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PZT Thin Film Bi-Layer Devices for Phase Controlled Actuation in MEMS

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Abstract. A potential application for ferroelectric thin films is micro positioning and actuation. For using PZT films as micro-actuators it is desirable to have film thicknesses of comparable size to the underlying structure. The amount of actuation possible is determined by a number of factors: the piezoelectric coefficient d_{31}, geometric factors and the compliance of both the actuator and cantilever and the electric field across the film. Using a bi-layer should therefore increase the amount of actuation for a given drive voltage. Bi-layer devices can also be driven at constant voltage, and their actuation varied by the phase difference of the drive voltage between the two layers. PZT films of thickness 0.5 μm have been deposited as a bi-layer. Micro-actuators have been fabricated using these structures, their electric properties measured and their electro-mechanical properties characterised and evaluated using optical beam deflection.

Keywords: MEMS, piezoelectric thin films, actuators

1. Introduction

Ceramic piezoelectric devices such as lead zirconate titanate (PZT) are extremely important materials in mechatronics and MEMS applications. In its bulk form PZT is not readily amenable for integration into silicon micro-mechanical devices. However PZT thin films are extremely promising as electro-mechanical elements for use with micro-mechanical structures. PZT is a polar dielectric, which exhibits a high degree of piezoelectric activity. PZT can be deposited by a number of processing routes onto silicon devices. The most common deposition methods are sputtering [1], sol-gel [2], organometallic chemical vapour deposition [3] and laser ablation [4]. Applications in the area of mechatronics [5] include: micro-optics [6–8], linear stepper motors [9], scanning mirror drives [10], microsurgery [11, 12] and scanning force microscopy [13].

To date, there appears to have been very little work carried out with thin film multi-layer devices. Bulk ceramic multi-layer actuators have been modelled by Desmare [14], and this work has considered layers connected in series and parallel and with varying numbers of both active and passive layers. Similar structures have also been characterised by Pertsch [15], but in terms of different material properties; such as hard or soft ferroelectrics. Gaucher [16] has investigated and modelled the potential of PZ-PT and PMN-PT thick and thin film for integrated micro-systems. However work on PZT thin film multi-layers has been mainly directed towards capacitors [17] and tuneable microwave devices [18].

We have previously used PZT films of <110> preferred orientation for micro-actuators [19]. The functionality of piezoelectric actuators is affected by poling conditions: time, field and temperature. However, for PZT thin films the breakdown voltage and coercive fields are considerably higher than for bulk PZT [20], the breakdown voltage and coercive fields being of the order 200–400 kVcm-1 and 50–100 kVcm-1 respectively. Because of the higher breakdown potential, thin films can be driven considerably harder, although the actuation field should not be large compared to the coercive field for reliable operation. In order to maximise actuation the ac drive field requires a dc field to be superimposed to maintain good polarisation within the film, however if the application of a dc bias field is not appropriate then Ti-rich PZT composition is required, as they exhibit a much larger coercive field. In bulk PZT applications, the amount of actuation available with a cantilever can be significantly increased, for the same applied field, by changing from a unimorph configuration to a bimorph configuration. A bimorph cantilever consists of two PZT layers, and for maximum actuation one layer is driven 180° out of phase with respect to the other. In order to compare the actuation the two layers are driven with variable phase—0° to 180°. In all cases the films were poled at room temperature.

2. Device Fabrication

PZT thin films, with a (Zr/Ti) ratio of 54/46, were prepared on platinised <100> oriented Si substrates of thickness 100 μm by r.f. magnetron sputtering. The deposition system has been described previously [21]. Lift-off processes, chosen for ease of implementation, formed the platinum top and middle electrodes and PZT layers. In the case of PZT, it is difficult to pattern the film by wet etching. Therefore dry etching such as ion beam sputtering can be chosen for the patterning of the piezoelectric layer. In this last case the end etching control must be done on very thin platinum and a possible total etch of this layer could lose the electrode. To realise fabrication of this structure a five-level masking system was required. The substrate temperature was controlled during PZT deposition: the temperature at the photoresist surface does not exceed 90°C to avoid lift-off problems. The platinum top, middle and bottom electrodes have a thickness of 0.1 μm approximately. The middle and top electrodes surface are 3 mm^2 and 1 mm^2 respectively. The upper and lower PZT layers have thicknesses of 0.8 μm and 0.4 μm respectively. After each sputtering deposition, the platinum and PZT layers are annealed. The platinum annealing was realised at 500°C for contact formation. The post-deposition PZT annealing (tubular furnace in air) is required to achieve a well-crystallised perovskite structure. Figure 1 shows the XRD pattern of the PZT film, showing that the film is highly orientated in the <110> direction. Both layers exhibit this orientation, and are in agreement with results obtained for a PZT mono-layer.

The SEM image confirms that the two PZT films have a different thickness (Fig. 2). The second (upper) layer has a thickness twice that of the first. The microstructure of the layers show that the thin PZT films are formed with large grain sizes (average dimension around a micron). Although the second layer has not been grown on platinum on SiO$_2$, its growth is identical to the first layer.

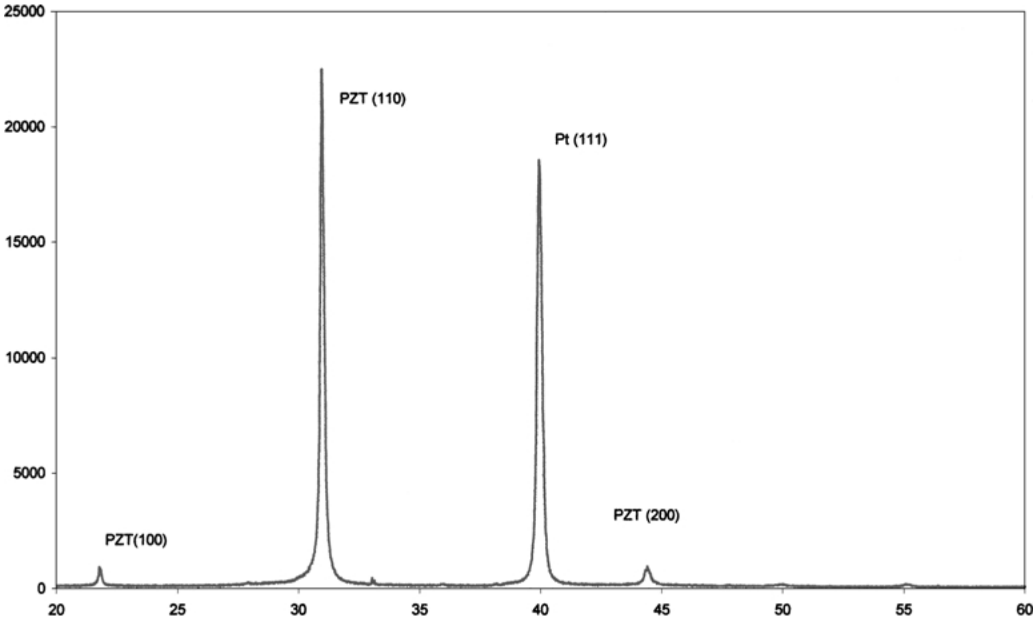

Fig. 1. XRD pattern of <110> orientated PZT film.

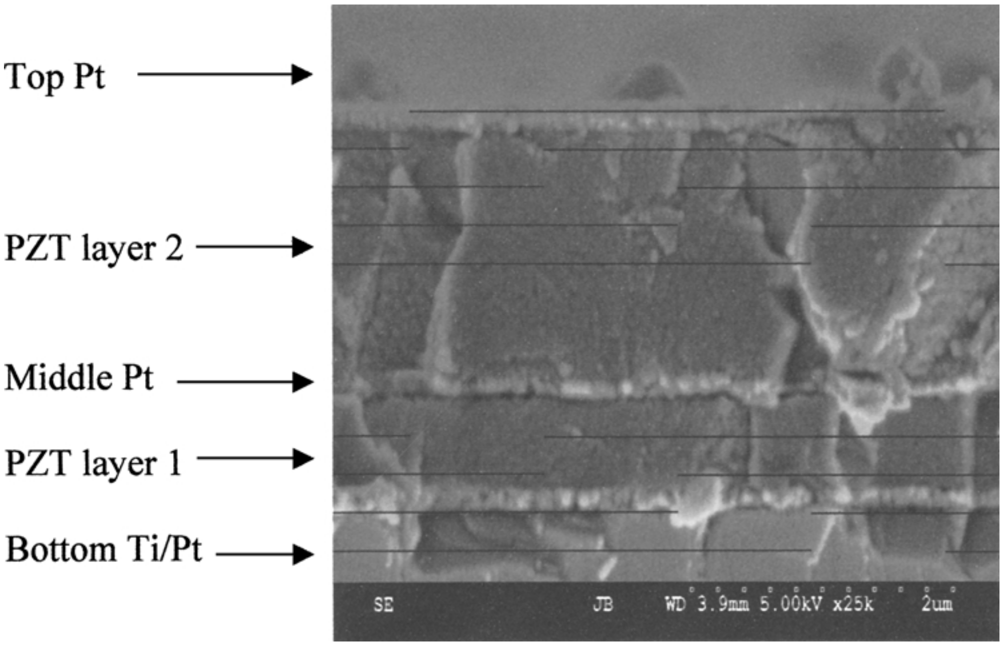

Fig. 2. SEM image of PZT bi-layers.

3. PZT Film Characterisation

Ferroelectric hysteresis measurements were made using the RT6000. Capacitance and loss were measured using a Hewlett Packard 4192 A multi-frequency LCR meter at a frequency of 1 kHz. The permittivity and losses measured on the two PZT thin films are of the same order magnitude to that obtained for a mono-layer. The presence of the first PZT layer does not affect the dielectric quality of the second layer. Hysteresis loops were measured on the first and second PZT layer between the bottom electrode and the intermediate electrode and between the intermediate electrode and between the intermediate electrode and the top electrode respectively. The coercive fields and remnant polarisation have been found, as shown in Figs. 3

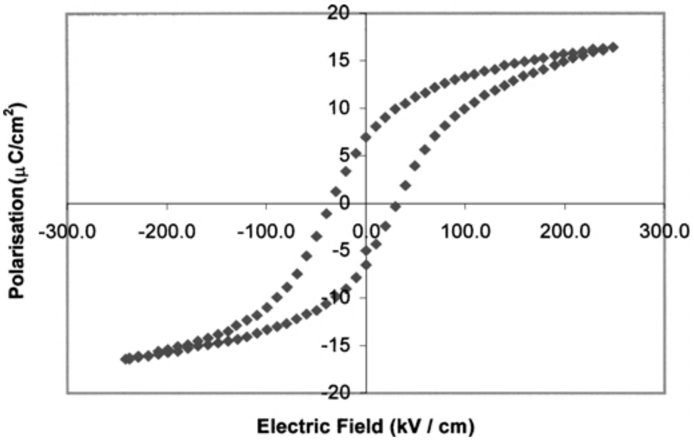

Fig. 3. Hysteresis loop for upper PZT layer.

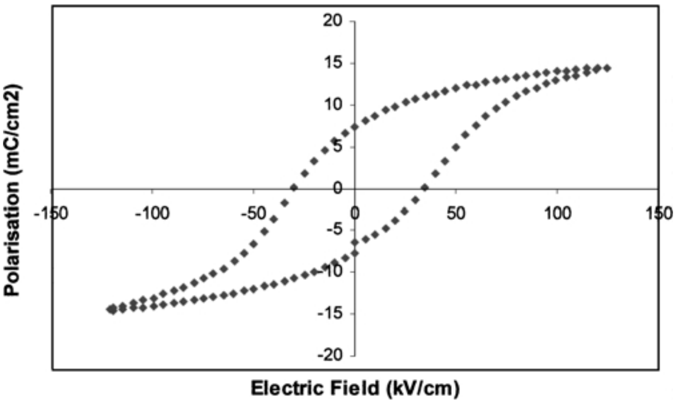

Fig. 4. Hysteresis loop for lower PZT layer.

and 4. Values of the saturation and remnant polarisation, as well as coercive field are equivalent for the two layers. The second hysteresis loop, Fig. 4, because of its thickness, and the limitation in available tension on the RT6000 (20 V), is not perfectly saturated. The value of remnant polarisation in the two cases is around 14 μC/cm^2 and coercive field is around 30 kV/cm.

Furthermore piezoelectric characterisations of the films composition, with similar thickness and identical crystalline orientation, have been realised on monolayers. With a double sided laser interferometer [22] and the cantilever techniques [23] the d_{33} and e_{31} coefficients have been measured to be 55 pm/V and -3.5 C/m^2 respectively.

Bi-Layer Devices

Small cantilevers fabricated using the ‘scribe and crack’ technique. Cantilever dimensions were 10.5 mm (free length) × 2.5 mm × 0.1 mm, as measured in an optical microscope. The free length was further confirmed from the measured fundamental resonance frequency of the cantilever [24]. In order for the PZT films to be used as active piezoelectric devices they have to be poled by applying an electric field across the film. The films were poled at 190 kV/cm, at room temperature. A typical bi-layer actuator is shown in Fig. 5.

4. Experimental

The authors have demonstrated that it is possible to implement simultaneously both active vibration control and micro-positioning of small cantilevers [25–28]. One issue that needs to be addressed for the use of piezoelectric thin films in MEMS devices is that of actuation capability. We have previously shown that the amount of available actuation is dependent on the thickness ratio (PZT : Si) and also on the respective Young’s moduli of PZT and Si [29]. Bulk PZT bimorph actuators are readily available commercially and enable increased actuation for a given drive voltage, as the electric field is higher per layer. Thin film PZT devices have a higher breakdown potential compared to bulk materials, enabling the films to be driven much harder at a lower operating voltage. These two effects make PZT thin films very suitable indeed for use as bi (or multi) layer actuators. The experimental arrangement used for this work is similar to that used previously by the authors [14]. In order to characterise the bi-layer actuators; the devices are driven at resonance (f_o) and off resonance—frequencies less than one fifth of f_o exhibit frequency independent response. A Feedback TWG500 function generator is used to drive the two PZT layers. It is able to drive both layers at exactly the same frequency and also to continuously vary the phase between the two layers. In this work the bi-layer devices were driven at the cantilever’s fundamental resonance frequency (1045 Hz) and at 191 Hz. The dynamic motion of the cantilever was monitored using optical beam deflection (OBD) [30], and measured using an EG&G 7260 DSP lock-in amplifier. After poling each film was independently capable of the yielding the same amount of actuation for a given drive voltage. For operation at resonance, each film was driven at 12.3 mV (rms) and the drive signal phase between each layer varied form 0° to 720° in 10° increments. Figure 6 shows the response obtained, and it can be seen that actuation

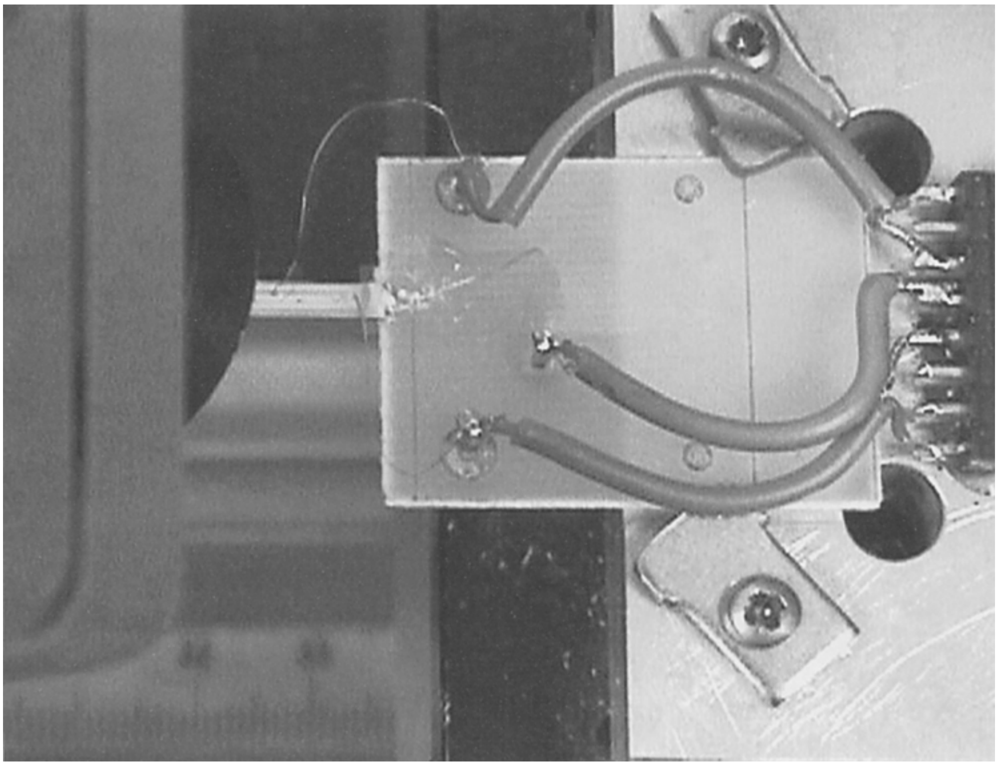

Fig. 5. Bi-layer actuator.

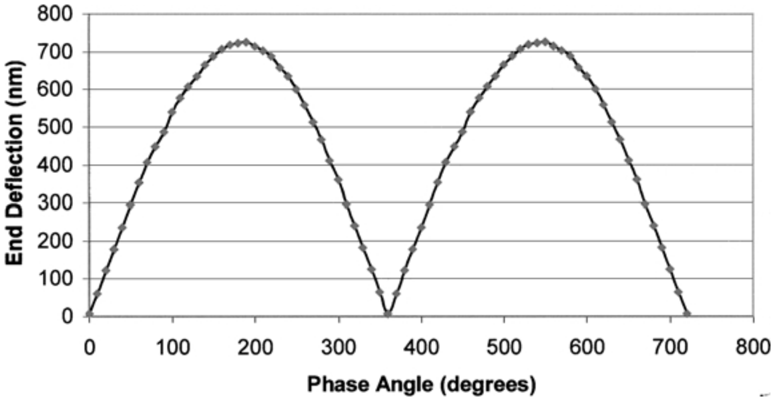

Fig. 6. Cantilever end deflection (rms) for PZT bi-layer actuator. Actuator voltage 12.3 mV (rms) at resonance yields a maximum end displacement of 722 nm (rms).

reaches a maximum at 180° and 540° and becomes zero at 0°, 360° and 720°. At 180° the actuation available from each device is equal, but half that would be produced for a single film of combined thickness.

When the device is driven off-resonance a higher drive voltage is required to obtain sufficient actuation. In this case the actuator was driven at 200 mV (rms) and the drive signal phase between each layer varied form 0° to 720°. Figure 7 shows the response obtained, and it can be seen that actuation reaches a maximum at 180° and 540° and becomes zero at 0°, 360° and 720°. Again, at 180° the actuation available from each device is equal, but half that would be produced by single film of combined thickness.

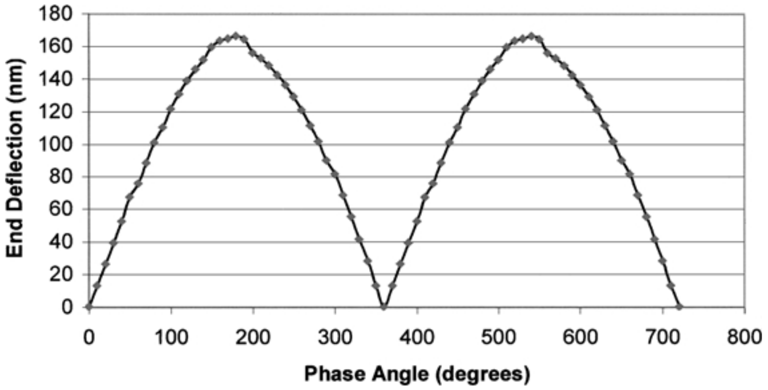

Fig. 7. Cantilever end deflection for PZT bi-layer actuator. An actuator voltage of around 200 mV (rms) in the linear response region yields a maximum end displacement of 166 nm (rms).

To optimise actuation, a dc field is superimposed to maintain good polarisation within the film. This was investigated for a single PZT layer, both on and off resonance. In both cases the films were driven by a 3 V pk-pk signal, and the end displacement measured for 0 and 5 V dc bias. Table 1 below shows the results obtained, and in each case the actuation increases with applied dc field.

When the cantilever is excited off-resonance (quasi-static mode), the piezoelectic coefficient d_{31} may be calculated for a given drive voltage, V, according to Gardiniers [31], for a mono-layer device.

$$d_{31} = \frac{1}{\left(1+\nu_{\mathrm{PZT}}\right)} \frac{s^{\mathrm{E}}_{11_{\mathrm{PZT}}}\left(1+\nu^2_{\mathrm{PZT}}\right) w_{\mathrm{b}} t_{\mathrm{b}}^2}{6 s^{\mathrm{E}}_{11_{\mathrm{Si}}}\left(1+\nu^2_{\mathrm{Si}}\right) w_{\mathrm{e}}} \frac{1}{\left(l_{\mathrm{b}} l_{\mathrm{e}} - \frac{l_{\mathrm{e}}^2}{2}\right)} \frac{\delta}{V} \tag{1}$$

Where $s^{\mathrm{E}}_{11\mathrm{si}}$ is the elastic compliance of silicon (m^2/N), ν_{PZT} and ν_{Si} are Poisson's ratio for PZT and silicon respectively, l_{b} and l_{e} are the lengths of the cantilever and electrode respectively (m), t is the thickness of the cantilever (m) and w_{b} and w_{e} are the widths of the beam and electrode respectively. It is assumed, in this case, that the second PZT layer, which for this calculation is passive, can be assumed to be negligible, as it is very thin (<1 μm) in comparison to the silicon thickness of 100 μm. For each single layer driven by an ac voltage (200 nm rms at 191 Hz) the end deflection was measured to be 83 nm (rms), yielding a value of 115 × 10^{-12} C/N for the d_{31} coefficient.

Table 1. Influence of dc bias field on cantilever end-deflection, for quasi-static and resonant operation.

Frequency (Hz)	AC voltage (pk-pk)	DC bias voltage	End displacement (pk-pk)
102	3	0	100 nm
102	3	5	486 nm
1045	3	0	7.0 μm
1045	3	5	12.9 μm

The PZT bi-layer is able to drive the cantilever on and off resonance. Maximum actuation capability is at one of the resonant frequencies. The actuator was capable of exciting the cantilevers first three modes. For this particular cantilever the measured modal frequencies were 1025 Hz, 6223 Hz and 18213 Hz. These frequencies are as expected theoretically [24].

5. Discussion

PZT bi-layer films have been deposited onto silicon, and after poling the actuation capability of the films assessed. The bi-layer device was driven at 1045 Hz (resonant mode) and at 191 Hz (frequency independent micro-positioning mode). At resonance a low voltage signal (12.3 mV rms) was able to yield an end deflection of 722 nm. At 191 Hz a higher voltage is required to get good actuation, with drive signal of 200 mV (rms) yielding an end deflection of 166 nm. This suggests that structures of this type are particularly useful in atomic force microscopy, both for quasi-static and resonant operation. In magnetic force microscopy there may be a simultaneous requirement for micro-positioning, to keep the probe tip at a constant height above the sample surface, and resonance for operating using the 'tapping mode' or 'lift mode'.

By varying the phase between the two layers it has been shown that actuation can be smoothly varied from zero to maximum, with maximum deflection occurring at half the drive voltage required for a single film of the combined thickness. As before, it has been confirmed that the application of a suitable dc bias field improves actuation capability, both on and off resonance.

The performance of ferroelectric thin films as microactuators can be improved by modifying the film's composition. For example, the addition of metals or rare earths enables us to modify and enhance the performances of PZT. In particular, concerning doped PZT thin films, very little has been published [32, 33]. However, the influence of Nb doping on the ferroelectric properties of PZT films has been discussed in recent papers [34, 35].

Niobium (Nb), substituted in site B of the perovskite, to form Pb(Zr,Ti,Nb)O3 (PNZT) ceramics. A weak concentration of Nb (typically 1–2%) improves the piezoelectric properties of PZT. Piezoelectric characterization indicated an increase of d_{33} and e_{31} with the introduction of Nb dopant; maximum values of around 115 pm/V and—4.5 C/m^2 respectively were obtained for a 1 at.% doped film. Thin doped PZT films with such composition will be able to be used in next bi-layer devices. The piezoelectric and electrical properties of the films will be measured and the actuation performance of the devices characterised.

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