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Functional Oxides for Photonics

Jean Fompeyrine[1], Felix Eltes[1] and Stefan Abel[1]

[1] IBM Research – Zurich
Säumerstrasse 4, 8803 Rüschlikon, Switzerland
jfo@zurich.ibm.com

Abstract

As a key asset for the future of information and communication technology, silicon photonic integrated circuits will greatly benefit from the integration of novel materials. They could enhance performance or create functionalities not available in the standard materials set used in photonic foundries. Several oxide materials have very interesting optical properties, and can nowadays be integrated with silicon while maintaining their superior optical characteristics. Using ferroelectric oxides as active element, our approach extends the toolbox available for designing integrated silicon photonics.

1. Introduction

Photonics has been the backbone for long range data communication since many years. More recently, the need for bandwidth drove the development towards a tighter integration of electro-optical systems, and silicon photonics (SiPh) became the baseline technology. The key advantages of SiPh are low fabrication costs, a reduced footprint for optical circuits enabled by the large contrast in refractive index between SiO_2 and Si, and the possibility to co-integrate high-speed driving circuits in electronic photonic integrated circuits (EPIC). Alike CMOS scaling was maintained with the introduction of new materials such as high-k dielectrics and high-mobility channels, one can extrapolate that novel materials will be critical to the future of SiPh. This technology is indeed missing several functionalities that do not exist in silicon. Integrated light emitters will only be possible if III-V materials can be brought onto the SiPh platform. Electro-optical modulation is implemented in SiPh with a limited efficiency using the plasma dispersion effect in silicon, although $LiNbO_3$ modulators are the standard technology as discrete components.

This latter example points out that oxides should be considered to add functionalities to SiPh as many compounds have indeed interesting optical characteristics. Their refractive indices can be altered by applying an electric, magnetic, thermal, or mechanical strain field, as summarized in Fig. 1. A review of recent reported work strongly supports the concept that modulation, switching or optical isolation can be mapped to the specific properties of several oxide materials.

2. Challenges

As per today, most of the challenges relate to the growth of materials with the appropriate optical properties, as well as to the methods required to integrate such materials with SiPh. The optical properties highlighted in Fig. 1 are tightly related to structural features, as e.g. in the Pockels effect. In this case, the refractive index changes upon application of an electric field E by an amount Δn, such as $\Delta n(E) \propto r \times E$. The Pockels coefficient "r" vanishes for centro-symmetric crystals, and this effect exists only in materials whose crystalline structure is non-centrosymmetric, such as $LiNbO_3$ or $BaTiO_3$ (BTO). Giant thermo-optic effects are also present in oxides that exhibit metal to insulator transition coupled to structural transition, as in VO_2 [1,2]. Magneto-optic effects can be exploited in materials with a strong Verdet constant, provided mixed valences do not translate in high optical losses. Growing thin films with the required structural and optical properties is therefore a challenging task. Specifically, substantial advances have been made on the use of ferroelectrics in optical

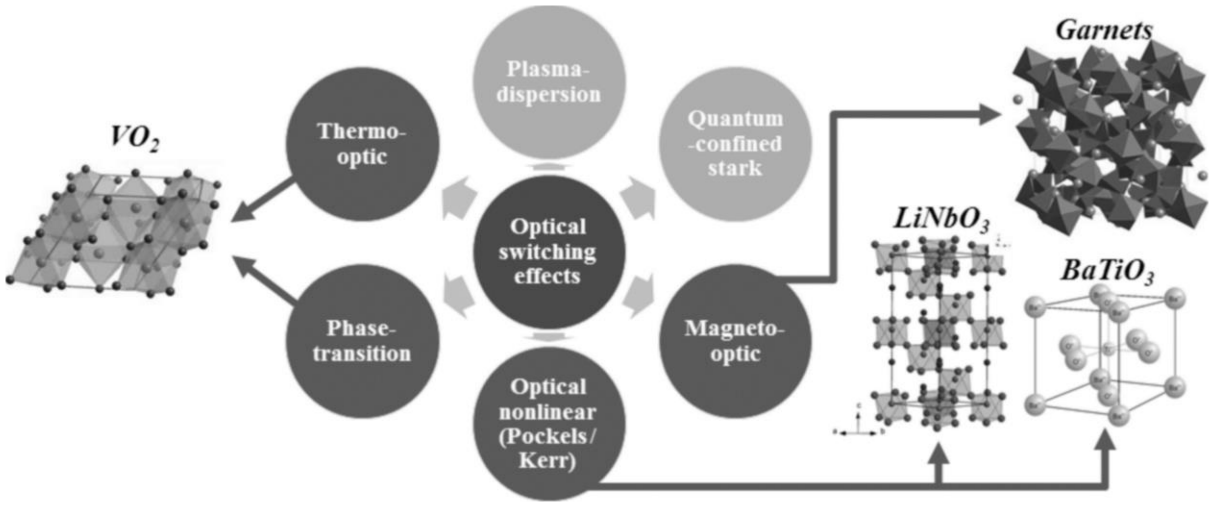

Fig. 1 – Overview of optical effects reported in oxide materials

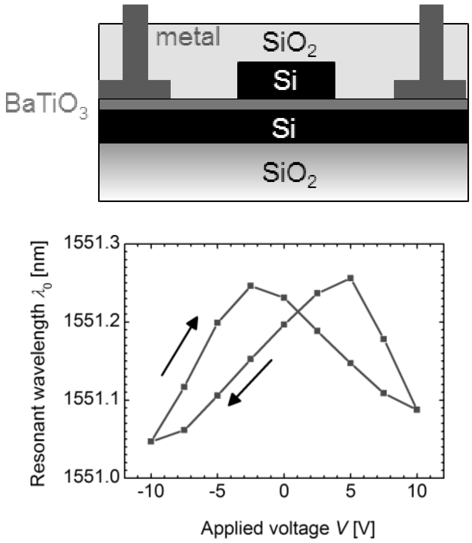

Fig. 2 – Device cross-section and DC characteristic of a ring-resonator on silicon using BTO as active element

devices. With the advent of new generic techniques, high quality BTO films can be grown on silicon and exhibit a strong Pockels effect [3,4]. Epitaxial strain has a strong impact on the direction of the ferroelectric polarization, and the device design must consider the tensorial nature of the Pockels coefficient [5]. The films must exhibit very low optical propagation losses when processed in waveguides, and recent work reports values of a few dB/cm [6]. As a path to integrate on SiPh, several approaches can be finally considered. Direct wafer bonding allows to optimize the oxide layer independently. It has been successfully used to integrate $LiNbO_3$ thin films onto SiPh [7], as well as for magneto-optical devices based on garnets [8]. Having the ability to grow on silicon makes the bonding approach technologically attractive, as it closes the gap between the diameter of the source wafer with the new oxide material and with standard SiPh wafer sizes.

3. Recent Results

In recent years, the potential of oxides in SiPh has been demonstrated in various device types. VO_2 has been largely investigated, and recent reports on electrically induced metal-to-insulator transition [9,10] open the path to fully integrated electro-optical switches using VO_2. Most recently though, switching and modulation in active BTO devices has been reported. Passive and active ring resonators and Mach-Zehnder modulators with a bandwidth of up to 5 GHz and 0.8 GHz, respectively, have been demonstrated [11,12]. Reported Pockels coefficient are an order of magnitude higher than in $LiNbO_3$ modulators, as in the work reported in Fig. 2. Remarkably, the excellent properties of BTO thin films are also maintained in nanometer wide structures [13]. The Pockels effect is observed in plasmonic modulators with critical dimension as low as 50nm, as shown in Fig. 3. The operating frequency (>50GHz) and temperature stability reported in [13] illustrate the benefits of using ferroelectric oxides for integrated SiPh circuits.

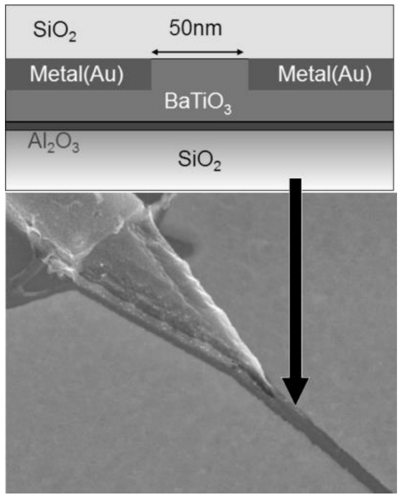

Fig. 3 – SEM micrograph and device cross section for a ferroelectric plasmonic modulator as reported in [13]

4. Conclusions

Together with the advent of integrated silicon photonics, the need to expand CMOS technology beyond its limit helped new deposition and integration techniques to emerge. This is true for the science and technology of functional oxides: seminal works have been reported in the last years, where the unique optical properties of these materials are exploited in devices co-integrated within a silicon photonic platform. Primarily focused on data communications, a technology like silicon photonics cross-fertilized with novel materials concepts might impact applications as different as quantum photonics, ultra-compact plasmonics, high-performance integrated sensors or optical neuromorphic computing.

Acknowledgements

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