Integration of Barium Titanate Thin Films in Silicon Photonics for Electro-Optic Modulation

E. Lievens[1,2], E. Picavet[3], K. De Geest[1,2], K. De Buysser[3], D. Van Thourhout[2], P. Bienstman[2] and J. Beeckman[1]

1. Liquid Crystals and Photonics Research Group, Ghent University, Technologiepark-Zwijnaarde 126, 9052, Zwijnaarde, Belgium
2. Photonics Research Group, Ghent University, Technologiepark-Zwijnaarde 126, 9052, Zwijnaarde, Belgium
3. Sol-gel Centre for Research on Inorganic Powders and Thin films Synthesis, Ghent University, Krijgslaan 281 S3, 9000, Gent, Belgium
enes.lievens@ugent.be

***Abstract*—An integration pathway for fully in-house developed lead zirconate titanate $BaTiO_3$ nanophotonic Pockels modulator is presented. In this work, the integration is done through chemical solution deposition of both the spin-on dielectric hydrogen silsesquioxane planarization layer and $BaTiO_3$ film.**

***Keywords*—nanophotonic, Pockels, chemical solution deposition, planarization**

I. Introduction

Silicon photonics has become one of the most widely used platforms for photonic integrated circuits (PIC) for a wide range of applications. Almost all of which require high-speed, low power operation. Modulators based solely on silicon rely solely on the plasma dispersion effect to achieve modulation. The plasma dispersion effect induces a refractive index change in the material through the movement of free carriers, which means that the operation speed is limited by the lifetime of these carriers, giving a maximum achievable bandwidth in the order of tens of gigahertz. Heterogeneous integration of novel materials on silicon is therefore considered as an alternative to solely silicon based modulators. Barium titanate (BTO) is one such material which can be integrated onto silicon. When deposited as a thin film on a photonic chip, BTO exhibits one of the largest Pockels coefficients of all electro-optic (EO) materials, while being chemically and thermally stable [1]. A simplified description of the Pockels effect is given by a linear relationship between the change in refractive index n due to an applied electric field E according to the following equation:

$$\Delta n(E) = -\frac{1}{2} r_{eff} {n_0}^3 E \qquad (1)$$

In this equation, Δn is the induced birefringence, r_{eff} is the effective Pockels coefficient, n_0 is the refractive index in absence of an electric field and E is the applied electric field. Despite its outstanding performance, the integration of BTO thin films on PIC is anything but trivial. In this work, a full-stack in-house developed integration pathway is proposed for the integration of BTO thin films on any substrate, albeit planar or non-planar via a chemical solution deposition (CSD) process and a lanthanum oxycarbonate (LOC) template film [2].

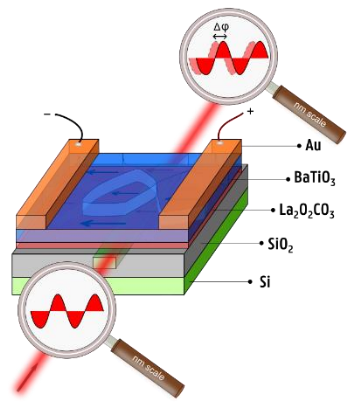


Fig 1. Cross-section of a silicon waveguide with heterogeneously integrated BTO thin film. By applying an electric field between the two electrodes, a phase change is induced in the optical mode travelling through the waveguide.

II. Device Fabrication

In this section, the technology necessary for the fabrication of these nanophotonic Pockels modulators is outlined. The resulting structure is represented in Figure 1. The silicon waveguides are fabricated through electron beam lithography starting from a blank silicon-on-insulator (SOI) substrate containing 220nm silicon. The photonic circuit is patterned onto a positive e-beam resist using a Raith Voyager electron beam lithography system. After development, a PlasmaPro 100 Cobra ICP RIE Etcher is used etch the circuit in the silicon through reactive ion etching. Now, before any additional processing, additional cleaning is needed to remove the remaining contamination present from the e-beam resist or etch process' gasses. Failure to remove this contamination might result in compromised device performance due to future processing steps. A combination of oxygen and UV ozone plasmas is used to clean the substrate after etching.

In the next step, hydrogen silsesquioxane (HSQ) is used as a spin-on dielectric in order to planarize the surface. After spin-coating, the chip is annealed at 650 °C in an oxygen rich environment, causing the HSQ to be transformed into an oxide which closely resembles the native oxide of the SOI substrate. This new top oxide is then etched down to within 40 nanometers of the silicon waveguide using the same PlasmaPro 100 Cobra RIE Etcher, using a different etch stoichiometry.

A fiber-textured BTO thin film can now be integrated through chemical solution deposition by using the LOC template film. This intermediate LOC layers acts as both a seed and buffer layer, ensuring proper growth of the BTO micro-structure without interdiffusion of lead into the silicon. Finally, electrical contacts are defined using photo-lithography using a SUSS MicroTec Mask Aligner and metal sputtering using a Leybold UNIVEX. A cross section of the total stack is shown in Figure 1.

III. Results

Both free-space and on-chip measurements were performed in order to characterize the performance of the BTO thin film. From the free-space measurements, it is possible to extract the EO response of the BTO thin film as a function of the applied electric field [3]. The resulting hysteresis curve is shown in Figure 2. From this, a maximum Pockels coefficient r_{eff} of 138.68 ± 5.78 pm V^{-1} was found.

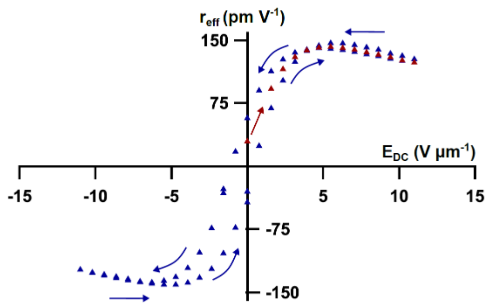


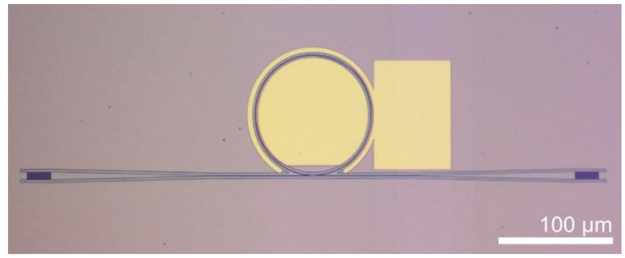
Fig 2. EO response of the BTO thin film because of the applied electric field. The BTO exhibits a hysteresis behavior due to the reorientation of the in-plane polarization domains.

Finally, the BTO is integrated on top of a silicon ring resonator as described in the device fabrication section to validate the device operation. A microscopy image of the top view such a ring resonator is shown in Figure 3. Light with a wavelength of 1550 nm is coupled into the ring resonator through grating couplers as a quasi-transverse electric optical mode. An external DC bias is then applied between the inner and outer electrodes, causing a refractive index shift in the BTO film. This change in refractive index changes the resonant wavelength of the ring resonator, turning it into a working EO ring modulator. The tuning efficiency is now defined as the slope of the wavelength shift due to the applied DC voltage $\Delta\lambda/\Delta V$. From this, the half-wave voltage length product can be found as:

$$V_\pi L = \frac{L\lambda_{FSR}\Delta V}{\Delta\lambda} \quad (2)$$

Here, L is the length of the phase shifter, λ_{FSR} is the free spectral range and $\Delta\lambda/\Delta V$ the tuning efficiency of the ring modulator. Additionally, the Pockels coefficient can now be calculated.

$$r_{wg} = \frac{\lambda g}{\Gamma n_0{}^3 V_\pi L} \quad (3)$$



Where λ is the wavelength, g the electrode gap, n_0 the refractive index of the BTO film, Γ the electro-optic overlap integral and $V_\pi L$ the half-wave voltage-length product of the ring modulator.

Fig 3. Top view of the silicon ring resonator with BTO thin film and gold electrode pads.

The resulting transmission spectrum and tuning efficiency is shown in Figure 4. From these measurements, the half-wave voltage-length product was found to be $V_\pi L$ = 9.863 V cm and the Pockels coefficient was found to be r_{wg} = 169.71 pm V^{-1}. The high half-wave voltage-length product is due to the high index contract between the silicon and cladding, resulting in an optical mode overlap of around 6% in the BTO film. Further optimization of the waveguide design can aid in bringing the half-wave voltage-length product towards that of state-of-the-art devices.

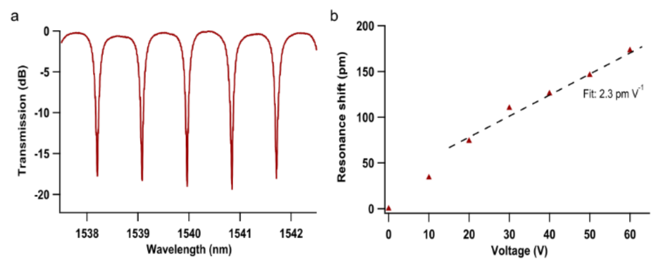


Fig 4. (a) Normalized transmission spectrum of the silicon ring modulator with λ_{FSR} = 0.88 nm. (b) Resonance wavelength shift as function of the applied voltage. A tuning efficiency of 2.3 pm V^{-1} is found.

IV. Conclusion

The integration of a BTO film on PIC was achieved through CSD. Non-planar waveguide structures can be planarized using a simple process turning HSQ into a native-like oxide and then etching back, instead of using chemical mechanical polishing. The BTO thin film is then deposited on this planar surface through the LOC template film, yielding excellent layer properties and an extremely high Pockels coefficient. Device operation was shown through a silicon ring resonator. Performance of the device still has room for improvement and is planned in the near future.

References

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