Non-Volatile Switching of Polycrystalline Barium Titanate Films for Integrated Optics Applications

I. Maqueira-Albo[1], S. Varotto[2], M. Asa[2], C. Rinaldi[2], R. Bertacco[2], F. Morichetti[1]

1 Dipartimento di Elettronica Informazione e Bioingegneria Politecnico di Milano, 20133 Milano, Italy
2 Dipartimento di Fisica, Politecnico di Milano, 20133 Milano, Italy
francesco.morichetti@polimi.it

The control of optical waveguide properties by exploiting novel materials physical effects and techniques is of high interest in integrated photonics. So far, one of the most established approach to modify the refractive index of optical waveguides is the use of thermo-optic actuators. However, power consumption and crosstalk limit the scalability of thermally actuated photonic circuits to very large scale of integration. To reduce power consumption, non-volatile actuators capable to maintain the switching state without an applied control signal are a promising route. In this work, we demonstrate the possibility to exploit the ferroelectric response of polycrystalline $BaTiO_3$ (BTO) thin films to realize self-holding phase actuators integrated in silicon waveguides.

Ferroelectric domains in BTO are characterized by their in-plane (*a*-axis) or out-of-plane (*c*-axis) orientation. Domain orientation can be switched by an applied electric field greater than the coercive field, leading to a large change of the refractive index *n* which is maintained when the field is switched off. As shown in Fig 1(a) a 100-nm thin BTO film was grown on a conductive silicon substrate by pulsed laser deposition. The film was deposited at a temperature of 600 °C at 40 mTorr of oxygen pressure in the chamber and then it was annealed at 700°C to fill the oxygen vacancies. A 200 nm layer of indium tin oxide (ITO) was sputtered onto the BTO film to realize the top electrode. A voltage control signal *V* was applied across the sandwiched BTO film and the change of the BTO optical properties in the near-IR range was measured after repeated switching cycles by means of spectroscopic ellipsometry. Figure 1(b), shows that after the application of a 10 V pulse, the in-plane refractive index of polycrystalline BTO changed from the reference values measured in the as-deposited material (black curve) to lower values in the switched state (red curve). At a wavelength of 1550 nm, the refractive index change is as large as $4 \cdot 10^{-2}$ and is not accompanied by any measurable change in the material loss. To prove the non-volatile nature of the switching phenomenon, the sample was measured after one week and only a small relaxation was observed (blue curve), demonstrating that the switched state was mostly preserved. Preliminary results suggest that the switching mechanism can be reversed by heating the sample above the Curie temperature (120°C).

Polycrystalline BTO was then employed as upper cladding material of silicon nanowaveguides. Figure 1(c) show the cross-sectional SEM photograph of a 220 nm high x 400 nm wide Si waveguide covered with a 200-nm-thin BTO film. For this waveguide geometry, electromagnetic simulations provide an overlap factor of the guided mode with the BTO material of about 18% for TE polarization and 28% for TM polarization. Owing to the large refractive index change shown in Fig. 1(b), a π-shift in the phase of the guided mode can be achieved in a waveguide actuator of less than 100 μm length. Transmission experiments demonstrate that across this length the excess insertion loss of the BTO covered waveguide is almost negligible. As shown in Fig. 1(d), at a wavelength of 1550 nm, both TE and TM 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, which increases for narrower waveguides and scales up quadratically with the waveguide refractive index contrast [1].

BTO cladded silicon waveguides were also successfully employed to realize integrated devices such as microring resonators. Results demonstrate the possibility to exploit the optical switching properties of BTO films to realize non-volatile phase actuators integrated in silicon photonics circuits.

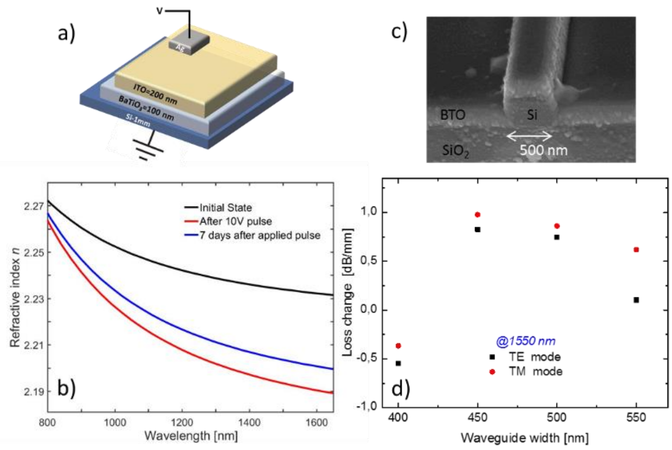

Fig. 1 (a) Sample structure for the optical characterization of electrically-driven BTO switching; (b) spectroscopic ellipsometry measurement of non-volatile change of BTO refractive index after ferroelectric switching; (c) SEM photograph of a silicon waveguide cladded with polycrystalline BTO; (d) Measured variation of the propagation loss of silicon waveguides after BTO deposition.

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[1] D. Melati, A. Melloni, and F. Morichetti, "Real photonic waveguides: guiding light through imperfections," Advances in Optics and Photonics, vol. 6, no. 2, pp. 156-224, May 2014