PZT based MEMS actuators for photonic integration

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Silicon photonics has been witnessing an influx of new technologies and functionalities realized through hybrid integration of new materials. One of the most promising materials recently added into this list is a photonic compatible (low-optical loss) Lead Zirconium Titanate (PZT) thin film. Bulk PZT is known for its high piezoelectric and electromechanical coupling coefficients. Integration of a PZT thin film can introduce a strong piezoelectric effect as a new feature to the Silicon-on-insulator (SOI) platform. In this work we explore the piezoelectric property of this PZT film deposited on an SOI substrate through electro-mechanical actuation. We fabricate microscale cantilever beams by under-etching the buried oxide in the PZT/SOI with HF vapor. We characterize the mechanical vibration of these MEMS actuators with a Laser Doppler Vibrometry (LDV). We demonstrate a shear vibration mode with the as-deposited PZT film (domains preferentially out of the substrate plane) and a longitudinal vibration mode after poling the PZT domains along the applied electric field. This opens the possibility of integrating PZT thin film based MEMS actuators and transducers into Silicon photonic integrated circuits (PICs).

Introduction

Silicon photonics is one of the most promising photonic platform. It offers several key building blocks such as laser, detector, modulator, isolater and filter. However, due to the Silicon's centro-symmetric nature, Silicon-on-insulator (SOI) based photonic platform lacks piezoelectric tuning[1]. Therefore, a photonic compatible piezoelectric film integration could be an alternate route to overcome this deficiency.

Lead Zirconate Titanate (PZT) is one of the strongest piezoelectric ceramic material and is widely used in MEMS and transducer technology[2]. However, it has been mostly elusive for the photonic integration. This is because the traditional growth of the PZT film involves Pt buffer layer which makes the film optically lossy. Recently a novel approach for growing high quality PZT films, using a thin transparent lanthanide based buffer layer (LaO_2CO_3), was reported[3]. The high quality of this PZT film has been proven through the demonstration of strong electro-optic (EO) modulators[4] and second harmonic generation[5]. This inspires an investigation into the piezoelectric capability of this film.

In this work, we fabricate suspended PZT/Si beam structures by under-etching the oxide layer in PZT/SOI. We demonstrate the piezoelectric capability of the PZT film by electrically actuating PZT/Si actuators. We use coplanar electrodes to apply the (in-plane) RF signal and measure the beam deflection using a laser Doppler Vibrometer (LDV).

Fabrication of the suspended beams

We deposited ~ 400 nm thick PZT film on an SOI substrate using Sol-gel method[3] . We then patterned electrodes on PZT using a contact photolithography, followed by Al metal evaporation and lift-off. Then we spin-coated Ti-35 photoresist on the sample and patterned the under-etch windows. We used an reactive ion etching (RIE) to etch through the PZT layer in the windows regions. Now, we exposed the sample in HF vapor to under-etch the sacrificial SiO_2 layer for 60 min. We made a cross-section with focused ion beam (FIB) on the widest beam on the chip (as shown in figure 1.b) to confirm the full suspension.

(a) (b)

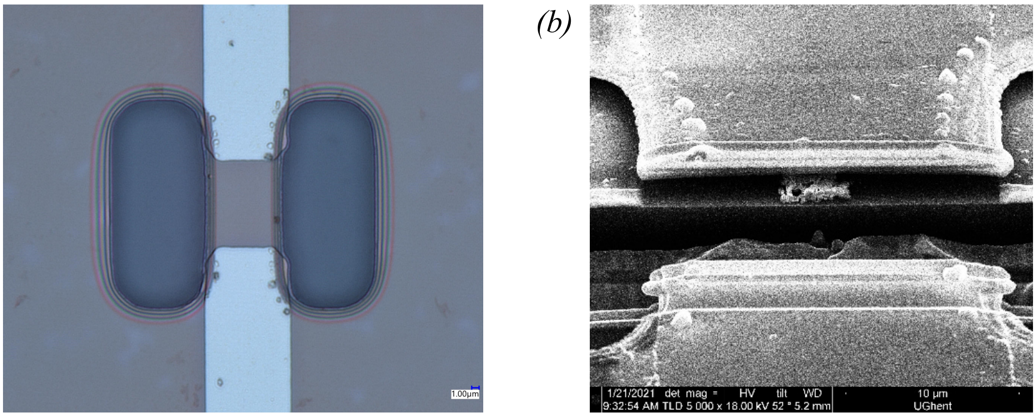

Figure 1 (a) Microscope image of a suspended PZT/Si beam (width 21 µm) . Two under-etch windows were used for lateral under-etching of the box-oxide. The Al electrodes were fabricated to apply in-plane electric field through the PZT film. (b) An SEM image of the cross-section made on a suspended beam (width 21 µm). There is no box-oxide attached under the beam confirming the full suspension.

Experimental setup

We built a setup, as shown in figure 2, to measure the actuated deflection in the beam. An RF generator was used to actuate the suspended beams with an AC signal. The AC probes were attached on a positioner to align the probes on to the electrical pads on the chip. An LDV sensor head was fixed vertically on top of the sample at the working distance (WD) of the in-built lens. The lens was used to focus the laser spot (diameter ~25 µm) onto the DUT. A CCD camera was used for the alignment purpose. Additionally, a DC source was used to pole the PZT samples to observe the effect of poling on the actuation. Both the LDV system and the RF source were automated through a MATLAB script for the data acquisition.

Results and discussions

The suspended beams were actuated with an RF signal (V_{pp} 10V). The beam deflection was measured on three locations on the beam (up, center and down) with respect to the RF frequency. The LDV data were collected in time domain. A high-pass filter and signal averaging was used, followed by an FFT to get the frequency response as shown in figure 3(a) and 4(a).

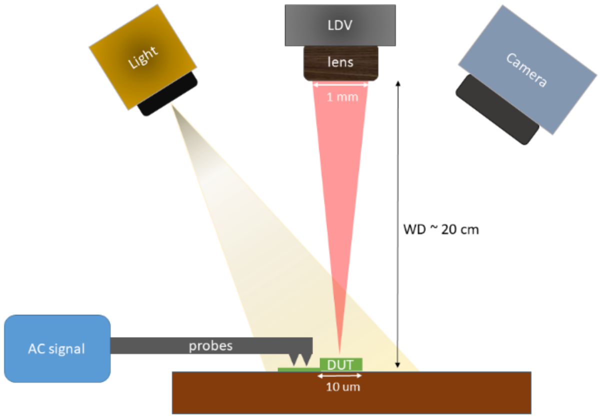

Figure 2. The experimental setup includes mainly an RF generator to actuate DUT with an AC signal, and an LDV system to measure the vibration. An in-built lens in the LDV head focuses the signal into the DUT. A CCD camera was used to align the signal spot on the suspended beam.

In figure 3(a), we show the deflection spectrum measured on a beam (dimension 26 µm x 8 µm) with as-deposited PZT film. We notice that the deflection amplitude (at the resonance) is insignificant at the center point, but higher (up to 7 nm) at the up and down points. This could be because the PZT is grown with preferential orientation out-of-the substrate plane (c-orientation). Thus, the applied transversal electric field actuates the shear mode as shown in the FEM simulation in figure 3(b).

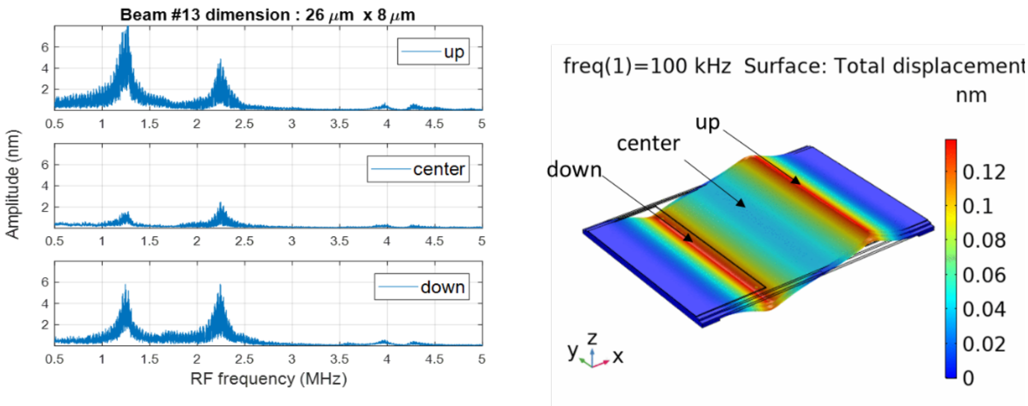

Figure 3. (a) The deflection amplitude of the as-deposited PZT/Si beam (dimension 26 µm x 8 µm) vibration with respect to the input RF frequency. (b) A 3D FEM simulation (using COMSOL) shows the shear mode actuation of the PZT/Si beam (dimension 25 µm x 21 µm) when actuated with an RF signal of amplitude 1V and frequency 100 kHz. In the simulation, the PZT domain polarization was set out-of-the substrate plane (along z).

In the following step, we applied a sufficiently high DC voltage to the electrodes (for 50 min) on the beam to align the PZT domains in-plane (along the applied electric field). Figure 4(a) shows the deflection spectrum measured on a poled PZT/Si beam (dimension 26 µm x 8 µm). Now contrary to the previous observation, here the deflection (at the resonance) is very low at the beam edges, up and down points, but higher (up to 40 nm) at the center point. Additionally, this beam deflection at the center is much higher (almost 7 times) than the edge deflections measured with the unpoled PZT. This is because now the electric field is applied along the (poled) PZT domain polarization, which actuates the longitudinal mode in the beam. This can be seen in the FEM simulation of a PZT/Si beam (dimension 25 µm x 21 µm) as shown in figure 4(b). The PZT domain in the simulation is aligned in the substrate plane (along x-axis).

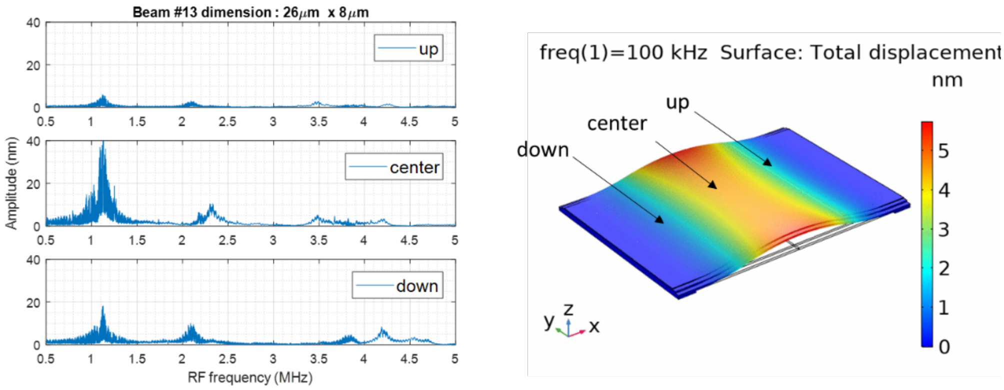

Figure 4. (a) The deflection amplitude of the poled PZT/Si beam (dimension 26 µm x 8 µm) vibration with respect to the input RF frequency. (b) A 3D FEM simulation shows the longitudinal mode actuation of the PZT/Si beam (dimension 25 µm x 21 µm) when actuated with an RF signal of amplitude 1V and frequency 100 kHz. In the simulation, the PZT domain polarization was set in-the substrate plane (along x).

Conclusion

We fabricated suspended beams with a photonic compatible PZT film deposited on SOI substrate. We measured the RF actuated deflection of the beams using an LDV setup. We observed a strong longitudinal actuation with the poled PZT, while a weaker shear mode actuation with as-deposited PZT film. The measured longitudinal and shear deflection modes were qualitatively verified with the FEM simulation. Thus, our results demonstrate the piezoelectric tuning capability of our photonic compatible PZT film. These piezo-MEMS actuators can be combined on Silicon PICs to realize efficient and novel photonic components such as filters, isolators, tunable couplers, modulators and phase-shifters.

Acknowledgment

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