BARIUM TITANATE

ABSTRACT

Barium titanate ($BaTiO_3$ or BTO) is a ferroelectric oxide with outstanding electro-optical properties featuring an ultra-high Pockels coefficient. For this reason, it is potentially an excellent active material for the fabrication of a large variety of electro-optical devices.

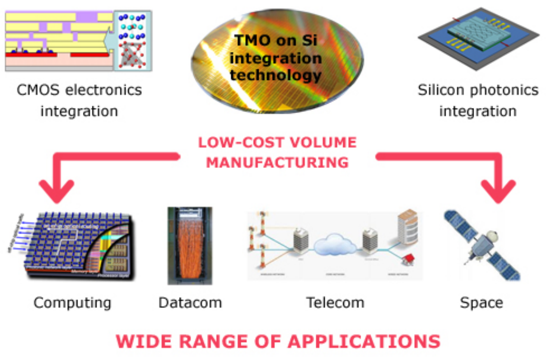

Fig. 1. The combination of TMOs with the Silicon platform mix the characteristics of both technologies allowing for new applications in a wide range of fields.

Silicon photonics technology is currently one of the most promising platforms for enabling automated and low-cost volume manufacturing of highly integrated and complex photonic circuits, mainly because the fabrication processing steps have been developed using standard CMOS (Complementary Metal Oxide Semiconductor) fabrication infrastructure. The development of individual components has been the subject of intense research during the last decade, highlighting the potential of silicon photonics for a wide range of applications but especially those requiring high-volume manufacturing such as telecom, datacom or sensing. However, despite the high potential of silicon photonics, several challenges have still to be addressed for enabling the full development of commercial products. One of the main challenges is to improve the performance metrics of key active photonic components. The intrinsic properties of silicon limits the ultimate performance that can be achieved in devices such as modulators. The integration of new materials on silicon is therefore emerging as an active field in silicon photonics, with the potential to generate technology breakthroughs leading to novel markets and applications. In this context, TMO (Transition Metal Oxide) materials offer a unique opportunity for enabling electro-optical modulation (Fig. 1). Up to now, the main approach followed for enabling these functionalities has been based on the plasma dispersion effect. However, this approach does not allow reaching simultaneously the requirements of low power consumption and high speed operations. Using small driving voltage (under 2V) is necessary for reducing the power consumption as much as for allowing the CMOS integration. That is why the best solution for achieving high operation velocity together with low driving voltage values and insertion losses is the integration of new high performance materials on silicon. For bulk, non-integrated devices, Lithium niobate ($LiNbO_3$) is widely used in commercially available modulators. This electro-optic material with high Pockels coefficients allows for obtaining high modulation velocity and low voltage values and insertion losses. However, its integration with silicon chips is challenging.

As an alternative material, barium titanate ($BaTiO_3$ or BTO) bulk single crystals exhibit a Pockels coefficient with r_{42} > 1000 pm/V at a wavelength of 1500nm. This is more than 20 times higher than $LiNbO_3$ single crystals [1], and it makes it attractive for further reducing the driving voltage of the devices, or further scaling their dimensions. In addition, recent development in the epitaxy of oxides makes it possible to grow such materials epitaxially on silicon. This makes $BaTiO_3$ an excellent material for fast and low power consumption modulator [2]. Barium titanate has traditionally been used in ceramic capacitors and in the last years has been considered for applications in microelectronics and optics. Nevertheless, due to its ferroelectric nature, this non-centrosymmetric material presents an electro-optic performance. $BaTiO_3$ has a tetragonal crystal structure at room temperature, which is shown in Fig. 2. The tetragonal form of the crystal structure implies that the material can be grown with two different orientations depending on the process conditions [3]. Therefore, the electro-optical performance will depend on how the $BaTiO_3$ is grown to fabricate the waveguide structure. The so-called a-axis or c-axis orientations will depend on if the optical axis (z-axis) is in-plane or out-of-plane in the $BaTiO_3$ layer. Since the ferroelectric polarization and the electro-optical properties have a tensorial nature, the orientation of the $BaTiO_3$ layer will largely impact the performance of the electro-optical devices. Orientation is crucial to the implementation of non-volatile electro-optical activity. Hence, the study of the crystalline orientation of the $BaTiO_3$ becomes an essential issue. Promising are in this respect the results obtained in the integration of 30-nm-thick $BaTiO_3$ layers on silicon with tetragonal c-axis orientation and measurable ferroelectric behaviour by IBM group [3].

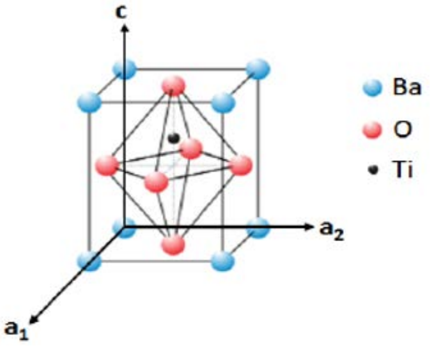

Fig. 2. $BaTiO_3$ crystal structure.

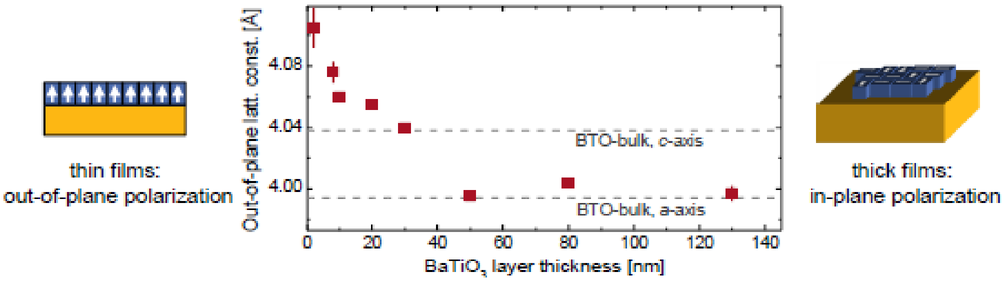

Fig. 3. Crystalline orientation of BTO thin films on Si substrates for various thicknesses. The polarization changes from out-of-plane to in-plane for thicker films [6].

In summary, $BaTiO_3$ is attractive for several reasons for electro-optical applications. On one hand, at optical frequencies thin films are transparent to light, and the refraction index can be considerably tuned by applying an electric field. Furthermore, it can be grown as an epitaxial single crystal on silicon, making it an ideal material for integrated optical modulators. Epitaxial growth of $BaTiO_3$ films on silicon substrate was recently reported [4]. This makes $BaTiO_3$ an attractive candidate in active silicon integrated devices. Table 1 summarizes the $BaTiO_3$ properties at optical wavelengths and the enhanced capabilities offered to the silicon platform. In order to achieve outstanding electro-optical performance, it has been theoretically analyzed and through simulation work the optimum $BaTiO_3$ ferroelectric domain orientation, achieving a V_π voltage as low as 1.35V [6].

Material unique properties at 1550nm optical wavelengths	**Key enhanced capabilities offered to the silicon platform**
• Ultra-high Pockels coefficient. • Very low optical losses. • High refractive index. • Bistable performance via ferroelectric domain switching.	• Ultra-fast and linear optical phase modulation. • CMOS compatible drive voltages with low insertion losses. • Electro-optical bistable performance for non-volatile photonic devices.

Table. 1. $BaTiO_3$ has disruptive properties at optical wavelengths which provide enhanced capabilities like ultra-small footprint and ultra-low power consumption to the silicon platform.

Therefore, the integration of barium titanate in silicon is one of the most promising options for the implementation of electro-optic functionalities with the best performance, especially modulation, which will push forward the limits of current silicon photonics technology.

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