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ABSTRACT

Lead Zirconate Titanate (PZT) is widely used for energy harvesting owing to its strong piezoelectric and electromechanical coupling coefficient as well as high temperature compatibility (Curie point ∼ 370°C).[1–3] The heterogeneous integration of a PZT thin film on the Si photonics platform can compensate the lack of piezoelectricity in the centro-symmetric Silicon, and enable a wide range of electro-optomechanical applications combining the benefits of a strong piezoelectric material and a matured photonic platform.

In this work, we directly deposit a PZT film on silicon-on-insulator (SOI) using a transparent Lanthanide based seed layer making it photonics compatible,[4] unlike the traditional PZT film grown with a metallic Platinum (Pt) buffer layer, which introduces unacceptable optical losses in the device.[5] We fabricate unimorph micro-cantilever beams with the hybrid PZT-SOI chip and demonstrate its piezoelectric actuation. The laser Doppler Vibrometry (LDV) measurements on these suspended actuators give a deflection up to 40 nm with an applied RF voltage of $V_{pp} = 10$ V at the fundamental resonance frequency. Next, through numerical simulations, we show that a PZT actuator integrated with a directional coupler allows for a strong tuning efficiency.

Thus, we demonstrate a PZT film based actuator that can be directly integrated on the Si photonic platform. This opens the possibility of achieving an efficient electro-optomechanical coupling and low-power MEMS applications in Si photonic integrated circuits (PICs).

Keywords: Photonic integration, novel materials, PZT, Si photonics, MEMS photonics

1. INTRODUCTION

Photonic integrated circuits (PICs) are increasingly attracting interest for applications ranging from high speed communication to quantum computing. In particular, Si PICs have emerged as a promising photonic platform owing to their compactness and compatibility with fabrication in CMOS foundries. For instance, Si PICs are being explored as a potential platform for programmable photonics, which rely on a large network of tunable phase shifters and couplers. However, commonly used tuning mechanisms in Si PICs, such as thermo-optic and plasma-dispersion based tuning, pose a bottleneck due to their limited speed, large footprint or high energy consumption. Thermo-optic based tuning typically requires 1-10 mW for 2π phase shift and has a maximum speed up to a few kHz. Additionally, the thermal cross-talk between the heating elements limits the compactness of the device. On the other hand, plasma-dispersion based tuning offers high bandwidth up to several GHz, but introduces significant optical loss due to the injection of mobile charge carriers in the waveguide.

As an alternative, micro-electro-mechanical system (MEMS) based tuning mechanisms have emerged as a promising option to achieve large scale PIC tuning thanks to its low power consumption (order $\sim \mu$W), low optical loss and small footprints.[6] Most of the MEMS-based photonic devices rely either on electrostatic or on piezoelectric actuation. In electrostatic actuation, the attractive force between the charged plates produces the driving force. This usually comes with a risk of pull-in and a collapse of the actuators. Also, the need for a large capacitance increases the RC time constant[7] and limits the tuning speed. On the contrary, the driving force

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in piezoelectric actuation is generated by the induced stress (or strain) from the piezoelectric material under an applied electric field. A strong piezoelectric material is therefore desirable for a low-power actuation. Lead zirconate titanate (PZT) is known to be one of the strongest piezoelectric materials and PZT-based actuators have been integrated with SiN PICs for strain-induced tuning[8,9] before. However, traditional integration of PZT relies on a Pt buffer layer. This is optically lossy and puts extra constraints on the scalability and design of MEMS photonics devices.

In this work, we use a photonic compatible PZT film directly deposited on an SOI chip using a transparent La based buffer layer and fabricate suspended hybrid PZT/Si beam structures. We actuate these structures with an RF signal and measure their deflection with an LDV. This demonstrates the integrated PZT film indeed allows for piezo-electric actuation and opens the possibility of integrating PZT based MEMS on Si PICs. We then numerically illustrate a tunable coupler based on a PZT actuator.

2. FABRICATION

We grew 400 nm thick PZT atop a standard SOI substrate with 220 nm Si layer, using a sol-gel process.[4] We patterned the Al electrodes using a lift-off process. Next, we used a Ti-35 resist-mask to pattern the under-etch windows using reactive ion etching. Finally, we exposed the sample to a HF vapor process in a Idonus VPE 100 reactor. After 90 minutes, we obtained the fully suspended beams as shown in figure 1(a), (b). To confirm the full suspension of the beam, we took a SEM image of a cross-section made on the widest beam using focused ion beam (figure 1(c)).

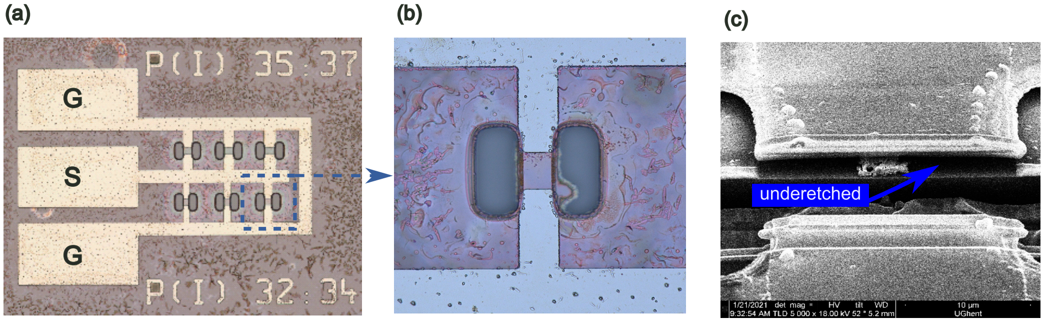

Figure 1. (a) Fabricated device containing multiple beams connected to the electrode pads in GSG configuration (ground-signal-ground), (b) image of a single beam, (c) cross-section of a fully suspended beam.

3. RESULTS AND DISCUSSIONS

We actuate the suspended beams with an RF signal and measure its vibration using an LDV system. The laser spot from the LDV is focused onto the chip using an integrated lens, which gives a spot diameter of about 25 μm. We align the laser spot on the desired DUT using a positioner attached to the laser head, while monitoring the spot position with a CCD camera. We measure in the time domain the deflection/vibration for an RF signal at a given frequency, and do a fast Fourier transformation (FFT) to get the frequency domain response and extract the deflection amplitude. This is repeated for every input RF frequency to get a deflection spectrum.

Figure 2 (a) shows the deflection spectrum measured for a beam of length 26 μm and width 8μm, when the beam is actuated with an RF signal of $V_{pp} = 10$V. In this first experiment, the PZT was left as deposited, i.e. not poled. We measured the deflection on 3 positions on the beam (up, center and down). We noticed that the deflection at the center point of the beam is the lowest. This is because the deposited PZT film has preferential domain orientation out of the substrate plane, hence the transversely applied (in-plane) electric field creates a shear mode vibration in the beam. This can be seen in the finite element method (FEM) simulation of the beam as shown in figure 2(b). In the simulation, the beam is piezoelectrically actuated with an RF signal of $V_{pp} = 10$V at 1 MHz.

We then apply a sufficiently high DC voltage on the electrodes for about 50 min to pole the ferroelectric domains in the PZT film of the suspended beam, along the applied electric field (in substrate-plane). Figure 2(c)

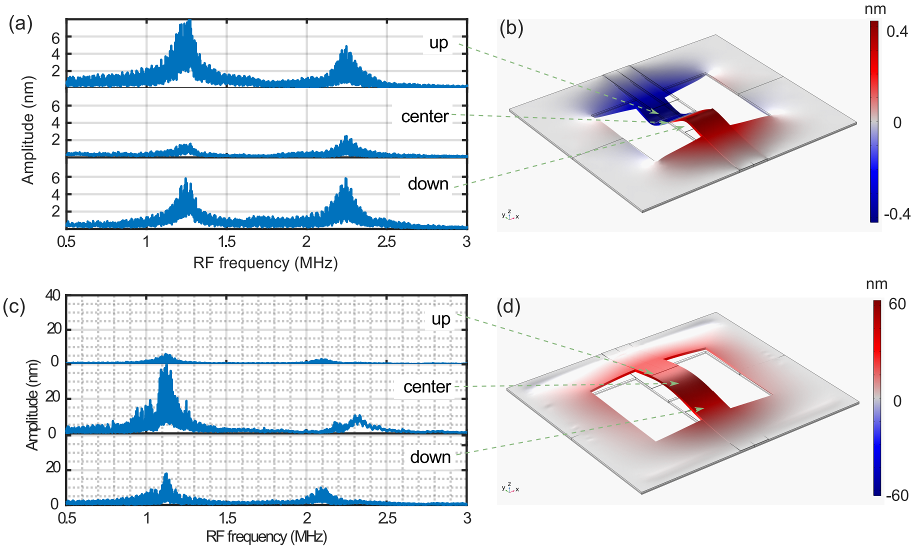

Figure 2. (a) Measured deflection spectrum of the as-deposited PZT/Si beam (dimension 26 $\mu m \times 8\ \mu m$) with $V_{pp} = 10V$, (b) a 3D FEM simulation of the PZT (c-orientation) on Si beam showing a shear mode upon actuated with an RF signal with $V_{pp} = 10V$ at 1 MHz,(c) measured deflection spectrum of the same beam after poling the PZT domains in-plane, (d) a 3D FEM simulation of the PZT (a-orientation) on Si beam showing a longitudinal mode upon actuated with an RF signal with $V_{pp} = 10V$ at 1 MHz.

shows the deflection spectrum measured on the beam after poling. Now, the highest deflection is observed at the center point of the beam. This is expected, as the electric field is now applied along the ferroelectric domains orientation in the PZT thin film creating a longitudinal vibration mode as shown in the simulation, figure 2(d). Additionally, we observe that the longitudinal actuation gives a deflection up to 40 nm, which is about 10 times larger compared to the shear actuation.

Figure 3(a) shows the deflection spectra measured at the center of poled PZT-on-Si beams with different lengths (width = 8 μm). As expected, the resonance frequency decreases proportionally with the increase in the beam length. These results confirm the piezoelectric actuation of the PZT film.

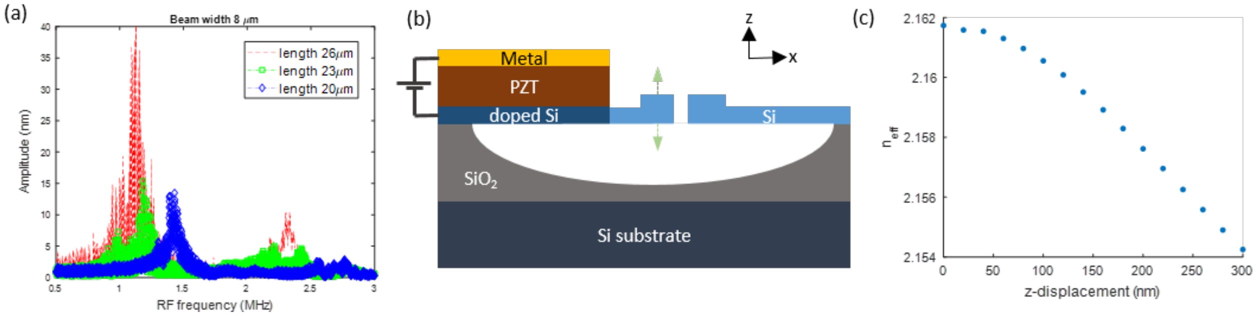

Figure 3. (a) Deflection spectra measured on the beams of different lengths (width = 8 μm), (b) a schematic of a PZT cantilever integrated tunable coupler, (c) simulated effective mode index tuning with respect to the z-displacement of the coupler waveguide.

In figure 3(b) we illustrate a suspended directional coupler, as a possible application of such PZT based actuator. The PZT thin film can be directly deposited on a doped Si layer (acting as a bottom electrode). We can define a top metal electrode and under-etch the sacrificial box-oxide to suspend the waveguide coupler. In figure 3(c), we show an FEM simulation of the effective mode index from this suspended coupler with respect to the z-displacement of the actuated waveguide. We obtain a strong effective mode index tuning with the displacement. Here, the separation between the coupler is 150 nm, the waveguide width is 400 nm and thickness is 220 nm. The waveguides are considered to be defined through a 150 nm etching step on a 220 nm Si layer.

Although such MEMS tuning (vertical displacement of the suspended waveguide) has also been achieved with electrostatic actuation, the waveguide had to be doped, introducing additional optical loss.[6] In our demonstration, the actuation is done piezoelectrically, hence the waveguides do not need to be doped. Additionally, unlike conventional PZT-based actuators, where the separation between the PZT film and the waveguide becomes crucial due to the Pt buffer layer,[8] our photonic compatible PZT is not bound by such limit and allows for compact devices and efficient electro-optomechanical interaction.

4. CONCLUSION

We experimentally demonstrated the piezoelectric actuation of a PZT on Si beam. This beam is fabricated with a direct deposition of a photonic compatible PZT film on an SOI chip. This opens the possibility of integrating piezo-MEMS actuators as tuning elements in Si PICs. As an example, we illustrate a tunable coupler where one waveguide is connected with the PZT/Si cantilever. The simulation shows promising tuning efficiency of the effective mode index. Therefore, such PZT based micro-actuators open the ways to realise piezo-MEMS based Si PICs for efficient electro-optomechanical applications.

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REFERENCES

[1] Auld, B. A., "Acoustic fields and waves in solids."

[2] Safaei, M., Sodano, H. A., and Anton, S. R., "A review of energy harvesting using piezoelectric materials: state-of-the-art a decade later (2008–2018)," *Smart Materials and Structures* **28**, 113001 (oct 2019).

[3] JAFFE, H., "Piezoelectric ceramics," *Journal of the American Ceramic Society* **41**(11), 494–498.

[4] George, J. P., Smet, P. F., Botterman, J., Bliznuk, V., Woestenborghs, W., Van Thourhout, D., Neyts, K., and Beeckman, J., "Lanthanide-Assisted Deposition of Strongly Electro-optic PZT Thin Films on Silicon: Toward Integrated Active Nanophotonic Devices," *ACS Applied Materials & Interfaces* **7**(24), 13350–13359 (2015).

[5] Izyumskaya, N., Alivov, Y.-I., Cho, S.-J., Morkoç, H., Lee, H., and Kang, Y.-S., "Processing, structure, properties, and applications of pzt thin films," *Critical Reviews in Solid State and Materials Sciences* **32**(3-4), 111–202 (2007).

[6] Errando-Herranz, C., Takabayashi, A. Y., Edinger, P., Sattari, H., Gylfason, K. B., and Quack, N., "Mems for photonic integrated circuits," *IEEE Journal of Selected Topics in Quantum Electronics* **26**(2), 1–16 (2020).

[7] Stanfield, P. R., Leenheer, A. J., Michael, C. P., Sims, R., and Eichenfield, M., "CMOS-compatible, piezo-optomechanically tunable photonics for visible wavelengths and cryogenic temperatures," *Opt. Express* **27**, 28588–28605 (Sep 2019).

[8] Jin, W., Polcawich, R. G., Morton, P. A., and Bowers, J. E., "Piezoelectrically tuned silicon nitride ring resonator," *Opt. Express* **26**, 3174–3187 (Feb 2018).

[9] Hosseini, N., Dekker, R., Hoekman, M., Dekkers, M., Bos, J., Leinse, A., and Heideman, R., "Stress-optic modulator in triplex platform using a piezoelectric lead zirconate titanate (pzt) thin film," *Opt. Express* **23**, 14018–14026 (Jun 2015).