# Electro-Optic Barium Titanate Modulators on Silicon Photonics Platform

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***Abstract*—Single crystal barium titanate with both c-axis and a-axis orientation have been epitaxially integrated on silicon-on-insulator wafers. Electro-optic Mach-Zehnder modulators with both X-cut and Z-cut configurations are fabricated that exhibit Pockels coefficients of 180 and 130 pm/V, respectively, with Vpi-length values of <5 V-mm.**

***Keywords—electro-optic, barium titanate, Pockels effect, Mach-Zehnder, silicon photonics***

## I. INTRODUCTION

Silicon on insulator (SOI) is an excellent platform for photonic applications due to the ability to fabricate waveguides with very low losses and high optical mode confinement [1-2]. To capitalize on this, active electro-optic (EO) devices need to be readily manufacturable on silicon (Si). While ferroelectric $LiNbO_3$ is well-established as an excellent material in terms of RF electro-optic gain-bandwidth, linearity, low optical loss, and overall robustness [3-4], it is not straightforward to integrate high quality material with silicon [5].

$BaTiO_3$ (BTO) is another ferroelectric material that exhibits one of the largest Pockels coefficients among electro-optic (EO) materials, with a coefficient as high as 1300 pm/V in the bulk [6]. In addition to the substantially larger Pockels coefficient compared to LiNbO3, BTO is much easier to integrate with Si [7-9]. Epitaxial BTO integrated on Si is a promising materials platform for building EO modulators based on the Pockels effect that can be used for fast, low-power optical switches, or even for new forms of computing including neuromorphic and quantum computing [10]. In addition, unlike $LiNbO_3$, BTO does not have any volatile components and is compatible with silicon fabrication processes.

Mach-Zehnder and ring resonator hybrid modulators based on Si waveguides patterned on top of BTO on silicon have been demonstrated by Eltes et al. [11] and Xiong et al. [12], respectively. These devices demonstrate that substantial electro-optic modulation can be achieved in Si photonics-compatible processes. In both cases, the devices utilized a portion of the $r_{42}$ component of the BTO Pockels tensor, which is the largest component and relies on the BTO film having its ferroelectric polarization in-plane (a-axis oriented or X-cut films). Such X-cut modulators have the benefit of being easily fabricated in a standard silicon photonics process flow without pattering the BTO. Waveguides can be made out of silicon or silicon nitride deposited and patterned on the BTO layer and electrodes deposited to form the TE-mode EO modulators [13].

However, fields applied along the X-direction of the crystal to access $r_{42}$ experience an extremely high dielectric constant, typically over 1000, in the BTO material. This high dielectric constant directly translates to decreased EO modulation efficiency. In contrast, fields applied along the Z-direction to access the $r_{33}$ Pockels component experience a typical BTO dielectric constant less than 60. This reduction in dielectric loading can more than offset the reduction in EO coefficient. We fabricate Mach-Zehnder modulators for both configurations and compare their ease of fabrication and modulation efficiency, and demonstrate that the BTO on Si platform is suitable for implementation of low-power, small footprint Mach-Zehnder modulators compatible with silicon photonics fabrication.

## II. BARIUM TITANATE FILM GROWTH

Standard photonic-grade SOI wafers from Soitec were used as the substrate for BTO thin film growth. Before BTO deposition, an 8-nm thick $SrTiO_3$ (STO) buffer layer was first deposited on the clean Si surface using molecular beam epitaxy (MBE) [9]. The BTO layer was deposited by off-axis RF magnetron sputtering at a substrate temperature of 680°C. This technique has been shown to grow optical quality single crystal BTO films at least 10 times faster than MBE, allowing it to be suitable for large scale production [9].For a-axis oriented material, films of 300 nm thickness were utilized, while for c-axis oriented material, films of 110 nm thickness were used. Crystallographic orientation and crystalline quality were confirmed using reflection high energy electron diffraction and x-ray diffraction

## III. OPTICAL CHARACTERIZATION

The complex refractive index for BTO films grown on SOI wafers was characterized via variable angle spectroscopic ellipsometry. The resulting index value was 2.280 at 1550 nm. We also performed a slab waveguide loss test using a Metricon 2010 prism coupler measurement system with optical loss attachment. Slab loss was measured to in the range of 1 to 1.5 dB/cm for both TE and TM modes at 1550 nm wavelength

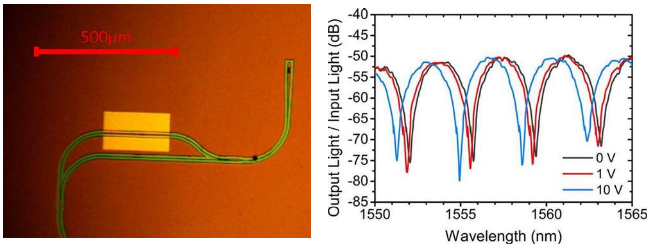

Fig. 1: (left) Optical microscope image of hybrid modulator; (bottom right) linear sweep modulation response when driving one of ther arms of the MZI

## IV. MACH-ZEHNDER MODULATOR CHARACTERISTICS

In order to determine real world performance of BTO on SOI, Mach-Zehnder interferometer (MZI) devices were fabricated on both a-axis and c-axis oriented material.

For a-axis oriented material, we utilized a hybrid waveguide configuration in which the silicon nitride is deposited on top of the BTO and then patterned into the MZI devices [9]. In such a configuration, part of the guided mode is in the silicon nitride and part is in the BTO. We used a device length of 250 μm and a contact spacing of 8 μm as shown in Fig. 1. The contacts are oriented such that the in-plane electric field is at an angle of 45° with respect to the crystallographic axes of BTO. From this device, we obtain a $V_\pi$-L product of 4.2 V-mm, which is similar to what IBM Zurich reported for a device made using wafer bonded BTO [11]. The effective Pockels coefficient was calculated to be 164 pm/V

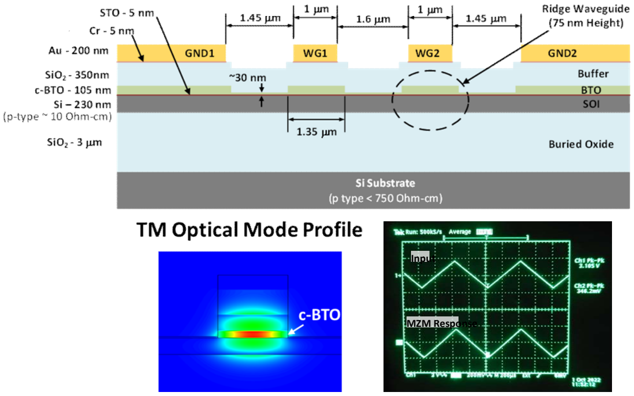

Fig. 2: (top) Cross-section of the Z-cut BTO MZI test device; (bottom left) TM mode optical profile; (bottom right) linear sweep modulation response when driving one of ther arms of the MZI

For c-axis oriented material, we used a device geometry based on a BTO ridge loaded Si waveguide as shown in Fig. 2. The device fabrication process steps entailed patterning and wet etching the BTO ridge, followed by a blanket $SiO_2$ deposition (400 nm) by plasma enhanced chemical vapor deposition (PECVD), and metallization via a patterning and metal lift-off process. The BTO ridge loaded waveguide test device had significantly reduced EO overlap relative to a more conventional slot waveguide design, due to the low relative permittivity $SiO_2$ buffer layer, and to the reduction of the optical mode in the BTO material. Specifically, the net EO overlap was reduced by over an order of magnitude, increasing simulated $V_\pi$-L to about 50 V-mm. The EO coefficient ($r_{33}$) was calculated from the measured $V_\pi$ value using a standard Pockels model and given the simulated EO overlap between the applied electric field and the optical mode in the BTO. The $r_{33}$ value was extracted to be 134 pm/V. This value is consistent with that of bulk BTO.

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