BTO-Enhanced Silicon Photonics

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Abstract *Silicon photonics enhanced with integrated barium titanate, BTO, as a material with ultra-high Pockels coefficients, enables large-scale, low-loss, power-efficient PICs operating at very high speed for communication, optical computing, and sensing. We discuss the status of the technology and the road to first commercial products. ©2023 The Author(s)*

Introduction

In the past decade, silicon photonics has evolved as a mature technology to realize important building blocks in communication networks around the globe. Although the main commercial application of silicon photonic chips today occurs in optical transceivers, other emerging fields such as sensing, beam-steering, and optical computing are betting on silicon photonics as underlying technology solutions.

In all those applications, the conversion of electrical and optical signals is of utmost importance. Components to encode electrical signals into the optical domain (electro-optic modulators) and to tune and reconfigure the optical network with electrical input signals (electro-optic switches and tuning elements) are critical for the performance of silicon photonic chips. Until now, those components utilize the plasma dispersion effect in PIN junctions [1] for high-speed modulation, and the thermo-optic effect in Si or SiN controlled by resistive heaters [2] for tuning and switching. The benefit of these components is the availability of all necessary processing steps in standard silicon photonic manufacturing lines. However, high insertion loss and limited bandwidth in high-speed modulators and large electrical power consumption and cross talk for switches impose severe limitations for upcoming silicon photonic product generations.

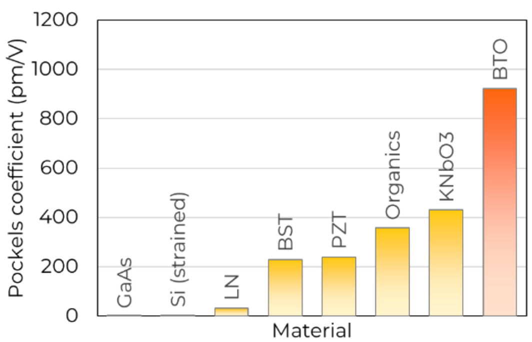

Fig. 1: Pockels coefficients in different material systems [9]

A solution to overcome such limitations is the introduction of new modulators and switches that utilize a material exhibiting a Pockels effect, such as lithium niobate, LN, [3] or barium titanate [4]. In such devices, the application of an electric field changes the refractive index in the waveguide region. The nature of the Pockels effect allows high-speed devices operating at hundreds of GHz, ultra-low insertion losses of below 100 mdB, and compact footprints of few hundreds of micrometers. However, a material with a non-vanishing Pockels effect is not readily available in standard silicon photonic fabrication processes, and hence requires a new approach in design, manufacturing, and testing. Several candidates, such as LN, PZT, or organics are explored in research as material systems with non-vanishing Pockels effect (Fig. 1).

BTO-enhanced integrated photonics

Among the main material options, barium titanate, BTO, shows two outstanding features: First, it exhibits the largest Pockels coefficients of ~1000 pm/V in bulk, and second, it can be deposited as high-quality films onto silicon [5]. In addition, BTO is compatible with large-diameter silicon wafers, shows good chemical stability, experiences low-absorption and high electro-optic performance, and has reached first commercial availability [6]. BTO can be combined with standard silicon photonic fabrication processes [7]. Such integration is a

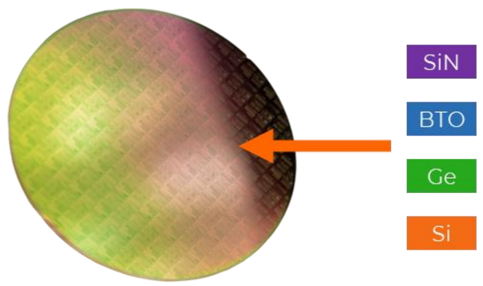

Fig. 2: Integration of BTO at wafer scale into a silicon photonic manufacturing line with all relevant photonic components and processes.

key enabler to utilize existing and established photonic designs and circuits, e.g. receivers with high-speed photodetectors, and extend the functionality with high-speed modulators and low speed tuning elements. These features of BTO has recently gained wide attention for the realization of high-speed modulators and compact switches.

Phase shifters in hybrid BTO/SiPh

An electro-optic phase shifter using a large Pockels effect of >500 pm/V is at the core of the BTO-photonic platform. The phase shift is realized by applying a voltage to electrodes positioned next to a photonic waveguide, which create an electric field and consequently a change of the refractive index in the waveguide core region (Fig. 3). Due to the strong materials response, phase shifters with small $V_\pi \times L$ products below 5 Vmm can be realized [4].
Since the Pockels effect is present at high frequencies, the BTO-based modulators can be used for high data rates of >200Gbps with drive voltages below 1 V_{pp} [8]. In addition, the electrodes are typically positioned at a distance from the waveguide to not cause any metal absorption, allowing low-loss phase shifters with <500 mdB. Since the electro-optic effect is based on the application of an electric field rather than an electric current, the static power consumption in tuning elements is very low, in the nW-range.

Summary and Conclusion

BTO-enhanced silicon photonics adds a new material system, barium titanate, with an ultra-large Pockels effect into the design and component environment of integrated photonics. The emerging technology allows efficient, high-speed, low-loss electro-optic modulation in an integrated photonic platform, enabling new generations of electro-optic transceivers, and upcoming large-scale photonic networks as needed in the field of optical computing, sensing, and beam steering. The technology has reached a stage of commercialization of BTO-enhanced photonic chips, for example via Lumiphase [6].

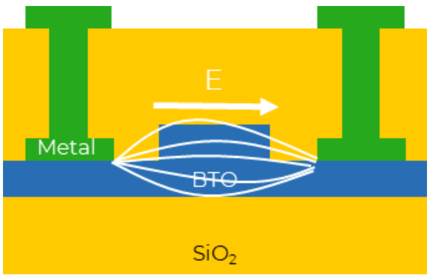

Fig. 3: Example of a cross section of a BTO-based photonic phase shifter. Two electrodes next to the photonic waveguide are used to create an electric field and hence a phase shift via the Pockels effect

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