Piezoelectric PZT Cantilever Array Integrated with Piezoresistor for High Speed Operation and Calibration of Atomic Force Microscopy

Hyo-Jin Nam, Young-Sik Kim, Seong-Moon Cho, Caroline Sunyong Lee, Jong-Uk Bu, and Jae-Wan Hong

Abstract— **Two kinds of PZT cantilevers integrated with a piezoresistor have been newly designed, fabricated, and characterized for high speed AFM. In first cantilever, a piezoresistor is used to sense atomic force acting on tip, while in second cantilever, a piezoresistor is integrated to calibrate hysteresis and creep phenomena of the PZT cantilever. The fabricated PZT cantilevers provide high tip displacement of 0.55μm/V and high resonant frequency of 73 kHz. A new cantilever structure has been designed to prevent electrical coupling between sensor and PZT actuator and the proposed cantilever shows 5 times lower coupling voltage than that of the previous cantilever. The fabricated PZT cantilever shows a crisp scanned image at 1mm/sec, while the conventional piezo-tube scanner shows blurred image even at 180μm/sec. The non-linear properties of the PZT actuator are also well calibrated using the piezoresistive sensor for calibration.**

Index Terms—**Atomic force microscopy, PZT cantilever, electrical coupling, high speed, piezoresistor, tip**

I. INTRODUCTION

Atomic force microscopy (AFM) has been a powerful tool for science and technology due to its high resolution. Despite the striking advances in the technology of AFM, the performance is still limited by slow scan speed. Improvement of operational speed is strongly required for new applications such as high speed AFM, scanning probe lithography (SPL)1) and high density data storage device2). As the scan speed is limited by the low speed of piezo-tube of conventional AFM, the self-actuating piezoelectric cantilever integrated with piezoelectric thin film has been studied to improve the scan speed. Minne. et al. developed the self-actuating ZnO cantilever integrated with a piezoresistor for high speed AFM3,4). Lee et al. have studied the PZT force sensor for dynamic scanning force microscopy5). Watanabe et al. have also fabricated a cantilever with sputtered PZT film for deflection sensor and feedback actuation in z-direction6). We reported that the scan speed of AFM was significantly improved using the PZT cantilever compared to conventional piezo-tube7). However, the reported ZnO cantilevers showed low tip displacement due to low piezoelectric constant of ZnO film. Also, PZT cantilevers showed process problems such as co-integration between the silicon tip and the PZT actuator. Additionally, the reported cantilevers with sensor and actuator showed the serious electrical coupling between the actuator and piezoresistor signals at high frequency operation3) and PZT actuator has inherent problems of

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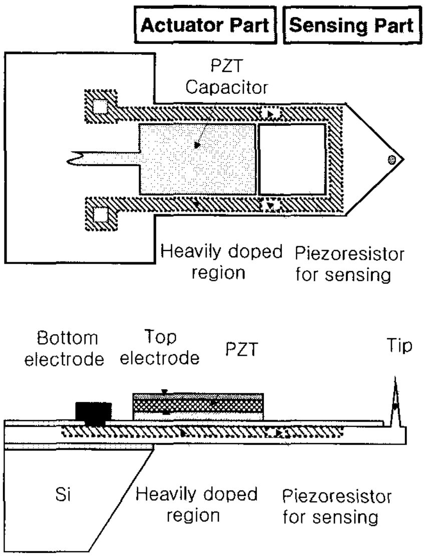
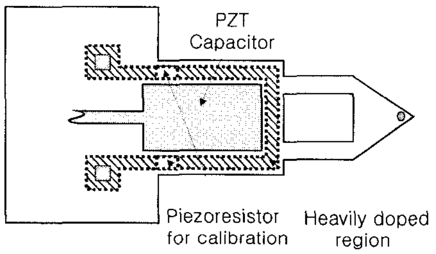


(a) PZT cantilever with piezoresistor for sensing



(b) PZT cantilever with piezoresistor for calibration

Fig. 1 Device structure of the PZT cantilever integrated with piezoresistor.

hysteresis and creep.

In this study, two kinds of piezoresistors are integrated in the PZT cantilevers for sensing of atomic force and calibrating of non-linear properties of PZT actuator, respectively. Especially, a new PZT cantilever structure is proposed to prevent the electrical coupling between the PZT actuator and piezoresistor. The improvement of speed using the fabricated PZT cantilever is confirmed through AFM image and the calibration properties of the piezoresistor are investigated by characteristics of piezoresistor.

II. DESIGN AND FABRICATION

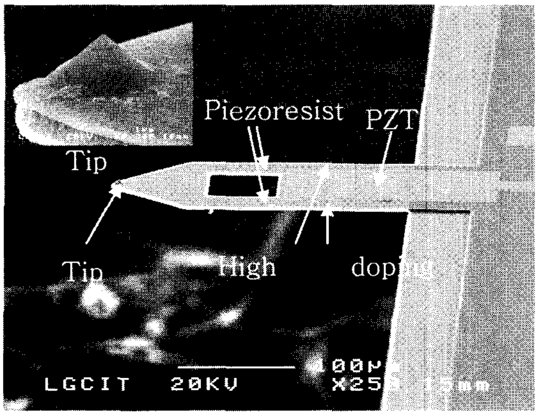
Figure 1 shows the PZT cantilever integrated with piezoresistive sensor schematically. Piezoresistor for sensing is formed at front side of PZT capacitor to sense atomic force acting on the tip as shown in Fig. 1(a), while that for calibration is formed near Si substrate to sense the deformation of the PZT cantilever as shown in Fig. 1(b). The cantilever consists of the actuator part and the force sensing part. The spring constant of the sensing part was designed to be about 10 times smaller than that of the actuating part to localize the atomic force to the sensing part of the cantilever.

The self-actuating PZT cantilevers integrated with piezoresistors have been fabricated as follows. AFM tip is formed on top of n-type (100) silicon on insulator (SOI) wafer. Boron was implanted at 40keV with dose of 5×10^{14} cm^{-2} at piezoresistor region and with dose of 5×10^{15} cm^{-2} at high doping region. The PZT actuator consists of $RuO_2/PZT/Pt/Ti/SiO_2/Si$. The 500nm-thick PZT film was prepared by sol-gel method. The PZT capacitor structure was patterned using inductively coupled plasma reactive ion etching. Finally, backside silicon was selectively removed by anisotropic etching in aqueous KOH solution.

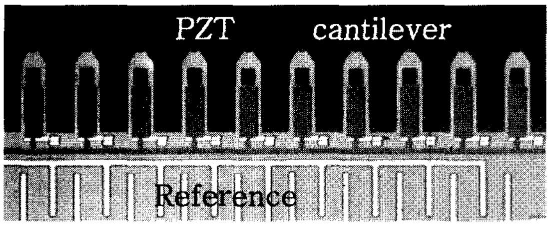
III. RESULTS AND DISCUSSION

1. *PZT cantilever for sensing*

Figure 2 (a) shows the SEM images of a fabricated PZT cantilever and the upper right side shows the enlarged picture of the tip. The actuator part and the sensing part of the cantilever are well defined. In this study, the tip is perfectly protected by novel etching technique[8)]. It is also found in Fig. 2 (b) that an array with 10 PZT cantilevers is well fabricated. Figure 3 (a), (b) shows P-E (polarization-electric field) curve and I-E (current density-electric field) characteristics of the PZT capacitor after fabrication of the PZT cantilever. The P-E curve is well saturated and is symmetrical with the remnant polarization of 18 μC/cm^2. This result shows that the PZT capacitor is not degraded during fabrication process of the PZT cantilever. The leakage current is below above 10^{-4} A/cm^2 until 600 kV/cm that corresponds to 30 V. Figure 5 shows the tip displacement of the PZT actuator as a function of applied voltage under DC bias condition. The actuator provides high tip displacement of about 0.55μm per unit applied voltage.



(a) PZT cantilever with piezoresistor for sensing

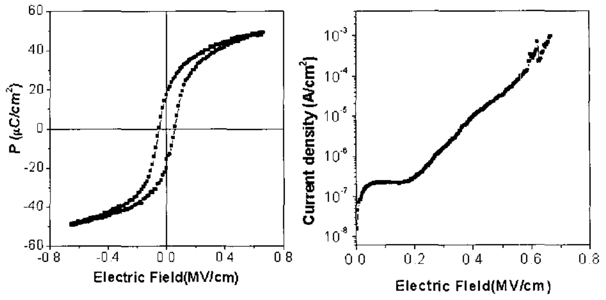


(b) PZT cantilever array

Fig. 2. SEM Image of the fabricated PZT cantilever with piezoresistor for sensing.

The actuator is well operated without breakdown until 30V and the operational range of the actuator is over 15μm. This operational range is much higher than that of the conventional atomic force microscopy. In this cantilever, the resonant frequency is found to be 73 kHz, about 100 times higher than conventional piezo-tube scanner. Therefore, a significant improvement of scan speed of AFM is expected using the PZT cantilever.

To verify major parameters that induce actuator-sensor electrical coupling at high frequency, the electrical analysis is accomplished using the simple equivalent circuit shown in Fig. 5. Figure 5 (b) shows A-A' cross section of PZT cantilever of Fig. 5 (a). C_{pzt} and C_{ov} are PZT capacitance and overlap capacitance between PZT bottom electrode and boron doped region. C_{ox} is oxide capacitance between the PZT bottom electrode and n-type silicon cantilever and C_j is junction capacitance between n-type silicon cantilever and boron doped region. This capacitor model is similar with p-type MOS transistor PSPICE model. Figure 5 (c) shows the B-B' cross section of PZT cantilever of Figure 5(a). R_{pt} , P_{piezo} and R_{p+} are resistor of PZT bottom electrode, piezoresistor and resistor of heavily doped region, respectively.



(a) Polarization Electric Field (P-E) curve.

(b) Current Density-Electric Field(I-E) curve.

Fig. 3 Electrical properties of the PZT capacitor after fabrication of the cantilever.

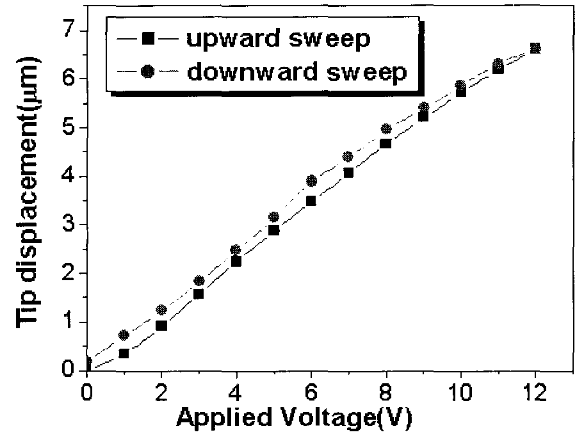


Fig. 4. Tip displacement with respect to voltage applied to the PZT cantilever.

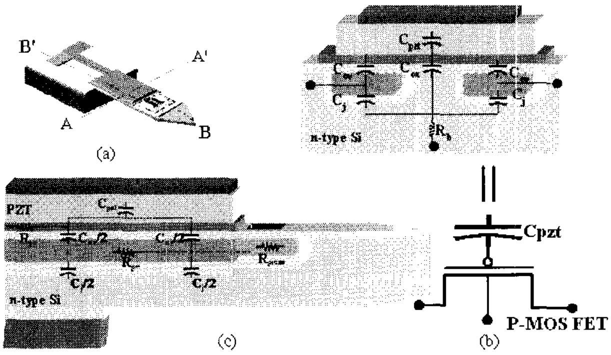


Fig. 5. (a) the PZT cantilever with an integrated piezoresistor for sensing (b) A-A cross section (c) B-B cross section.

To explore these parasitic parameter trends, the relationship between the coupling voltage and parasitic parameters is analyzed by utilizing PSPICE simulator. The actual component values for the simple equivalent circuit made from discrete components are listed in Table I. Although the resistance of PZT bottom electrode

Table 1. Component values for the simple equivalent cantilever with actuator and sensor model.

Component	Component parameter	value
R_{p+}	Resistance of p+ region	3kΩ
Cpzt	Capacitance of PZT	1.5nF
Tox	Oxide thickness	240nm
CGSO, CGDO	Overlap capacitance	1nF/m
CJ	Junction capacitance	50uF/m^2
CJSW	Side junction capacitance	50pF/m
R_{pt}	Resistance of bottom electrode	300Ω

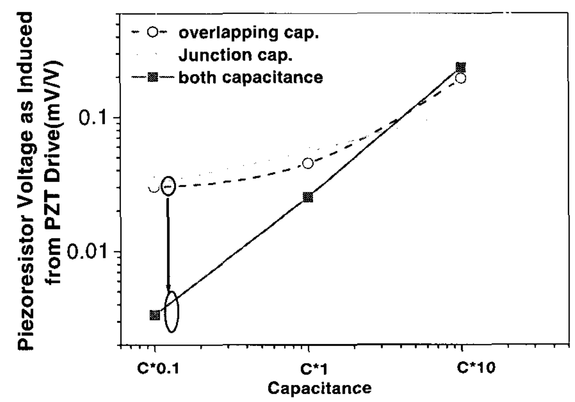


Fig. 6. Coupling voltage of piezoresistor per unit voltage applied to the PZT cantilever as a function of parasitic capacitance at 30kHz.

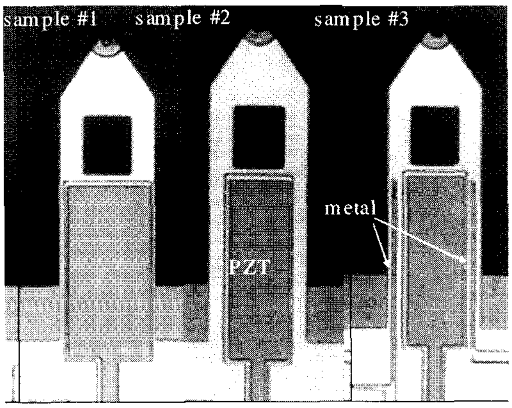


Fig. 7. Photo images of three type cantilevers to investigate the coupling voltage between PZT dirve and piezoresistor.

is major factor to decrease the coupling signal, a significant decrease of the resistance is difficult due to the limitation of bottom electrode$^{3)}$. In this simulation, the dependence of capacitances on coupling signal is investigated. Figure 6 shows that the coupling voltage is significantly reduced with the decrease of both the p-n junction capacitance (C_j) and overlap capacitance (C_{ov}). Because both capacitors are parallel connected, there are two paths of electrical coupling at PZT cantilever of Fig. 5(a). The one electrical coupling path is related with overlap capacitance, the other is related with junction capacitance. To reduce the electrical coupling voltage, both capacitances have to be reduced simultaneously. To experimentally investigate the effect of parasitic parameters on electrical coupling, three types of cantilevers are fabricated as show Fig. 7. The PZT capacitor of sample #2 is shrunk not to overlap with heavily doped piezoresistor for decreasing overlap capacitance (C_{ov}) in comparison to that of sample #1. To reduce p-n junction capacitance and overlap capacitance simultaneously, we propose the sample #3, in which heavily doped conduction line is replaced with Au/Ti metal shown in Fig. 7. Figure 8 shows the electrical coupling voltage between the piezoresistor sensor and PZT actuator as function of PZT drive frequency. The

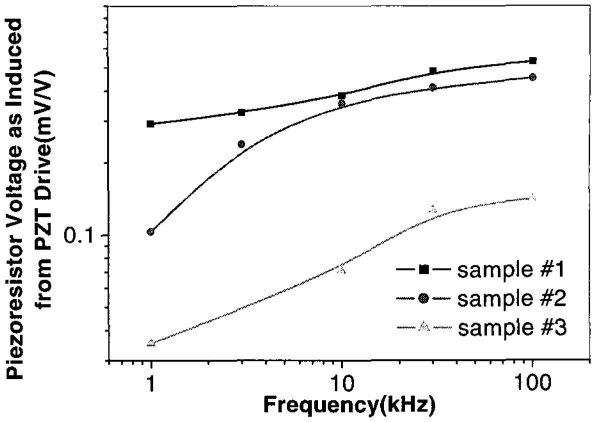


Fig. 8. Coupling voltage between the piezoresistor and PZT actuator as function of PZT drive frequency for sample #1, #2 and #3.

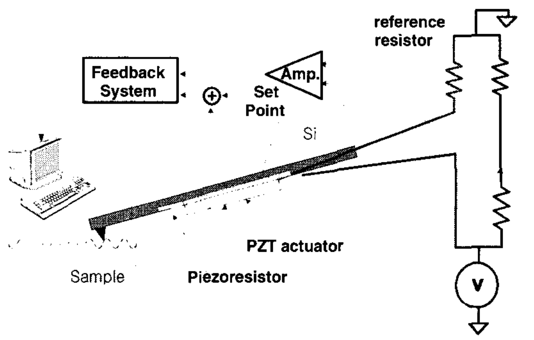
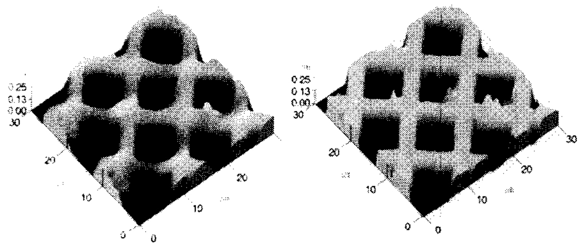


Fig. 9. Schematic diagram of AFM system using the PZT cantilever with piezoresistor for sensing.



(a) Piezo-tube (at 180μm/sec) (b) The PZT cantilever (at 1mm/sec)

Fig. 10. Comparision of AFM images.

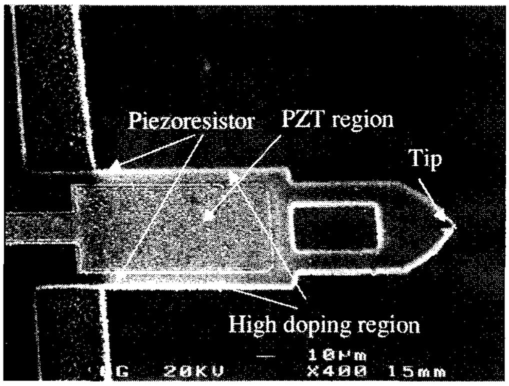
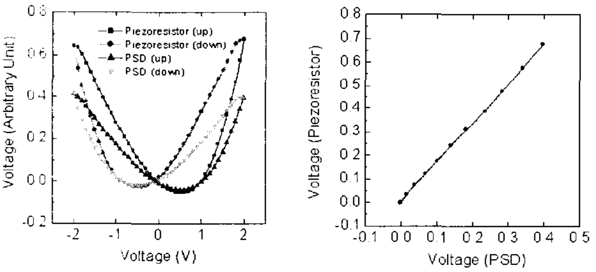


Fig. 11. SEM Image of the fabricated PZT cantilever with piezoresistor for calibration.



(a) Voltage of piezoresistor & PSD vs. PZT drive voltage (b) Voltage of piezoresistor vs. voltage of PSD

Fig. 12. Characteristics of piezoresistor for calibration.

measured coupling voltage of sample #2 is a little smaller than those of PZT cantilever with the previous structure (sample #1). The coupling voltage of sample #3 is 5 times smaller than that of the previous structure (sample #1). These results are well matched with the simulation results and show that the coupling voltage can be effectively reduced by the cantilever structure with metal interconnection line (sample #3).

Figure 9 shows the schematic drawing of AFM system using the fabricated PZT cantilever integrated with piezoresistor. The piezoresistor is placed in series with a reference resistor to form a Wheatstone bridge circuit and is used to detect the cantilever deflection caused by atomic force acting on the tip. Figure 10 shows AFM images of the standard calibration sample with 10μm period and 100 nm height, which were taken by two different operating modes. In first method, the bulk piezo-tube scanner is used for adjusting the tip in z-direction. Secondly, the self-actuating PZT cantilever is used for positioning the tip in z-direction. In case of using bulk piezo-tube scanner, the contour of the image does not look sharp. This shows that the bandwidth of the tube scanner limits the scanning speed of AFM. In case of using the self-actuating PZT cantilever, we can obtain a crisp image at high scan speed of 1mm/sec since the PZT cantilever has high resonant frequency of 73 kHz.

2. *PZT cantilever for calibration*

The PZT cantilever with pizoresistive calibration sensor of Fig. 1 (b) is well fabricated as shown in Fig. 11. The tip and the PZT actuator are well defined.

It is well known that the PZT piezoelectric actuator has nonlinear properties such as hysteresis and creep effect. These phenomena cause various distortions or errors in the topographic AFM image, which is a set of applied voltages on the z-actuator. The hysteresis causes error in the dimensional measurement near the topographic step. Also creep effect represents various image distortions which are related to the historical behavior depending on the path of the motion. The calibration performance of the integrated piezoresistor on the hysteresis of the PZT actuator is confirmed by investigating the linearity of piezoresistive calibration sensor. Generally, the output voltage of PSD (photo sensitive detector) of AFM is proportional to the deflection of AFM cantilever. Therefore, the linearity of piezoresistive calibration sensor can be investigated by comparing to PSD.

Figure 12 (a) shows the output signals of the piezoresistor and PSD with respect to the voltage applied to the PZT actuator, in which the sweep rate is 1 Hz. The PZT actuator shows the typical hysteresis of a piezoelectric material and the integrated piezoresistive sensor represents an output signal similar to that of PSD. This result explains that the voltage of the piezoresistor is proportional to that of PSD. This is also confirmed by

Fig. 12 (b) which shows the linear relationship between the voltage of the piezoresistive sensor and that of PSD, which corresponds to the deflection of the cantilever. These results show that the non-linear properties of the PZT actuator can be effectively calibrated by the integrated piezoresistive sensor.

IV. CONCLUSION

Newly designed two kinds of PZT cantilevers with piezoresistors are fabricated, and characterized to sense atomic force acting on tip and calibrate non-linear properties of the PZT actuator. The fabricated PZT cantilevers provide high tip displacement of 0.55μm/V and high resonant frequency of 73 kHz. The electrical coupling voltage is also significantly reduced by new cantilever design. The PZT cantilever shows a crisp scanned image at high scan speed of 1mm/sec. The piezoresistor for calibration represents linear relationship with respect to tip displacement. Therefore, the non-linear properties of the PZT actuator are effectively calibrated using the piezoresistive senor.

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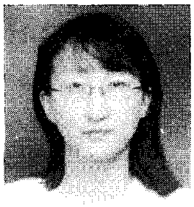

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