TRANSPARENT PIEZOELECTRIC TRANSDUCERS FOR LARGE AREA ULTRASONIC ACTUATORS

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ABSTRACT

This work focuses on the fabrication of transparent piezoelectric transducers on glass substrates for ultrasonic actuation. Transparent Lead Titanate Zirconate (PZT) thin films are grown on glass following a sol-gel route and InterDigital Electrodes (IDE) patterned by photolithography. The electrodes design aims to optimize the volume of active piezoelectric material together with the transparency of the actuator stack. The actuator is used in d_{33} mode offering high transduction capabilities, while the IDE design allows for increasing the area of the actuator in the cm² range. The results demonstrate that fully transparent actuators with ultrasonic range resonant frequency (~100kHz) can be fabricated on glass substrates. Direct applications of these actuators are haptic devices for tactile sensation of surface roughness.

INTRODUCTION

Piezoelectric thin films have been extensively deployed in MEMS components for both actuation and sensing applications [1-3]. MEMS devices are mainly manufactured on silicon substrates and large efforts have been achieved to stabilize the fabrication process of piezoelectric thin films. Physical vapor deposition (PVD) and Chemical Solution Deposition (CSD), which include sol-gel and metal-organic decomposition techniques, have reached industrial maturity [4,5]; while Pulsed Laser Deposition (PLD) techniques are still under development even though homogeneous PZT thin films on 6” silicon wafers have been realized [6]. Moreover, recent works have demonstrated the fabrication of PZT thin films on glass substrates exhibiting well-crystallized perovskite phase and transmittance in the visible range higher than 50 % [7].

The processing of transparent PZT thin films on glass substrates opens new opportunities in terms of applications. The reported studies on transparent piezoelectric thin films on glass substrates for electromechanical transduction are generally based on parallel plate metallic electrodes (PPE) capacitive stack. We have reported studies with metallic electrodes [8], which make the structure opaque to visible light, and also devices with transparent electrodes, namely indium tin oxide (ITO) [7].

In this work, we aim to develop large area ultrasonic transducers based on thin piezoelectric films that can be integrated on glass. Although piezoelectric haptic prototypes on glass substrates have been realized [9], the structures employ parallel plate metallic electrodes, preventing uniform positioning of the actuators on glass. The choice of transparent IDE opens up plenty of design options while keeping high transmittance (cf Fig. 1, 3).

DESIGN

The design of the capacitors is based on the interdigital electrodes configuration. In a first step, small capacitors with 14 parallel electrodes, a constant length of 90 µm, and nominal capacitance in the order of 1 pF were used for process validation. To increase the actuators area, the IDE design shown in Fig. 1 was implemented. The diameter of the device varies from 1 to 8 mm, and different combinations of gap and electrode width are available (Table 1).

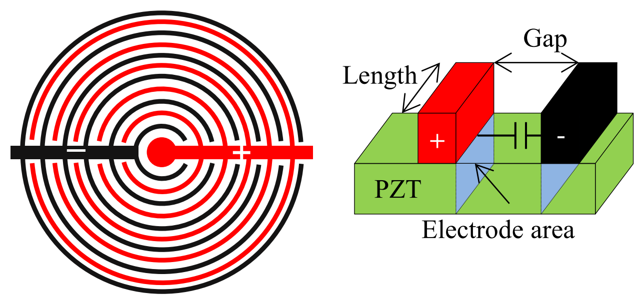

Figure 1: IDE capacitor design and illustration of electrode area considered in the model.

Table 1: Dimensions of large area IDE capacitors

Diameter (mm)	1	2	4	8
Gap (µm)	2,5,10	2,5,10	2,5	2,5,10
Elec. width (µm)	5,10	5,10,20	5,10,20	5,10,20

The calculation of the capacitance in the circular IDE design in Fig. 1 is based on a simple model where we consider a parallel plate capacitor between two electrodes. The electrode area is given by the length of the electrodes multiplied by the thickness of the PZT.

The expected capacitance value normalized by the area occupied by the actuators is plotted in Fig. 2. For gaps larger than 10 µm, the capacitance per unit area is lower than 1 nF/cm². Maximum capacitance is obtained for smallest gaps and electrodes, which corresponds to the largest volume of piezoelectric material exposed to electric field. Considering the process constraints, we have access to a maximum of 6 nF/cm² corresponding to 2 µm gaps and 5 µm electrodes. Indeed, achieving lower gaps with lift-off lithography would decrease yield. When comparing with PPE configuration where the gap has to be compared to PZT thickness, achievable capacitance is two orders of magnitude larger. However, a thickness higher than 2 µm and an area in the order of 1cm² are not compatible with the process. Realistic top electrode area in PPE configuration are in the order of 1 mm², resulting in similar values obtained with IDE configuration.

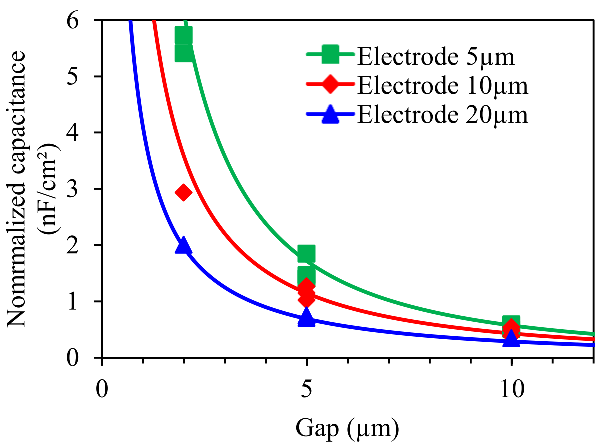

Figure 2: Normalized capacitance per unit area calculated from the geometry of circular IDE capacitors. We consider a 200 nm thick PZT layer with an effective dielectric constant of 500. Dots correspond to the experimental values measured on capacitors with Ti/Au electrodes.

PROCESS

$Pb(Zr_{0.52}Ti_{0.48})O_3$ films are deposited on fused silica substrates where a 10 nm thick TiO_2 buffer layer has been processed first. Then top electrodes are patterned on PZT with lift-off lithography. Different conductive materials were tested for electrodes, namely indium tin oxide (ITO) and aluminum-doped ZnO (AZO) as transparent materials as well as Pt and Ti/Au for reference.

Fused silica substrate was chosen for its higher glass transition temperature (T_g=1100°C) compared with more mundane glass such as soda-lime (T_g=550-600°C).

Sol-gel process is used to grow up to 1 µm thick PZT. The sol is prepared from 99.99% pure metal precursors from Sigma Aldrich: lead(II) acetate trihydrate, zirconium(IV) butoxide solution in butanol, and titanium(IV) isopropoxide. 2-methoxyethanol (2MeOH) was employed as main solvent. Lead(II) acetate trihydrate was initially dissolved in 2MeOH and the obtained solution was evaporated under reduced pressure. The dehydrated lead precursor was then dissolved in 2MeOH. A solution of zirconium and titanium precursors in 2MeOH was added to the previous one and the obtained mixture was heated at reflux under argon during two hours. Stoechiometry was adjusted to get a sol with 10% lead excess and a 53/47 PZT composition, and a concentration of 0.3 mol/l. The solution was stored under argon at 5°C and has remained stable for several months.

To grow the PZT films, the sol is spin coated on the fused silica wafer with a top 10 nm thick film of oxidized titanium. After spinning at 1800 rpm during 30s, the wafer is dried at 130°C for 5 minutes and then annealed at 350°C for 5 minutes. Deposition is repeated three times and then crystallization is performed in an oven at 700°C for 5 minutes. This process results in 200 nm-thick PZT layers. To increase thickness, the same cycle was repeated up to four times, resulting in 800 nm thick PZT layers.

Electrodes are finally patterned by lift-off lithography with an undercut to improve lifting process. Indeed, the IDE patterns exhibit large area and high length to width ratio. Metallic electrodes of platinum (100 nm) or gold/titanium (50 nm/5 nm) were evaporated, transparent electrodes of AZO were deposited by ALD, and ITO electrodes were sputtered. Figure 3 shows a 2” fused silica wafer (500 µm thick) with barely visible patterned transparent ITO circular IDE electrodes.

Figure 3: 2” fused silica substrate with 10 nm thick oxidized titanium layer, 200 nm thick crystallized PZT, and 300 nm thick sputtered ITO top IDE

RESULTS

The crystallized PZT layers on fused silica substrate are homogeneous and do not crack during the fabrication process (Fig. 3). Our experiments have shown the necessity of an adhesion layer with a minimum thickness of 10 nm. For thinner or no adhesion layers, the PZT film would crystallize but also exhibit large cracks. The SEM cross-section in Fig. 4 shows a dense polycrystalline microstructure. XRD pattern in Fig. 5 was obtained on a Panalytical diffractometer, the PZT is crystallized in perovskite phase, without parasitic phase and no preferential orientation.

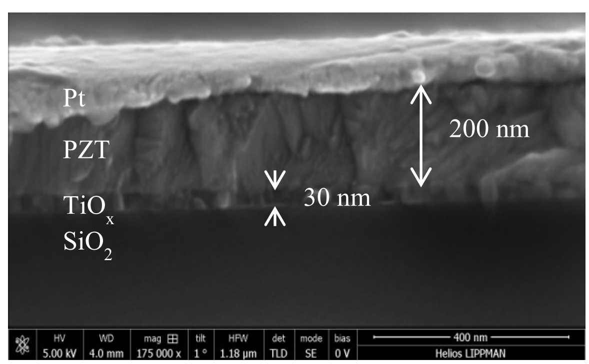

Figure 4: SEM cross-section of PZT on glass

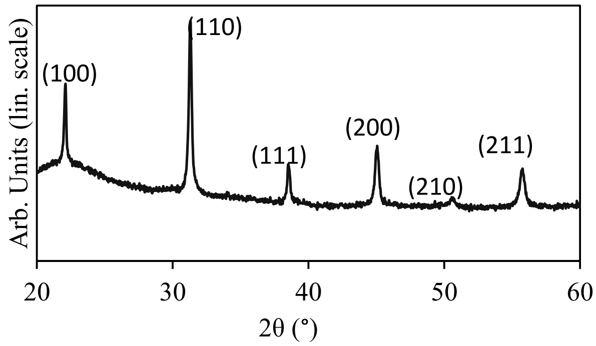

Figure 5: XRD diagram, 200-nm thick PZT on glass

The light transmittance of the stack was measured on a TECAN absorbance instrument. The transmittance measured through the stack (Fig. 6) without the top electrodes is higher than 60 % in the visible range. The oscillations observed on the curve with top PZT layers are caused by Fabry-Pérot interference in the thin film structure.

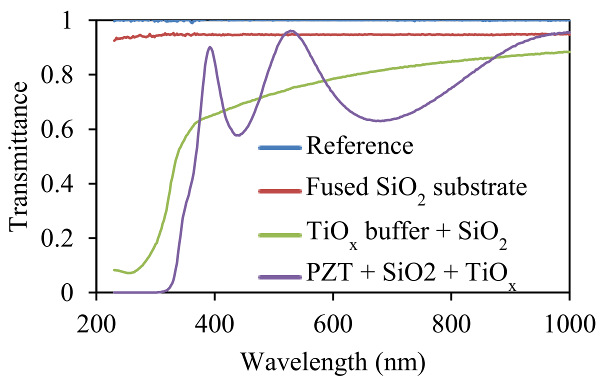

Figure 6: Optical transmittance of PZT thin film on fused silica substrate

The electrical characterization of the interdigital capacitors was done on a PM8 manual prober. We plot the results for an 8 mm diameter actuator with Ti/Au gold electrodes on 800 nm thick PZT. This device has 5 µm as gaps and electrodes width. In Fig. 7 are plotted both capacitance and dielectric losses measured at 1 kHz on an Aixacct ferroelectric probe station as a function of the voltage. Nominal capacitance C_0=1.1 nF at zero field corresponds to a capacitance per unit area of 2.2 nF/cm², even though 50% of the piezoelectric material in the actuator is not active because of the unsolicited PZT material beneath the electrodes. Fig. 8 shows the hysteresis loop measured on the same device. Coercive voltage is 27 V and the remanent polarization 20 µC/cm².

The characterization of other capacitors with different sets of diameter, gap and electrode dimensions is reported in Fig. 2 (dots). We can see that the experimental values follow the behavior predicted by the model. The maximum value of capacitance per unit area of 5.7 nF/cm² is obtained for the 2 µm gaps / 5 µm electrodes capacitors.

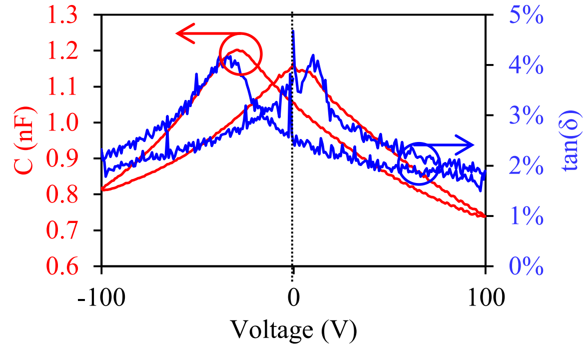

Figure 7: Electrical characterization of an 8 mm diameter IDE capacitor on 800 nm thick PZT layer

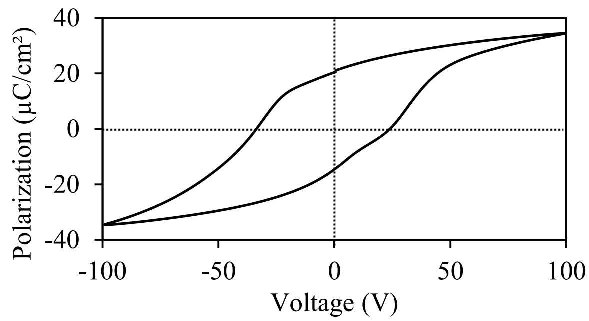

Figure 8: Hysteresis loop of an 8 mm diameter IDE capacitor on 800 nm thick PZT layer

Indirect piezoelectric measurements on a cantilever-like structure with 200 nm thick PZT layer yields d_{33} = 140 pm/V. The mechanical resonance of the 8 mm diameter actuator after wire-cutting from the wafer is measured with a laser vibrometer (Fig. 9). The first resonant frequency f_0=104 kHz measured at the center of the device, results in a peak-to-peak displacement of 32 nm when actuated with a 10 V_{pp} sinusoidal voltage, corresponding to a quality factor Q=109 in air.

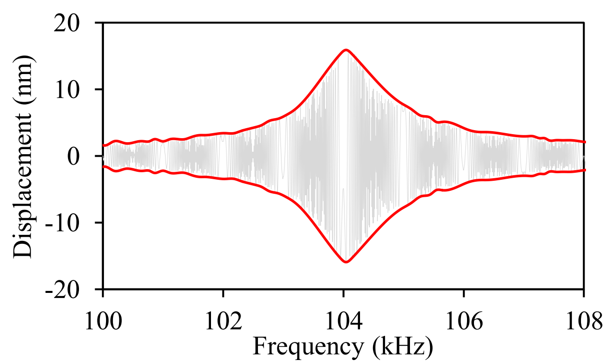

Figure 9: Resonance of an 8 mm diameter IDE capacitor on 800 nm thick PZT layer (10V_{pp} actuation)

DISCUSSION

The simple model implemented in the design correlates correctly with the experimental capacitance values measured on IDE piezoelectric actuators with area from 1 mm² to 1 cm². However, the effective dielectric constant used for the calculation is half of typical values obtained for thin film morphotropic PZT in parallel plate configuration [10]. Similar value of dielectric constant $\varepsilon_{PZT} = 620$ was reported by Dimos et al. [11] on IDE structure on PZT sol-gel films grown on sapphire. An advanced characterization of the PZT films poled in IDE configuration seems necessary to understand such a difference, as well as the influence of the underlying layers and substrate.

The results obtained from electrical and mechanical characterization of circular IDE capacitors demonstrate that the process allows for manufacturing ultrasonic actuators with large area compared to parallel plate devices. To integrate an actuator on a transparent interface, such as touchscreens, the light transmittance in visible range has to be improved. For this, other materials are being investigated for the adhesion layer that was demonstrated necessary to grow the PZT without cracks. Moreover, other glass substrates with thermal expansion coefficient closer to the one of PZT are being evaluated. Transparent electrodes of AZO have been successfully tested on small capacitors (90 µm electrodes length) even though the lift-off step was difficult because of the conformal deposition of the ALD process. Transparent ITO electrodes were DC sputtered and lift-off patterned on 200 nm thick PZT (Fig. 2), demonstrating a full transparent stack with large area actuators. However, ITO deposition conditions have to be optimized to improve electrodes conductivity.

The capacitors with Ti/Au electrodes exhibit constant dielectric losses lower than $tan\delta = 0.04$ up to 500 kHz, which is a good indicator of poor conduction losses in the electrodes, despite their length up to several centimeters. Mechanical resonances were measured in the order of 100 kHz at low actuation voltages (10V). Increasing the actuation voltage in the order of 100V together with matching electrical impedance of the circuit should allow for reaching hundreds of nanometers displacement at resonance. These results on functional large area and transparent thin films piezo-actuators demonstrate the potential for ultrasonic and haptic applications.

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