NON-VOLATILE FERROELECTRIC ACTUATORS INTEGRATED IN SILICON PHOTONIC CIRCUITS

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Abstract

In this work, we investigate a novel approach to realize non-volatile phase-actuators integrated in silicon waveguides. We aim to exploit the ferroelectric response of polycrystalline $BaTiO_3$ *(poly-BTO), whose domain can be re-oriented by applying an external electric field so as to induce a large change of the refractive index. Owing to the polarization remanence of ferroelectric materials, such index variation is maintained when the electric field is turned off. Experimental results on poly-BTO demonstrate the possibility to achieve a non-volatile change of the poly-BTO refractive index in the order of* 10^{-2}*, which is consistent with a 90° reorientation of the ferroelectric domains. We also integrated thin poly-BTO films on Si waveguides with a low additional propagation loss (<1 dB/mm), enabling the realization of PICs with the proposed poly-BTO Si-photonics platform.*

Index Terms – Integrated optics materials, Ferroelectrics, Optical waveguides, Photonic integrated circuits, Silicon photonics

I. INTRODUCTION

Low-energy optical actuators are needed in integrated optics to either compensate fabrication tolerances or dynamically control and calibrate the functionality of reconfigurable and programmable circuits. Conventional actuators technologies exploit local heating of the optical waveguides as well as carrier injection/depletion effects in semiconductor waveguides. Albeit being effective and well consolidated, these solutions typically require high power consumption or suffer from large crosstalk that limits PIC scalability. Non-volatile actuators capable to maintain the switching state without an applied control signal are a promising route to tackle this issue. To this aim, several approaches based on phase change materials (GST) [1] and insulator-metal phase transition materials [2] have been proposed, which however mainly provide a control of the imaginary part of the refractive index of the waveguide, thus realizing “intensity actuators” solutions only.

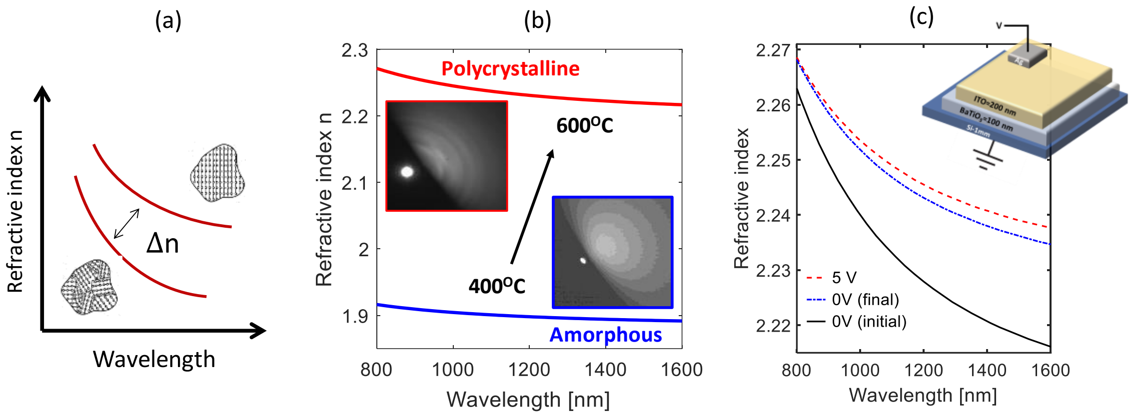

FIG. 1 – (a) Schematic of the refractive index change associated with domain switching in poly-BTO film. (b) Measured refractive index of amorphous (blue curve) and polycrystalline (red curve) BTO films deposited by PLD at different temperatures. RHEED measurements in the insets confirm the amorphous and polycrystalline nature of the films. (c) Measured refractive index of the poly-BTO film in the pristine state (black solid curve), during the application of a 5V pulse (red dashed curve) and in the final state (blue dash-dotted curve).

In this work, we propose a novel approach to realize self-holding phase actuators integrated in Si waveguides. We aim to exploit the ferroelectric response of polycrystalline $BaTiO_3$ (poly-BTO) directly deposited on a Si substrate. We observed a large non-volatile change of the poly-BTO refractive index, in the order of 10^{-2}, which is consistent with a 90° reorientation of the ferroelectric domains. We also demonstrated the possibility to integrate thin poly-BTO films as an upper cladding of Si waveguides with a low additional propagation loss (<1 dB/mm), enabling the realization of microring resonators and other integrated devices with the proposed poly-BTO Si-photonics platform.

II. SELF-HOLDING OPTICAL SWITCHING IN BTO THIN FILMS

Ferroelectric materials are characterized by domains with in-plane (*a*-axis) or out-of-plane (*c*-axis) orientation, which in polycrystalline films are almost randomly distributed. Domains orientation can be manipulated by applying an external electric exceeding the coercive field of the material and as a consequence of the re-orientation a large change of the refractive index n can be achieved. Due to the polarization remanence of ferroelectric materials, the refractive index variation is maintained when the electric field is turned off (see Fig 1.a).

BTO films with a thickness of 100 nm were grown by pulsed laser deposition (PLD) on conductive Si(001) substrate, after the removal of native SiO_2 from the substrate surface by standard wet etching in hydrofluoric acid. By controlling the temperature (400 °C - 600 °C) and the oxygen pressure (pO_2= 20 mTorr - 80 mTorr) during the deposition, BTO films with amorphous and polycrystalline structure were deposited. A post-annealing at 600°C was performed in 0.5 atm O_2 pressure to fill the oxygen vacancies.

Reflection high-energy electron diffraction (RHEED) measurements (insets of Fig. 1b) indicate that films deposited at 600°C exhibit a polycrystalline structure (poly-BTO), whereas at lower deposition temperatures amorphous films (a-BTO) are obtained. Surface roughness as measured by atomic force microscopy (AFM) is between 0.7-0.9 nm rms. The refractive index n of α-BTO films (~1.9 at $\lambda > 1300$ nm) is lower than poly-BTO films (~2.2 at $\lambda > 1300$ nm), as measured by spectroscopic ellipsometry (see Fig. 1b), in agreement with data in [3].

To perform switching experiments a 200 nm layer of indium tin oxide (ITO) was sputtered onto the poly-BTO film to realize the top electrode. By applying a 5 V signal (Fig. 1.c), a large change of the refractive index of poly-BTO is induced (red dashed curve) with respect to the initial state (black solid curve), that is as large as $3 \cdot 10^{-2}$ in the 1550 nm range, with no change in the material loss. Such refractive index variation suggests the occurrence of ferroelectric domains reorientation (from *a* to *c* axis) in the poly-BTO film [4]. After the electric signal is switched off (blue dashed-dotted curve), the switched state was mostly preserved with only a small relaxation in the refractive index (red dashed curve). We also observed that the pristine state of the film can be restored by heating the sample above the Curie temperature of BTO (120°C).

III. LOW-LOSS POLY-BTO-COATED SILICON WAVEGUIDES AND CIRCUITS

Polycrystalline BTO was then employed as upper cladding material of Si nanowaveguides. Figure 2(a) shows the cross-sectional SEM photograph of a 220 nm x 400 nm Si waveguide covered with a 200-nm-thin poly-BTO film. For this waveguide geometry, the overlap factor of the guided mode with the BTO material is about 18% for TE polarization and 28% for TM polarization. Given the large Δn measured on poly-BTO films, this would enable a π–phase shift in a waveguide actuator of less than 100 μm length. As shown in Fig. 2(a), at a wavelength of 1550 nm, both modes exhibit a loss change of less than 1dB/mm after the deposition of the BTO layer, thus resulting in less than 0.1 dB actuator loss. The loss decrease observed in the narrowest waveguide (400 nm width) is due to the mitigation of the roughness-induced scattering loss [5].

Figure 2(b) shows the TE transmission measured at the drop port of a silicon microring resonator with a radius of 40 μm. Before the deposition of 200-nm-thick poly-BTO upper cladding (black dashed line), the air-coated silicon microring has a free spectral range of 2.45 nm, a 3 dB bandwidth of about 25 GHz, resulting in a Q factor of about 8000, and an off-band isolation of 18 dB. After the deposition of the BTO cladding (red solid curve), the shape of the transmission spectrum is almost entirely preserved, the Q factor reduction to about 6000 (33 GHz bandwidth) being essentially due to the higher coupling coefficient of the BTO-cladded directional coupler of the microring.

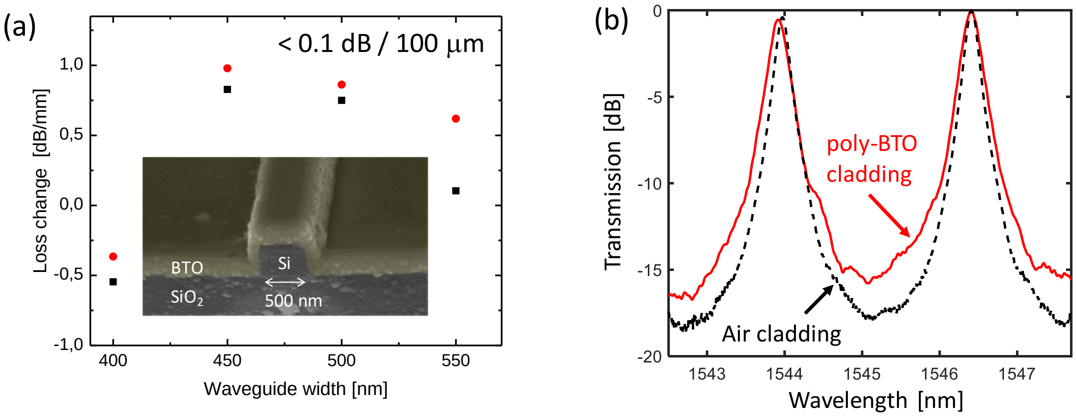

Fig. 2 - (a) Variation of the propagation loss of a Si nanowaveguide (SEM cross-sectional picture in the inset) after the deposition of a 200 nm thick poly-BTO coating. (b) Normalized transmission at the drop port of a microring resonator before (black dashed curve) and after (red solid curve) the deposition of the poly-BTO upper cladding.

IV. CONCLUSION

We demonstrated an electrically-driven non-volatile change of the refractive index of polycrystalline BTO films, which is consistent with a 90° reorientation of the ferroelectric domains. The large refractive index variation ($3\cdot10^{-2}$) would enable the realization of compact (< 100 um), low-loss (<0.1 dB), self-holding phase actuators integrated in silicon optical waveguides. We also successfully integrated poly-BTO films on Si waveguides and microring resonators, demonstrating the possibility to realize PICs with the proposed poly-BTO Si-photonics platform.

V. ACKNOWLEDGEMENT

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VI. REFERENCES

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