Barium Titanate Electro-Optic Modulators for Silicon Photonics Grown by Off-Axis Sputtering

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Abstract: Barium titanate thin films with have been epitaxially integrated on silicon-on-insulator wafers. They exhibit excellent structural quality with effective Pockels coefficient >180 pm/V and intrinsic propagation loss <2 dB/cm. Hybrid waveguide modulators based on this material exhibit Vπ-length of 0.42 V-cm. © 2023 The Author(s)

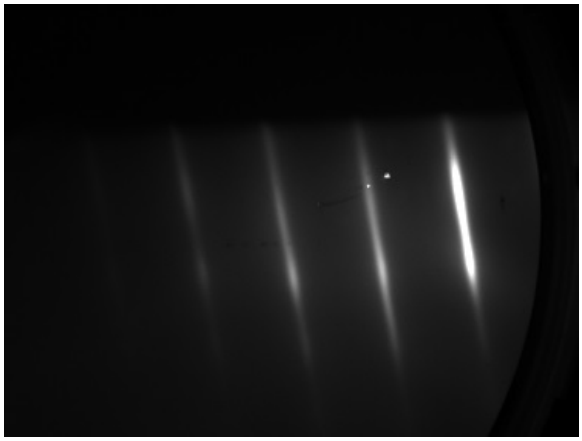
Introduction

$BaTiO_3$ (BTO) is a 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 [1]. In addition to the substantially larger Pockels coefficient compared to the alternative $LiNbO_3$, BTO is much easier to integrate with Si [2-5]. Epitaxial BTO integrated on Si or Si-on-insulator (SOI) is a promising materials platform for building EO modulators based on the Pockels effect that can be used for fast, low-power optical switches, with applications ranging from sensors to novel forms of computing including neuromorphic and quantum computing [6].

Film Growth and Characterization

Epitaxial BTO was deposited from a stoichiometric target by off-axis rf magnetron sputtering on STO-buffered photonic silicon-on-insulator (SOI) wafer. The sputtering was performed at a power density of 2.2 W/cm 2 in a 3:7 O 2 :Ar mixture at a total pressure of 10 mTorr. Deposition was done at a substrate temperature of 700°C and the sample was cooled down at 5°C/min to room temperature. Typical growth rates were ~2 nm/min, about ten times faster than growth by molecular beam epitaxy (MBE). Both 110 nm c-axis oriented and 300 nm a-axis oriented films were grown.

The BTO samples were measured using in situ reflection high energy electron diffraction (RHEED) and in situ X-ray photoelectron spectroscopy (XPS) prior to being unloaded from the vacuum system. These measurements show a very flat and highly ordered crystalline surface as-grown and 1:1 Ba to Ti ratio. X-ray diffraction (XRD) was used to determine in-plane and out-of-plane lattice constants. Rocking curve scans in the out of plane direction show typical full width at half-maximum values of 0.5°. Cross-section transmission electron microscopy imaging confirms the high-quality epitaxy of the BTO, with sharp interfaces and dense layers. Fig. 1shows typical RHEED and XRD analysis of the BTO films grown on SOI.



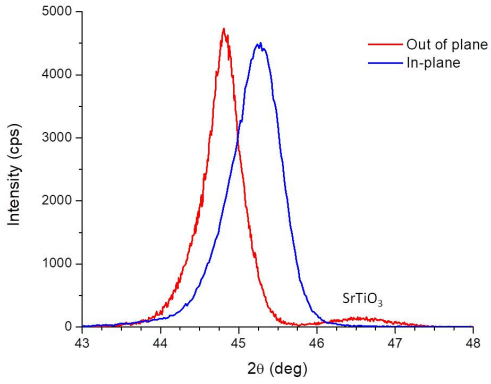


Fig. 1: (a) RHEED pattern of rf sputtered c-oriented 100-nm BTO on Si taken along the <110> azimuth of BTO; (b) In-plane and out-of-plane X- diffraction scans of a BTO film on an SOI wafer.

Optical Characterization

The complex refractive index for sputter-grown epitaxial BTO films on SOI was characterized over visible and near-infrared wavelengths via variable angle spectroscopic ellipsometry. The resulting index value was 2.280 at 1550 nm. This result was in line with values reported for optical grade BTO films. A slab waveguide loss test was done using a Metricon 2010 prism coupler measurement system with optical loss attachment. Slab loss was measured to be in the range of 1.0 to 1.5 dB/cm for fundamental transverse electric and transverse magnetic modes at 1550 nm wavelength..

Electro-optic Characterization

The electro-optic modulation was also measured in a free space transmission geometry for a-oriented films, and in slot waveguide geometry for both a- and c-oriented films (Fig. 2). The effective Pockels coefficient for the a-oriented films (combination of r_{42} and r_{13} Pockels tensor components) is measured to be 180 pm/V, while that for c-oriented films (r_{33}) is 130 pm/V. These yield V_{π}–L values of 0.42 and 0.3 V-cm, respectively, for the a- and c-oriented films. These results show that off-axis sputtered BTO films can yield electro-optic modulation similar to that of high-quality MBE-grown films [5] and that the material would be suitable for implementation of low power Mach-Zehnder interferometer (MZI)-type electro-optic modulators integrated on silicon.

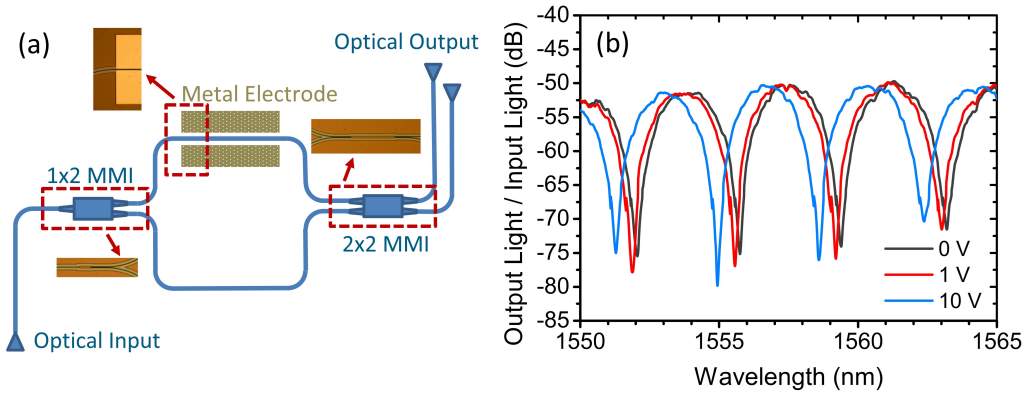


Fig. 2: (a) Schamatic of hybrid MZI device based on silicon nitride to characterize EO modulation; (b) EO modulation results

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