer was plugged to the piezoelectric actuator, which was used to oscillate the nano-cantilever, and the output of the laser Doppler vibrometer was plugged to the input of the network analyzer[17]. By using this setup, we were able to measure the vibration amplitude spectrum of the cantilever.

A vibration amplitude spectrum obtained in vacuum of 10^{-6} Torr for a nano-cantilever with a length of 8μm and a thickness of 60nm is shown in Figure 6. From the experimental result, the first vibration mode had the resonance frequency of 1.202MHz and the quality factor of about 8400. The resonance frequency of two adjacent cantilevers differed only by less than 0.01%. A typical nano-cantilever we have measured had a resonance frequency ranging from 1Mhz to 6MHz and a Q factor ranging from 8000 to 10000. We are now aiming to raise the Q factor by cleaning the surface of the nano-cantilever, since most of the damping is occurring at the surface.

We also observed the oscillation of the nano-cantilever in air. Figure 7 shows the vibration of the piezo actuator and Figure 8 shows the vibration of the nano-cantilever both at the resonance frequency of the cantilever 4.75MHz. From the result, the Q factor was calculated to be under 10. Most of the damping that is limiting the Q factor seems to originate from squeeze effect of air under the cantilever.

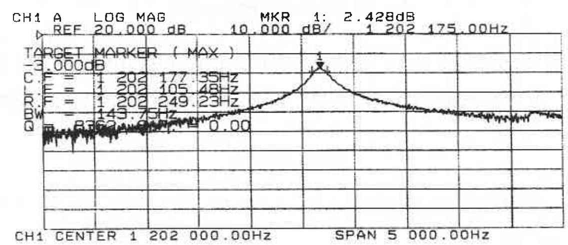

Fig. 6　Vibration amplitude spectrum of a typical nano-cantilever.

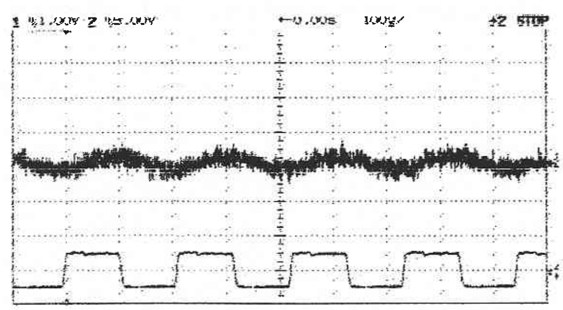

Fig. 7　Vibration of piezoelectric actuator. Vibration amplitude was 1.6 nm p-p.

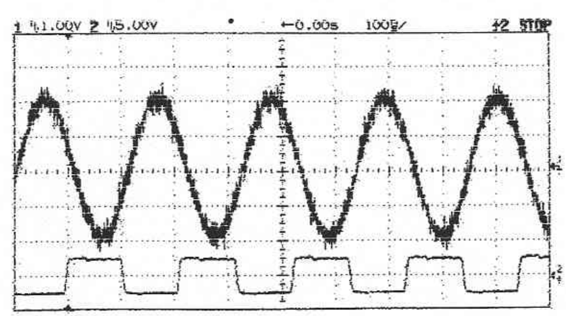

Fig. 8　Vibration of nano-cantilever. Vibration amplitude was 8.4 nm p-p.

4. Conclusion

From experiments, for a nano-cantilever with a length of 8um and a thickness of 60nm, spring constant was 3 to 5 N/m, resonance frequency was 1.2MHz, and Q factor was about 8400 in vacuum. From these figures, presumed minimum detectable force of this cantilever is in the order of 10^{-16} N if operated under vacuum at 4 degrees Kelvin. We are aiming to reduce the minimum detectable force by raising the Q factor of the cantilever through surface cleansing.

Apart from having a capability of being used as high Q cantilever in vacuum, the nano-cantilevers may be used as an ultra low Q cantilever in air.

(Manuscript received, December 13, 2000)

5. Acknowledgement

We would like to thank Professor Esashi and Professor Ono for help on the measurement of dynamic characteristics in vacuum.

References

1) G. Binnig, C. Gerber and C. F. Quate: Phys. Rev. Lett. **56** (1986) 930.
2) T. R. Albrecht, P. Gutter, D. Horne and D. Rugar: J. Appl. Phys. **69** (1991) 668.
3) M. Nonnenmacher, M. P. O'Boyle, and H. K. Wickramasinghe: Appl. Phys. Lett. **58** (1991) 2921.
4) H. O. Jacobs, H. F. Knapp, and A. Stemmer: Rev. Sci. Instrum., **70** (1999) 1757.
5) Todd G. Ruskell, Markus L_hndorf, and John Moreland: J. Appl. Phys. **86** (1999) 664.
6) D. Rugar, O. Züger, S. Hoen, C. S. Yannoni, H.-M. Vieth, and R. D. Kendrick: Science **264** (1994) 1560.
7) K. Wago, O. Zügar, J. Wegener, R. Kendrick, C. S. Yannoni, and D. Rugar: Rev. Sci. Instrum. **68** (1997) 1823.
8) K. Wago, O. Zügar, R. Kendrick, C. S. Yannoni, and D. Rugar: J. Vac. Sci. Technol. B **14** (1996) 1197.
9) D. Rugar, C. S. Yannoni,, and J. A. Sidles: Nature **360** (1992) 563.
10) K. Y. Yasumura, T. D. Stowe, E. M. Chow, T. Pfafman, T. W. Kenny, B. C. Stipe, and D. Rugar: J. Micromechanical Systems, 9 (2000) 117.
11) T. D. Stowe, K. Yasumura, T. W. Kenny, D. Botkin, K. Wago, and D. Rugar: Appl. Phys. Lett. **71** (1997) 288.
12) Tilman E. Schäffer, Mario Viani, Deron A. Walters, Barney Drake, Erik K. Runge, Jason P. Cleveland, Mark A. Wendman, and Paul K. Hansma: SPIE, Vol. 3009, 48.
13) Tilman E. Schäffer, and P. K. Hansma: J. Appl. Phys. **84** (1998) 4661.
14) M. B. Viani, T. E. Schäffer, A. Chand, M. Rief, H. E. Gaub, and P. K. Hansma: J. Appl. Phys. **86** (1999) 2258.
15) J. A. Harley and T. W. Kenny: Appl. Phys. Lett. **75** (1999) 289.
16) Kimitake Fukushima, Daisuke Saya, and Hideki Kawakatsu: Jpn. J. Appl. Phys. **39** (2000). 3747.
17) Jinling Yang, Takahito Ono, and Masayoshi Esashi: Sensors and Actuators **82** (2000) 102.