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PIEZOELECTRIC Pb(Zr, Ti)O_3 MICRO-DEVICES FOR SCANNING FORCE MICROSCOPY AND ULTRA-DENSITY DATA STORAGE

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In this paper we report two types of micro devices based on Pb(Zr, Ti)O_3 (PZT) thin films for improving the throughput of scanning force microscopy (SFM) or data storage using SFM. One is a piezoelectric cantilever array integrated with force sensor as well as z-actuator on each cantilever for parallel operation. The 125-μm-long PZT micro cantilever with a natural resonant frequency of 189 kHz has a high actuation sensitivity of 75 nm/V. Independent parallel images using two cantilevers of the array were obtained. The other is a novel micro-SFM device that is expected to replace the cantilever, the deflection detection unit, and the macro-fabricated scanner which is the bottle neck limiting the single probe acquisition rate. The bridge-structured device has shown a microscopy sensitivity of 0.32 nA/nm in vertical direction and actuation abilities of 70–80nm/±V in the lateral direction.

Keywords: scanning force microscopy, piezoelectric microdevice, ultra density data storage
PACC: 0779, 7760, 9365

I. INTRODUCTION

With the invention of the atomic or scanning force microscope (AFM, SFM) in 1986, the surface topography of conductive or insulated samples can be easily observed with atomic resolution. In addition to the image mode, AFM-based data storage offers an interesting alternative to current magnetic data storage because it has great potential for considerable data density improvement compared to conventional magnetic storage techniques.[1] However, there are problems to be solved before SFM can be used for practical surface lithography or data storage, in particular, its extremely low data rates. In a commercially available AFM or SFM, the deflection of the cantilever beam is obtained by external optical detection, and the samples are moved in the three directions by means of external piezoelectric stages. The data rate is limited by its large volume and complicated structure. To overcome the problems, much higher acquisition rate of a single probe or/and multi-probe parallel operation systems is required.

To elevate the acquisition rate of a single probe, the SFM structure has to be simplified. The simplification and miniaturization of SFM systems started with the introduction of force-sensing cantilevers, such as the piezoelectric type[2,3] and the piezoresistive type.[4] Because no external optical deflection detection system is needed, parallel operation, which can in principle achieve virtually unlimited data rates, can be implemented more easily in a SFM using a force-sensing cantilever. Recently, Micro electromechanical system (MEMS) technology has been used to integrate the scanning probes with actuators.[5,6,7] Akamine *et al.* reported a structure and fabrication process for a micro-scanning tunneling microscope (STM) device based on a ZnO piezoelectric actuator.[5] Xu *et al.* reported micro-fabricated micro-STMs based on an x/y comb drive actuator.[6] Lutwyche and Wada reported a micro-STM fitted into a transmission electron microscope (TEM) sample holder.[7] Sehr *et al.* reported a thermally actuated vertical bimorph scanner for integrated AFM.[8]

In this paper we present two types of micro-fabricated devices based on Pb(Zr, Ti)O_3 (PZT) thin films for improving the throughput of scanning force microscopy (SFM) or data storage using SFM. One is a piezoelectric cantilever array integrated with a force

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sensor as well as a z-actuator on each cantilever for parallel operation. Another is a novel micro-SFM device, that is expected to replace the cantilever, deflection detection unit, and the macro-fabricated scanner which is the bottle neck limiting the single probe acquisition rate.

II. PIEZOELECTRIC CANTILEVER ARRAY FOR MULTI-PROBE PARALLEL SFM OPERATION

A. Device structure and micro-fabrication

For the multi-probe parallel operation, two functions are necessary, one is self-displacement sensing or self-force sensing; the other is independent control of tip-sample spacing for each different probe. Because the optical sensor array is hard to built in and operate, and the tip-sample spacing for each different probe would not be same. Each cantilever in the array is a beam including a sol-gel derived PZT thin film that has a high piezoelectric constant in comparison with sputtered ZnO films. The cantilever is excited and actuated in z direction by applying ac and feedback dc voltages to the PZT layer. The variation of the vibration amplitude is detected by measuring the change of current flowing through the PZT layer. By actuating the self-excited cantilever to keep the current constant, an independent dynamic operation without z feedback actuation of the sample-side scanner could be realized, and independent parallel images using two cantilevers of the array could be obtained.

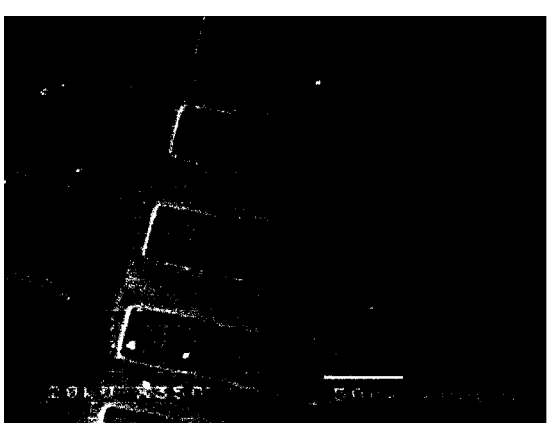


Fig.1. SEM photo of a magnified view of the piezoelectric PZT cantilever array.

A 125-μm-long PZT cantilever array has been successfully prepared by a micro-fabrication process.[9] This process uses Ar ion beam etching to pattern electrodes and PZT layer, C_3F_8/O_2 reactive ion beam etching to pattern bottom SiO_2 mechanical layer and SiO_2 passivation layer, and KOH wet etching to remove the bulk silicon beneath the cantilevers. The SEM photo of several cantilevers of the derived PZT cantilever array is shown in Fig.1. Ten free-standing PZT cantilevers and their reference patterns with same area which are located at the rear part of the same chip are formed by this micro-fabrication process.

B. Characterization of the cantilever and parallel imaging

Figure 2 shows the current outputs from the cantilever and the reference pattern versus driving frequencies. The offset value can be estimated by subtracting the current output of the reference pattern from the current output of the cantilever. This value is in good agreement with the current output from the differential amplifier, as shown in Fig.2. The current output from the differential current amplifier is the piezoelectric current output which is corresponding to the mechanical vibration amplitude. In other words, the piezoelectric current spectrum is considered to be the same as the mechanical vibration spectrum. The resonance frequency and quality factor measured in the piezoelectric current spectrum are 189kHz and 256. The successful offset cancellation of the capacitive current and resistance current from the total current going through the cantilever can be done by using a differential current amplifier to record the outputs from the cantilever and reference pattern.

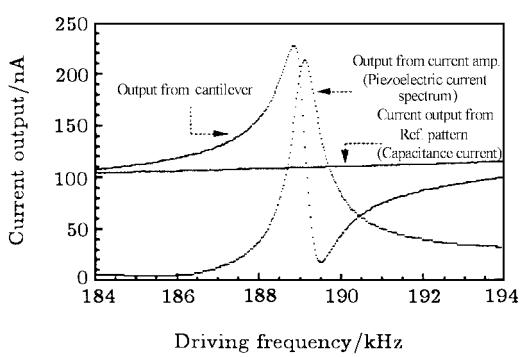


Fig.2. The current output from the PZT cantilever and its reference pattern. The piezoelectric current output spectrum can be recorded from the output of the differential current amplifier.

In the operation of the cyclic contact mode, the cantilevers in the array are self-excited near their resonance frequencies by applying an ac voltage to each of them, while the x-y-scanning is executed by the

tube scanner. Different dc bias voltages can be applied to individual cantilevers in order to make the initial height for each cantilever the same. As shown in Fig.3, the variation of the vibration amplitude of each cantilever according to the topography is individually detected by measuring the change of the current output from the differential current amplifier. Then different dc feedback voltages are individually applied to the cantilevers to keep the individual current output for each cantilever at the same initial value. This means that the z-directional displacement is feedback actuated by the cantilever itself instead of a scanner. And these parallel feedback signals are taken as the parallel traces of each relative cantilever end, i.e., the parallel images.

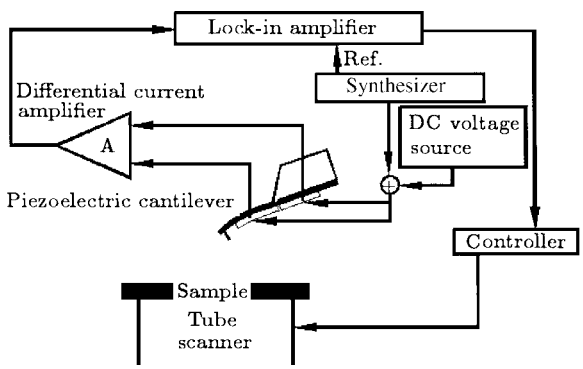


Fig.3. The block diagram of a multiprobe SFM using the self-excited force sensing PZT cantilever array.

Figure 4 shows the dependence of the piezoelectric current output of one PZT cantilever in the array versus the displacement of the cantilever end. In other words, the displacement of the cantilever end equals the sample displacement when the feedback z-directional actuation is performed by the scanner. This curve is the so-called force curve for SFM in cyclic contact mode. The vertical resolution can be estimated as 0.1nm at the bandwidth of 125Hz. It may be attributed to the fact that the unwanted noise signals from the surrounding has been offset-canceled as well by using differential amplifier to record the signals from the reference-cantilever structure.

The z-directional feedback actuation ability can be derived from measuring the shift of intersecting point for the force curve changing from the cyclic contact region to static contact region, when various superimposed dc voltages are added on a vibrating cantilever which is excited by an 25mV ac voltage. The linear actuation fitting line is observed in this range and the actuation ability is 75nm/V, as shown in Fig.5.

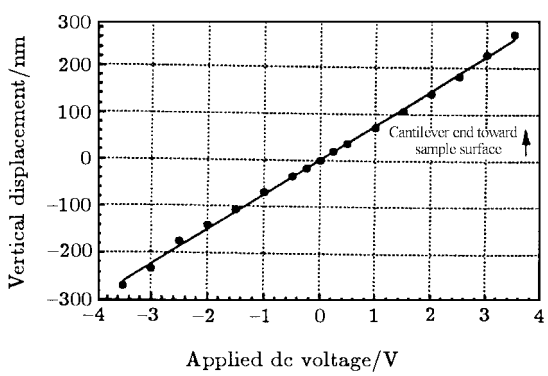


Fig.5. The applied dc voltage dependence of the displacement of a 125μm cantilever end showing the actuating ability of the cantilever to be about 75nm/V.

The parallel cyclic contact images of the topography of 1-μm pitch gold film coated grating obtained by the multi-probe SFM using two cantilevers of the cantilever array are demonstrated in Fig.6, the parallel images being taken simultaneously in the constant height mode.

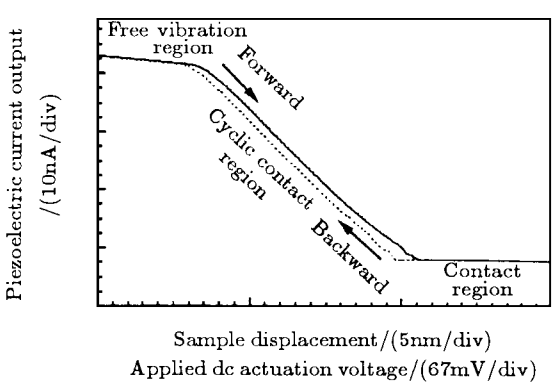


Fig.4. The cyclic contact force curve, i.e., piezoelectric current output vs z-directional actuated displacement of cantilever end. This curve is recorded by one cantilever of an array when the excitation voltage is 37mV.

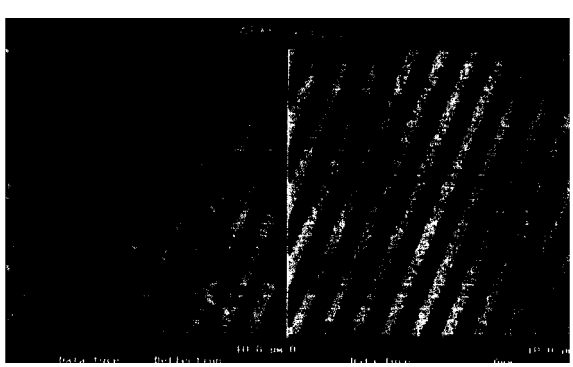


Fig.6. Parallel cyclic contact images of a 1.0-μm-pitch gold coated SiO_2 grating simultaneously obtained by a multiprobe SFM using two PZT cantilevers in a 10x1 array.

Ⅲ. A NOVEL MULTI-BRIDGE STRUCTURED MICRO-SFM DEVICE

A. Structure design

Our target is to develop a device to replace the cantilever (force sensor), the cantilever deflection detection unit and the macro-fabricated scanner currently being used, by a micro-fabricated thin film structure. For this purpose, a PZT bimorph structure in the shape of a cantilever supported by bridges was designed. The schematic drawing of the device is shown in Fig.7(a). To actuate the tip located at the free end of the cantilever in three dimensions, the outer electrode layers of each bimorph lever are longitudinally divided into two sections, and then independent electric potential can be applied to the PZT sections. If the same potential is applied to the two upper sections of the cantilever and the opposite potential is applied to the two lower sections, deflection occurs in the z direction. Similarly, deflection occurs in y direction when a same potential is applied to the two left sections and the opposite potential is applied to the two right sections of the cantilever. The deflection in the x direction is due to the bending of the bridges in the middle.

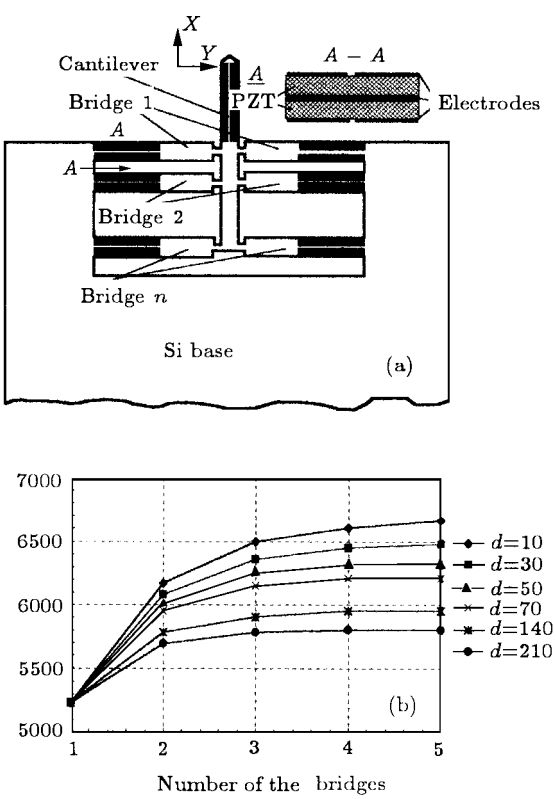


Fig.7. (a) Schematic drawing of a multibridged piezoelectric micro-SFM. (b) Effect of the bridge number on the resonance frequency. d is the distance between cantilever.

The theoretical response of the piezoelectric cantilever is calculated by considering the bending moment associated with the longitudinal piezoelectric strain induced in the piezoelectric sections as bias voltages are applied to the electrodes of the sections. The deflection of the bridges (δ_x), which is at its maximum when the electrodes cover half of the bridge levers, is given by $\delta_x = M_{\rm p}L_{\rm b}^2/(8K_{\rm f})$, where $M_{\rm p}$, $L_{\rm b}$ and $K_{\rm f}$ are the piezoelectric bending moment, the length of the bridge lever, and the flexural rigidity to bending in the x direction, respectively. On the other hand, in the case of the cantilever part, if the bending moment $M_{\rm p}$ is generated throughout the whole length $L_{\rm c}$ of the cantilever and flexural rigidity is $K_{\rm f}$, the deflection δ_y is given by $\delta_y = M_{\rm p}L_{\rm c}^2/(2K_{\rm f})$. The y deflection of the cantilever and the x deflection of the bridge are the same if $L_{\rm b}$=2$L_{\rm c}$. We use this ratio for the multibridge bimorph device, so that the scanning ranges in x and y directions are equal. PZT films prepared by the sol-gel method are used as the piezoelectric layers in the designed device, which are sandwiched by Pt/Ti films as the electrodes. The d_{31} of the PZT films is reported to be about –93fC/N, which is about 20 times higher than that of ZnO. The 3-μm-thick PZT can be safely used with 10 volts applied across them. The length of the cantilever is 500μm and that of the bridge levers is 1000μm. The widths of the cantilever and the bridge are 70μm. Substituting the above data, we obtained the scanning range in both x and y directions of about 3μm. The ANSYS simulation results for the bending of the bridges and the cantilever agree with the above calculations.

The changes of the resonant frequencies according to the number of bridges were analyzed using ANSYS software. Figure 7(b) shows the change with the number of bridges. We found that the resonance frequency increased by about 30% when the number of bridges increased from 1 to 6. However, no great improvement appeared when the number was greater than 6. Thus we designed the number of bridges to be 6. For comparison, we also fabricated a device with 1 bridge, which possesses the same actuation sensitivities but lower resonance frequency compared with the multibridged structure.

B. Microfabrication processes

The microfabrication processes begin with thermal oxidation of a (100) Si wafer on both sides. The SiO_2 on the back of the wafer is then partly etched by reactive ion etching (RIE) to form masks for bulk

Si etching in a KOH solution. A 0.3-μm-thick Pt/Ti film is then deposited on the front side by RF magnetron sputtering, and is then patterned by electron cyclotron resonance (ECR) etching to form the bottom electrode. The sample is then coated with a 3-μm-thick layer of PZT and a 0.2-μm-thick Pt/Ti film by a modified sol-gel method and RF magnetron sputtering, respectively. ECR dry etching is then employed to shape the middle electrodes and the first piezoelectric layer. The second PZT and top electrode (Au/Cr) layers are then coated by the sol-gel process and evaporation, and patterned by ECR etching. Then, a Si_3N_4 layer is coated and patterned as the passivation layer for all electrodes. Au/Cr film is then deposited by evaporation onto the surface and patterned by ECR as the bonding pads of all electrodes. In order to remove the Si bulk below the device, anisotropic etching in KOH solution is employed until the Si membranes are thinner than 30μm at the opening. Finally, RIE dry etching in SF_6 and O_2 is employed to remove the Si membranes from the back

In the microfabrication process, the preparation of the PZT films is the most critical step.[10] We modified the sol-gel process from the precursor preparation to the annealing sequence, so that we can coat a PZT film more than 23 times to achieve a thickness of above 3μm. The precursor solution was prepared from $Pb(CH_3COO)_2$, $Zr(C_3H_7O)_4$ and $Ti((CH_3)_2CHO)_4$. A solution with nominal excess 15% mol Pb was prepared with a Zr/Ti ratio of 53/47. The final concentration of the solution was adjusted to 0.4M $Pb_x(Zr_{0.53}Ti_{0.47})O_3$ by the addition of 2-propanal. The PZT films were fabricated onto $Pt(111)/Ti/SiO_2/Si$ substrates using a spin coater operated at 2700rpm for 20s and 400rpm for 40s. The substrate was prepared by sputtering 0.05μm of titanium onto the thermally oxidized silicon wafer, followed by 0.25μm of platinum. The coated wet PZT films were dried at 120°C for 10min, 300°C for 30min and finally at 600°C for 30min. These steps were repeated until the desired thickness was obtained.

C. Experimental results and discussion

The phase and crystal orientations of the derived PZT films were checked with an X-ray diffractometer (XRD, Rigaku RINT2000). X-ray diffraction patterns revealed that the film consists only of the perovskite phase and exhibits a preferred orientation in the (100) direction. The P-E hysteresis loop of the films was measured using a standard ferroelectric test system (Radiant Technologies, RT-60A) that employs the principle of the Sawyer-Tower circuit. The ferroelectric parameters were as follows: saturation polarization P_s=34.7μC/cm^2, remnant polarization P_r=15.1μC/cm^2, and coercive field E_c=37.1kV/cm. The effective longitudinal piezoelectric coefficient (d_{33}) of the PZT films is detected using laboratory-built equipment based on the piezoelectric AFM cantilever. The d_{33} of the sol-gel-derived PZT film is measured as 0.09nm/V.

The prototypes of devices with a single bridge as well as six bridges have been successfully fabricated. Figure 8 shows a SEM micrograph of a prototype micro-SFM device with six bridges. The piezoelectric

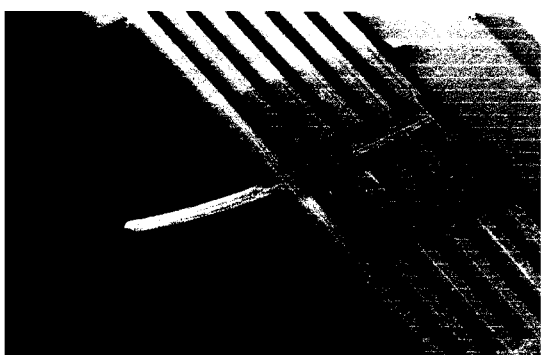


Fig.8. SEM micrograph of the 6-bridge micro-SFM.

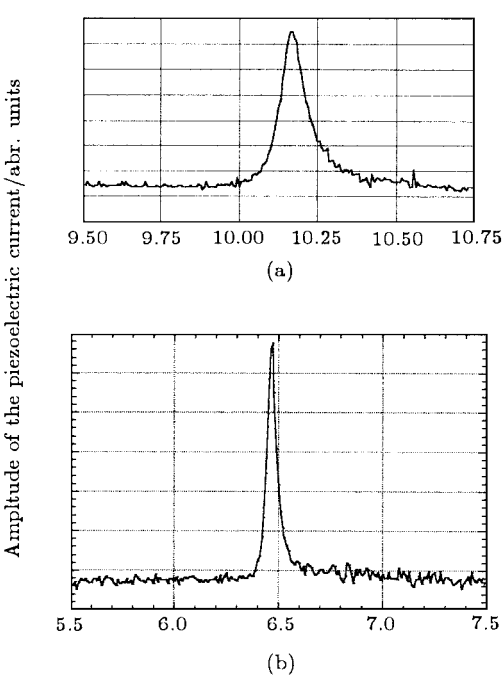


Fig.9. Q-curves of piezoelectric currents flowing through the cantilever in the micro-SFM device: (a) 6-bridge device, and (b) 1-bridge device.

output of the cantilever as the force sensor was detected with a differential preamplifier and a lock-in amplifier. In order to excite the cantilever to vibrate in z direction and obtain pure piezoelectric charge current, we applied an ac driving signal to a PZT section in the upper layer and a section in the lower layer of the cantilever, and conducted the two currents into the differential amplifier. In this way, we can offset the capacitance currents because the two sections have the same area and thickness, and obtained pure piezoelectric current with high S/N ratio. The piezoelectric currents and Q (quality factor) curves are shown in Fig.9, in which (a) was collected from a 1-bridge device and (b) from the 6-bridge device. When scanning the frequency to record these curves, the amplitude of the driving voltage was kept constant. From the curves, the 1^{st}-order resonant frequencies and Q-values are measured as 6.4kHz and 92 for the 1-bridge device, and 10.2kHz and 114 for the 6-bridge device. In order to test the force sensing and actuation abilities, we installed a 1-bridge device in a commercial SFM system. The driving frequency is set at the 1^{st}-order resonant frequency of the device. The amplitude of the piezoelectric current traveling through the cantilever, which is proportional to the cantilever vibration amplitude, is used as the DSFM (dynamic scanning force microscopy) signal. From a force curve collected with the micro SFM device in cyclic contact mode, the microscopy sensitivity in the vertical direction is measured to be 0.32nA/nm. The actuation abilities in the x and y directions were tested by applying dc electric potential to the device during the scanning of a sample under the self-sensing mode SFM, and observing the image shifts. Figure 10 shows the obtained SFM images. Figure 10(a) is the image obtained when no actuation voltage is applied. Figure 10(b) is the image obtained when an actuation voltage of ± 9.6 V was applied in the x direction. Figure 10(c) is the image obtained when an actuation voltage of ± 9.6V was applied in the y direction. The actuation sensitivities are estimated to be around 83nm/$\pm$V in the y direction and 73nm/$\pm$V in the x direction.

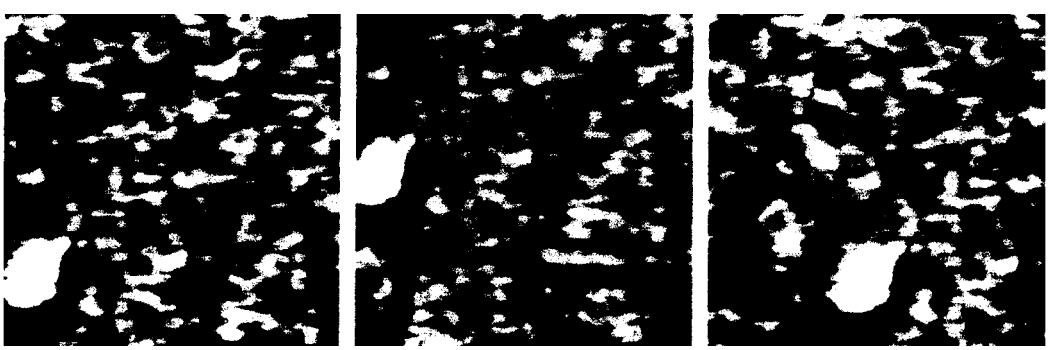


Fig.10. Shift of the SFM image when actuating voltages are applied to actuate the tip in x and y directions.

IV. CONCLUSION

The micro-machined piezoelectric PZT cantilever array and a multi-bridge structured micro-SFM device have been successfully developed. Each cantilever of the array has good and similar electromechanical properties. The operation of the multi-probe SFM using this cantilever array has been developed and clear parallel images have been taken by the multi-probe SFM. The developed micro-SFM device was shown to possess microscopy sensitivity of 0.32nA/nm in vertical direction, with actuation sensitivities of 70–80nm/V in the lateral direction. The multibridged structure was proved to be effective in elevating the eigenfrequency, which is very important for improving the SPM data rate.

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