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Analysis of BTO-on-Si-waveguides for energy-efficient electro-optical modulators

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ABSTRACT

In this work, we analyze a horizontal slot waveguide configuration, which evaluates the potential for an integration of barium titanate (BTO) based modulators into a photonic integrated circuit (PIC) technology based on silicon-on-insulator (SOI) wafer. The waveguide configuration consists of a doped crystal silicon layer, a $Ba_{0.7}Sr_{0.3}TiO_3$ (BST) template layer, a barium titanate (BTO) layer and a doped poly-silicon layer on top. In contrast to current approaches, we analyze the performance of this waveguide-structure by using a vertical electrode configuration that is formed by the doped silicon layer. In this way, the electric field strength is dramatically increased compared to current horizontal electrode configuration.

Keywords: Pockels effect, Ferroelectric Materials, Barium Titanate, Electro-Optical Modulators, Slot Waveguide, Pockels Modulator

1. INTRODUCTION

Silicon photonics has become the major platform for optical communication systems due to its high scalability and mass-production capability.¹ Several electro-optical effects like the Pockels,² DC Kerr^{3,4} or electric field-induced Pockels effect⁵ can be used for optical modulators. However, coherent optical communication⁶ requires a highly linear dependence of the modulated optical signal from the electrical input signal, while the employed electro-optical effect should be off-resonant in order to modulate the refractive index but not the absorption. In this way, higher order modulation formats like m-th quadrature amplitude modulation (QAM) can be realized.

Unfortunately, silicon lacks intrinsically from an efficient Pockels effect, also known as the linear electro-optical effect (LEOE),⁷ making high-speed modulation with advanced modulation formats challenging, while the energy-consumption is relatively high and the bandwidth is limited. As a consequence, heterogeneous integration of novel materials like electro-optical polymers,^{8–11} ferroelectric materials^{12,13} or III-V materials is required.¹⁴ One focus of current research lies on the hybrid-integration of ferroelectric materials like barium titanate (BTO) into silicon-based photonic integrated circuits (PIC),¹⁵ giving rise to an extraordinary Pockels effect.^{16–18}

We present an analysis of a horizontal slot waveguide configuration consisting of barium titanate (BTO) on silicon using a $Ba_{0.7}Sr_{0.3}TiO_3$ (BST) layer as template material. We propose the use of a vertical electrode configuration, which is formed by the doped silicon layer. Using BTO in the slot waveguide leads to a large field confinement inside the BTO layer. The BTO layer is out-of-plane oriented. This allows to provide a larger Pockels coefficient and results in a large LEOE in the center layer. State-of-the-art waveguides use bulk metal electrodes beside the waveguide in order to generate a horizontal electric field. This, however, is accompanied with a relatively large electrode distance and, hence, this makes it challenging to enable a sufficient co-integration with state-of-the-art electronic technologies.

In contrast to current approaches, we analyze the performance of this waveguide-structure by using a vertical electrode configuration that is formed by doped silicon layer. In this way, the electric field strength is dramatically increased compared to current horizontal electrode configurations. This allows the efficient use of the Pockels effect, which results in lower driver voltages.

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2. RESULTS

The most common electrode configuration is shown in Figure 1a. In this case, the distance between two electrodes is about $2\ \mu\text{m}$ and a strontium titanate (STO) template layer is used to get a -axis BTO.² In this work, we propose a vertical electrode configuration, as shown in Figure 1b. This has the advantage of a lower electrode distance. However, since the external electric field is then aligned along the z -direction, the Pockels effect is dramatically reduced.¹⁹ Therefore, it is necessary to grow c -axis BTO, i.e. the c -axis lies perpendicular to the plane of the substrate. This can be achieved by using a solid solution of barium and strontium titanate ($\text{Ba}_{0.7}\text{Sr}_{0.3}\text{TiO}_3$, BST). For example, a c -axis oriented epitaxial BTO film has been grown on (001) Si by reactive molecular-beam epitaxy.²⁰

In the following, we use $c\text{-Si} = 220\ \text{nm}$, $\text{BST} = 30\ \text{nm}$, $\text{BTO} = 80\ \text{nm}$ and $a\text{-Si} = 80\ \text{nm}$ as layer thickness, which are typical values for PIC technologies and results in an electrode distance of $110\ \text{nm}$. In fact, a reduced electrode distance is lowering the required driving voltage of electro-optical modulators based on the Pockels effect, which motivates our investigation on a vertical electrode configuration.

Figure 1. (a) Typical electrode configuration for an a -axis BTO, using a STO template layer. (b) A vertical electrode configuration is proposed. A BST template layer is used to get c -axis BTO.

The Pockels effect describes the electric field induced refractive index change described by the change of an ordinary (Δn_o) and extraordinary (Δn_e) refractive index. The optical indicatrix

$$a_{11}x^2 + a_{22}y^2 + a_{33}z^2 + 2a_{23}yz + 2a_{31}zx + 2a_{12}xy = 1 \quad (1)$$

is related to the Pockels coefficients r_{ij} of BTO using the tensorial expression

$$\begin{bmatrix} a_{11} - \frac{1}{n_1^2} \\ a_{22} - \frac{1}{n_2^2} \\ a_{33} - \frac{1}{n_3^2} \\ a_{23} \\ a_{31} \\ a_{12} \end{bmatrix} = \begin{bmatrix} 0 & 0 & r_{13} \\ 0 & 0 & r_{23} \\ 0 & 0 & r_{33} \\ 0 & r_{42} & 0 \\ r_{51} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} E_x \\ E_y \\ E_z \end{bmatrix}, \quad (2)$$

where E_x , E_y and E_z represent the external electric field in x , y and z -direction, respectively. Here, we assume a BTO film mostly with c -axis ferroelectric domain orientation, as it is typically the case.^{19,21} The Pockels coefficient is described by r_{ij} . Here, we used the in the Voigt notation (i.e. $x = 1$, $y = 2$, $z = 3$, $xx = 1$, $yy = 2$, $zz = 3$, $yz = 4$, $xz = 5$, $xy = 6$). The zero components in Eq. 2 can be explained by the crystallographic point group $4mm$ of BTO. This also leads us to the relations $r_{13} = r_{23}$ and $r_{42} = r_{51}$. The Pockels coefficients for stress-free BTO are $r_{13} = r_{23} = 10.2 \pm 0.6\ \text{pm/V}$, $r_{42} = r_{51} = 1300 \pm 100\ \text{pm/V}$ and $r_{33} = 105 \pm 10\ \text{pm/V}$, as reported by Zgonik et al.²²

Presuming a small change of the refractive index and restricting the external electric field to be aligned along the z -direction ($E = E_z$) and taking into account that $n_1 = n_2 = n_o$ and $n_3 = n_e$, the indicatrix (Eq. 2) can be

Figure 2. (a) Refractive index change as a function of the external voltage. The upper function (black squares) shows the refractive index change of the TM-mode and the lower function (red dots) shows the same function but multiplied with the field confinement factor (calculated for BST=30 nm, BTO=120 nm). (b) Calculated field confinement factor as function of BTO and BST thickness. (c) Field confinement factor as function of BSTs refractive index.

approximated as

$$\frac{x^2}{(n_o - \frac{1}{2}n_o^3 r_{13} E_z)^2} + \frac{z^2}{(n_e - \frac{1}{2}n_e^3 r_{33} E_z)^2} = 1. \quad (3)$$

Here, we have neglected the y -component because the light can only be guided as TE-mode (electric field along x -direction) or TM-mode (electric field along z -direction).

In case of TE-mode, the refractive index change can be described by

$$\Delta n_{TE} = -\frac{1}{2}n_o^3 r_{13} \frac{V}{d} \quad (4)$$

and in if the guided mode is TM, the refractive index change is given by

$$\Delta n_{TM} = -\frac{1}{2}n_e^3 r_{33} \frac{V}{d}, \quad (5)$$

where V/d equals E_z and V and d are the external voltage and electrode distance, respectively. The ordinary and extraordinary refractive index is $n_o = 2.3$ and $n_e = 2.27$, respectively.²³ For our simulation study, we use the same refractive index for c -Si and a -Si of 3.47.²⁴ The refractive index of BST is 1.86.²⁵

From Eq. 4 and Eq. 5 it becomes apparent that the TM-mode is preferable because it allows the use of the Pockels coefficient r_{33} , which is ten times larger than r_{13} and, therefore, allows the efficient use of the proposed vertical device concept. Please note that we use a Pockels coefficient of $r_{33} = 105 \pm 10$ pm/V for our study, as reported by Zgonik et al.²² Abel et al. have reported a Pockels coefficient of $r_{33} = 342 \pm 93$ pm/V in thin film BTO.² This value is ten times higher than that of lithium niobate ($r_{33} = 30$ pm/V²⁶). In the following we will use the lower value of $r_{33} = 105 \pm 10$ pm/V.

Figure 2 shows the simulation results. The values are calculated for a wavelength of 1550 nm and a refractive index for BST of 2.0. The refractive index change as a function of the external voltage is depicted in Figure 2a. The upper function (black squares) shows the refractive index change of the TM-mode and the lower function (red dots) shows the same function but multiplied with the field confinement factor (calculated for BST=30 nm, BTO=120 nm). The optical field confinement is defined as the ration of the optical power inside the BTO layer and the entire optical power

$$\Gamma_{BTO} = \frac{P_{BTO}}{P_{\infty}}, \quad (6)$$

where the optical power is calculated by

$$P = \int \int \frac{1}{2} \text{Re}\{\mathbf{E} \times \mathbf{H}^*\} dx dy, \quad (7)$$

where E and H are the electric and magnetic field vectors, respectively.^{27–29}

Figure 2b shows the calculated field confinement factor as function of BTO and BST thickness. From this figure it is apparent that the optical field confinement inside the BTO layer is increased by increasing the BTO thickness, while the BST thickness needs to be minimized. Since the refractive index of BST can vary and depends strongly on the deposition method and conditions, we have calculated the influence of the BSTs refractive index on the optical field confinement inside the BTO layer, as shown in Figure 2c. It is revealed that a high refractive index of BST is increasing the field confinement and therefore the overall refractive index change due to the Pockels effect.

3. CONCLUSIONS

We have analyzed a vertical electrode configuration by employing c -axis BTO. It is revealed that the Pockels coefficient r_{33} can be efficiently used by designing a horizontal slot waveguide. A BTO thickness of 120 nm is recommended, while the BST thickness should be minimized and a high refractive index of BST is preferable. From our results it can be concluded that an energy-efficient Pockels modulator can be realized from the proposed waveguide configuration, while it provides perspectives towards BTO-based photonic devices that are hybrid-integrated into a silicon-based PIC technology.

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