FABRICATION OF PIEZOELECTRICALLY DRIVEN MICRO-CANTILEVER USING $Pb(Zr,Ti)O_3$ FILMS

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Abstract - Piezoelectrically driven micro-cantilevers using $Pb(Zr,Ti)O_3$ (PZT) films have been successfully fabricated by bulk micro-machining. PZT thin films were made by sol-gel process using a 1-3 propanediol and modified alkoxide precursors. The cantilever structures consist of piezoelectric PZT capacitors fabricated on a low stress SiN_x supporting layer. Flat micro-cantilever has been obtained by controlling the stress in Pt electrode and PZT layers. The dielectric constant and loss of the PZT thin films in the cantilever structure were 1000 and 2 % at 100 kHz, respectively. The remanent polarization was 20 $\mu C/cm^2$. The micro-cantilever had a dc response of 84 nm/V. The micro-cantilevers had a resonant frequency of 19.5 kHz and the corresponding displacement of 2.97 μm at the applied bias of 1 V.

INTRODUCTION

Recently, micro-electro-mechanical system (MEMS) devices employing a piezoelectric PZT thin film have been studied for micro-mechanical sensor and/or actuator applications [1-3]. Most piezoelectrically driven MEMS devices have been fabricated in the form of a micro-cantilever, in which the vertical displacement (bending) was actuated by a piezoelectric layer. This actuation (or sensing) mode has been applied to scanning probe microscopes and IR detectors, etc.

For the vertical displacement, transversal piezoelectric mode (i.e., d_{31}) is utilized in a unimorph cantilever structure. In other words, a piezoelectric layer exhibits a displacement along the in-plane direction upon applying an electric field to the piezoelectric layer in the vertical direction.

Several piezoelectric materials have been employed for the micro-cantilevers. Minne et al. have fabricated piezoelectric ZnO micro-cantilevers which have a dc response of 15 nm/V [4]. AlN has also been used for the micro-cantilevers. Micro-cantilevers with sputtered PZT films have been fabricated and exhibited a dc response of 50 nm/V [2,5].

Among these piezoelectric materials, PZT materials have advantages over other piezoelectric materials since PZT has superior piezoelectric properties to the other materials. For example, d_{31} of PZT is higher by 50 times than that of ZnO [2,6]. Moreover, the piezoelectric properties of PZT material can be tailored by varying the ratio of Zr/Ti.

In this study, we have integrated PZT thin films into the micro-cantilever which has the low stress SiN_x as a supporting layer for the unimorph structure. We report the fabrication of the micro-cantilevers and electro-mechanical characteristics.

EXPERIMENTS

Piezoelectric PZT layers have been fabricated by sol-gel process. For the sol-gel process, PZT precursor solutions were prepared from lead acetate trihydrate $[Pb(CH_3COO)_2 \cdot 3H_2O]$, titanium diisopropoxide bis $[CH_3COCHCOCH_3]_2Ti[OCH(CH_3)_2]_2$, and zirconium (IV) n-propoxide $[Zr(OCH_2CH_2CH_3)_4]$ with 1-3 propanediol as a solvent [7]. It is well known that the deposition of PZT films at elevated temperatures causes the loss of a lead component [8]. The PZT precursor solution with 10 % excess Pb was made in order to compensate Pb loss during crystallization.

Electrode was deposited by DC magnetron sputtering. The bottom electrode (BE) was deposited at various substrate temperatures from room temperature to 350 °C in order to have the enhanced adhesion of the electrode to the substrate. The top electrode (TE) was deposited at room temperature.

PZT thin films were coated using the modified

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precursors by sol-gel methods. The thickness of the PZT films was 500 nm.

The dielectric properties and polarization-electric field hysteresis loop (P-E) were measured using a HP4194A impedance analyzer and Radiant Technologies testing system (RT66A), respectively. The displacement characteristics of the micro-cantilever were examined using laser doppler vibrometers (LDV) including optical instruments for accurate measurement of the displacement of a vibrating micro-actuator. All these measurements were carried out at room temperature.

FABRICATION

Fig. 1 shows fabrication steps of the micro-cantilever. A flat cantilever is important so as to utilize into a micro-electronic device. Supporting layer (SiN_x) for the cantilever has been prepared to have low residual stress for a flat cantilever. Low-stress silicon nitride (SiN_x) and low-temperature oxide was deposited on silicon by low-pressure chemical vapor deposition (LPCVD). For the deposition of the low stress SiN_x layer, dichlorosilane and ammonia were used at the flow rate of 6:1. Low stress (57 MPa) SiN_x layer has been obtained at 850 °C. The thickness of SiN_x was 1.2 μm. Subsequently, low temperature oxide (LTO) with a thickness of 200 nm was deposited at 400 °C. Then, metallic layers, Pt and Ti, were deposited using DC magnetron sputtering technique on the LTO/SiN_x layer (Fig. 1-(a)). Ti buffer layer was sputtered at room-temperature, and Pt electrode was deposited at 350 °C. The thickness of Pt bottom electrodes (BE) was about 150 nm. The next procedure was the deposition of PZT thin film and the top electrode (Fig. 1-(b)). The precursor solution of PZT was coated on the platinized silicon substrate by spin coating at 3000 rpm for 30 seconds, followed by drying at 300 °C for 1 min on hot-plate. Multiple coating was performed to increase the thickness of PZT thin films. These PZT thin films were crystallized by post-annealing at 700 °C for 5 min in a pure oxygen atmosphere using conventional tube furnace. After the deposition of the PZT layer, the Pt top electrode was defined on PZT/Pt/Ti/LTO/SiN_x/Si by photo-lithography and lift-off (Fig. 1-(c)). The thickness of the top electrode was about 70 nm. After the patterning of the top electrode, the etching of the PZT thin film and the bottom electrode was performed (Fig. 1-(d)) with inductively coupled plasma (ICP) etcher systems. A 500 nm thick PZT layer has been etched out using ICP at a plasma power of 600 W with a gas mixture of 50 % BCl and 50 % Ar. 1.2 μm thick photo-resist (PR) film was used as a mask. The bottom electrode (Pt/Ti) was etched

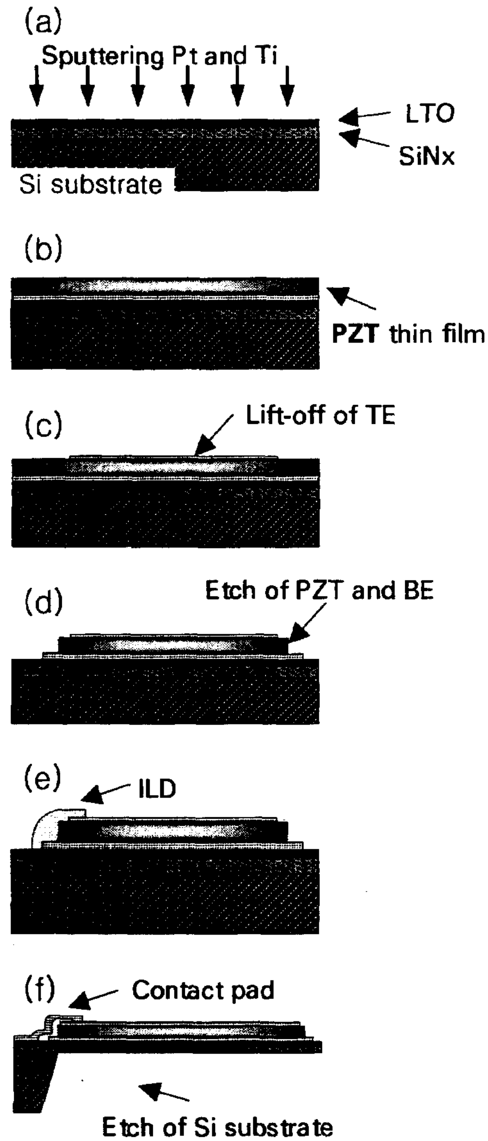

Figure 1. Cantilever fabrication procedure

at plasma power of 600 W and with a gas mixture of a 10 % HCl and 90 % Ar. During the etching process of the bottom electrode, sputtered Pt was re-deposited on the PR mask, resulting in the fence along the side of bottom electrode. The fence was higher than the PZT layer. As a result, the PZT capacitor failed due to short circuit between the top and bottom electrodes. However, we could remove the fence by using the relative thin PR and appropriate PR baking.

The deposition and patterning of inter-layer dielectric (ILD) was carried out (Fig. 1-(e)). In order to drive a displacement in a PZT thin film, we have to apply a bias into the top-electrode. For the isolation between the top and bottom electrodes, we incorporated ILD between the top and bottom electrodes. SiO_2 with the thickness of 200 nm was used for ILD. ILD was deposited by e-beam evaporation. Magnetically enhanced inductively coupled plasma (MEICP) etching was used to pattern the ILD. The ILD was etched with CF_4 gas. In this case, the whole body of the cantilever except the ILD covered by the PR mask was exposed to plasma during the etching process. However, there was no damage from plasma in the properties of PZT thin films. The contact pad was defined using a lift-off process (Fig. 1-(f)) after the deposition of 80 nm thick Pt by DC magnetron sputtering.

The back side of the silicon substrate and the supporting layer, SiN_x, were etched. In order to etch out the back side silicon, we first have defined the pattern for back side silicon by MEICP etching. The mask used for back side silicon etching was a SiN_x layer because the etching selectivity of SiN_x and Si was significantly high. Then the back side silicon substrate was wet etched with a KOH solution at the temperature of 110 °C. The bare silicon was attached to the front side of the cantilever with a crystal wax in order to protect the electrodes and the PZT layer during the etching of silicon. Finally, a cantilever arm, SiN_x, was defined with a 6.2 μm thick PR mask and etched out by MEICP etching. Fig. 1-(f) shows the side view of the piezoelectrically driven micro-cantilever.

RESULTS AND DISCUSSION

Fig. 2 shows the variation of a hysteresis loop as the fabrication procedure proceeds. P-E hysteresis loop of the PZT thin film in the cantilever structure was measured after each process. The significant variation of the polarization and coercive field in the hysteresis loops was not observed. This means that there are no plasma etching damages.

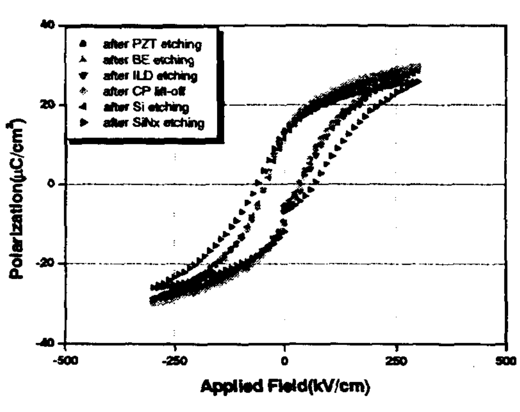

Figure 2. Variation of hysteresis loop with fabrication procedure

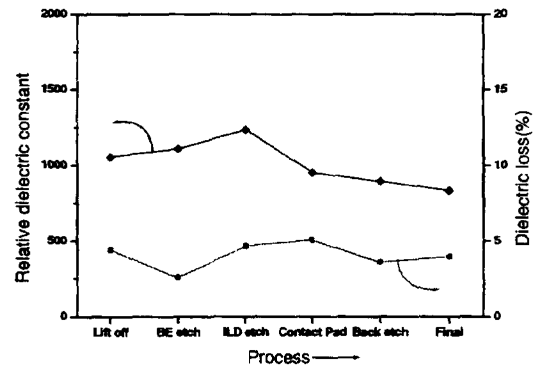

Figure 3. Variation of the dielectric constant and dielectric loss with fabrication procedure

Fig. 3 shows the variation of dielectric constant and dielectric loss measured with the procedure. All these capacitance and loss have been measured by a small signal of 100 kHz and 0.01 V ac. Fig. 3 also shows that the PZT thin film suffered no plasma damage with the process such as the dry etching of PZT, bottom electrode, ILD, and SiN_x. A small decrease of dielectric constant has been observed with the procedure, as shown in Fig. 3. However, we fabricated a micro-cantilever without severe variation of the dielectric constant of the PZT thin film in the micro-cantilever.

Fig. 4 shows the SEM image of the micro-cantilevers fabricated with the procedure described above. Fig. 4-(a)

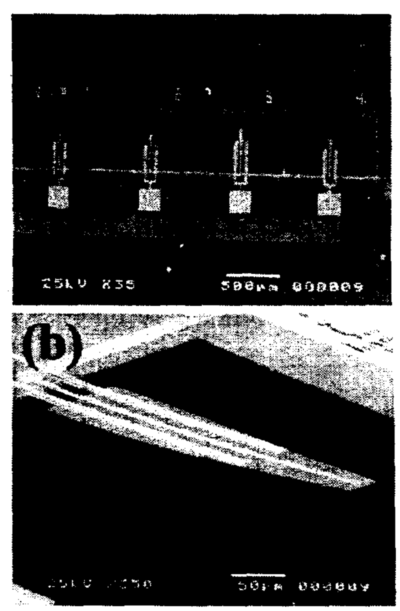

Figure 4. SEM image of (a) the cantilever array and (b) a cantilever in the array

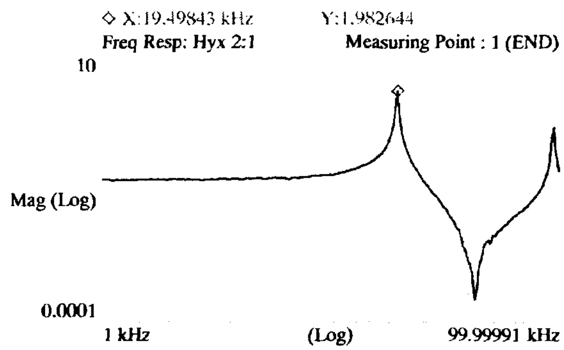

Figure 5. Displacement of the micro-cantilever as a function of vibrating frequency

shows the top view of the array consisting of four cantilevers with different dimensions. Fig. 4-(b) is one of the cantilevers. The micro-cantilever with the piezoelectric PZT thin film showed a bending less than 2°.

Fig. 5 illustrates electro-mechanical characteristic, i.e., the displacement at the applied bias voltage of 1 V as a function of frequency. The displacement was measured at the end of the micro-cantilever. The micro-cantilevers had a dc response of 84 nm/V. The micro-cantilever has a resonant frequency of 19.5 kHz and the corresponding displacement of 2.97 μm at the resonance at the applied voltage of 1 V.

CONCLUSIONS

Diol-based $Pb(Zr_{0.52}Ti_{0.48})O_3$(PZT) thin films were prepared on platinized LTO/SiN_x/Si substrates by sol-gel method. PZT thin films were made using a 1-3 propanediol based precursor solution. The micro-cantilever consists of a low stress SiN_x, LTO, the bottom electrode (Pt/Ti), PZT, the top electrode, ILD and contact pad. The PZT and the bottom electrode (Pt/Ti) were etched by ICP, while ILD, LTO and SiN_x were etched by MEICP. The Pt fence occurred after the Pt etching was removed by selecting an appropriate PR mask and modifying the bake condition of the PR mask. We have found serious hydrogen damage during the deposition of ILD by plasma enhanced chemical vapor deposition (PECVD). However, no damage on the electrical properties of the PZT layer was found when the ILD layer was deposited by electron beam evaporation. Therefore, we have no serious plasma and hydrogen damages from the deposition and etching. Finally, we have successfully fabricated the flat micro-cantilevers with the PZT layer, i.e., Pt/PZT/Pt/Ti/LTO/SiN_x/Si. The dielectric constant and dielectric loss of the PZT thin films in the micro-cantilevers were 1000 and 2 % at 100 kHz, respectively. The remanent polarization and coercive field were 20 $\mu C/cm^2$ and 41 kV/cm, respectively. The micro-cantilevers had a dc response of 84 nm/V. These micro-cantilevers also had a resonant frequency of 20 kHz and the corresponding displacement was 2.97 μm.

ACKNOWLEDGEMENTS

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