# Functional oxides in photonic integrated devices

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## Abstract

On-chip integrated photonic/electronic circuits are seen as essential for the future development of information and communication technologies. One key aspect is to add optical modulation and routing capabilities to enable optical interconnects with enhanced performance. For that purpose, modulators and switches are key components for next-generation photonic integrated circuits. In view of their unique optical properties, the integration of functional oxides into Si-photonic chips is considered to be a strategic objective in the field. Among metal oxides, some materials stand out for their particularly remarkable properties. On the one hand, ferroelectric oxides, such as $LiNbO_3$ and $BaTiO_3$, display outstandingly large electro-optical properties, which can be exploited to modulate optical signals with ultra-high speeds and low losses. Alternatively, the metal-insulator transition in oxides, such as $VO_2$, shows large electrically-induced changes in the refractive in the range of telecommunications wavelengths, offering a promising route towards energy efficient photonic switches. Finally, novel concepts for photonic devices stem from the possibility of achieving epsilon near-zero regimes for optical communications in transparent conductive oxides. We provide here a critical survey on the current status of the integration of functional thin film oxides into Si and the progress in their optical functionalities with respect to the standards of Si photonics. Future prospects in emerging fields, such as optical networks for neuromorphic computing are also considered.

**keywords** (silicon, photonics, functional oxides, electro-optics, switching)

## 1. Introduction

Since the introduction a decade ago of multicore design in chip manufacture, the speed of processing units has increased steadily fast, to the point that signal frequencies beyond 100 GHz are expected to be within reach very soon. At such clock rates the existing on-chip copper interconnects –that link and transmit data between the processing cores– are unsustainable, as the signal integrity is degraded due to the impedance of copper lines. Consequently, alternatives to conventional on-chip electrical wiring have been keenly explored over the few past years. Among them, silicon photonics is considered to be a promising solution [1-2], offering the ability to shift data around with improved speed, energy efficiency and immunity against electromagnetic interferences. Silicon photonics is also foreseen to drive the transition from current optical interconnects, where optics is simply used for data transmission, to a new generation of systems, where switching and routing operations are performed by optoelectronic devices [3-4]. Nevertheless, the plasma dispersion effect used in silicon photonics suffers from drawbacks in terms of speed, energy efficiency or optical losses due to the limitations that silicon show for the electric switching of their optical properties –e.g., the refractive index– [5]. In this context, as described below, functional metal oxides stand out for their ability to have unique optical properties and, consequently have raised a large interest for their integration into Si-compatible photonic circuitry.

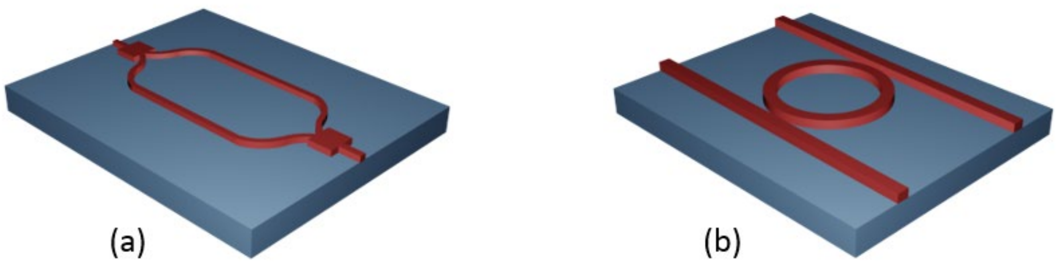


**Fig. 1**. (a) Mach-Zehnder interferometer and (b) ring resonator photonic structures.

As aforementioned, next generations of optical interconnects will require optical modulation and routing capabilities with high performance and, therefore, modulators and switches are one of the most relevant components for photonic integrated circuits. With this in view, the integration of functional oxides into Si-photonic chips has been mostly investigated in device architectures based either on Mach-Zehnder interferometers (MZI) or microring resonators. Briefly, the MZI structure, shown in Fig. 1(a), is based on inducing relative phase shifts between two optical paths derived from a single source. Alternatively, in microring resonators structures straight waveguides are placed between circularly shaped waveguides, as depicted in Fig. 1(b). At resonance, light is passed through the loop from the input waveguide, so that its intensity rises steeply due to constructive interference, which is detected at the output waveguide. The advantage of ring resonators is that they minimize the footprint but this reduction comes at the expenses of optical bandwidth that can only be increased by using more complex structures or switching techniques. Conversely, MZI structures have a wider optical bandwidth but commonly have larger footprint and consume more electrical power, which limits the scalability.

It is also important to distinguish between modulation and switching functionalities. The electro-optic modulator is a device that changes the properties of an optical wave, usually the amplitude or phase, by means of an electrical signal. The most relevant parameters are the electro-optical bandwidth, modulation efficiency and insertion losses. Electro-optical bandwidths above 40 GHz are required for datacom applications that eventually could enable data bit rates up to 100 Gb/s depending on the modulation format. The modulation efficiency is normally quantified in terms of the $V_{\pi}L$ product, which relates the length and driving voltage required to achieve a π-phase shift. Commercial modulators have typically values around 4 to 8 V·cm while insertion losses are around 5 dB. However, low driving voltages below 3 V are mandatory for allowing the co-integration with CMOS electronics. Lower insertion losses are also needed for efficiently integrating many optical functionalities into a single chip. In that context, ferroelectric oxides have grabbed a specific interest because of the large linear electro-optical coefficients intrinsic to their noncentrosymmetric crystal structures and their feasibility to be integrated with silicon photonic devices [6].

Optical switches are used to route an optical signal from an input port to an output port. The optical bandwidth of the switch determines the maximum date rate of the optical signal that can be routed with minimum insertion losses and crosstalk to adjacent output ports. Optical routing of signals with data rates above 100 Gb/s are expected to meet the future needs of data centers. On the other hand, the switching speed is related with the time required to change the state of the switch by applying an electrical excitation or, in other words, the routing of the high-speed optical signal from one output port to another. The requirement in terms of switching time depends on the application. However, fast responses in the order of the nanosecond are pursued to reduce latency in data communications. An additional relevant property is the power of the electrical signal used to change the switching state, i.e. the power consumption of the optical switch, which will determine, together with the footprint, the capacity to scale the number of ports. Power consumptions in the miliwatts range or below are expected for enabling large switching matrices. In that case, strong electronic correlations in metal oxides and transparent conducting oxides are currently promising approaches for electro-optical switching applications.

In the following, an overview is given on the current status and future challenges of functional oxides for silicon photonic applications.

## 2. Current and future challenges

*Ferroelectric oxides.* Today commercial electro-optical modulator devices used in fiber-optics communications are mainly based on the Pockels effect in lithium niobate ($LiNbO_3$) technology.

Having access to such electro-optic effect is highly desirable due to the inherent ultra-fast speed, optical lossless performance and high linearity for enabling multilevel modulation formats. Unfortunately, Pockels effect is not present in silicon due to its centrosymmetric diamond crystal structure. Therefore, alternative approaches are currently being investigated such as applying stress to the silicon waveguide to break the crystal symmetry or the integration of active materials into the silicon platform. In the latter, ferroelectric oxides are excellent candidates due to their high Pockels coefficients. $LiNbO_3$ is the first evident option as the technology is mature and commercially available so material properties are very well controlled. Modulation bandwidths up to 50 GHz with modulation efficiencies below 6.5 V.cm have been demonstrated in hybrid $LiNbO_3$/Si photonic structures [7]. However, $LiNbO_3$ cannot be grown on top of silicon and bonding techniques are required for enabling the integration with silicon photonics [8], which remains as the main future challenge. These considerations suppose a serious roadblock for the development of integrated electro-optic modulators based on $LiNbO_3$.

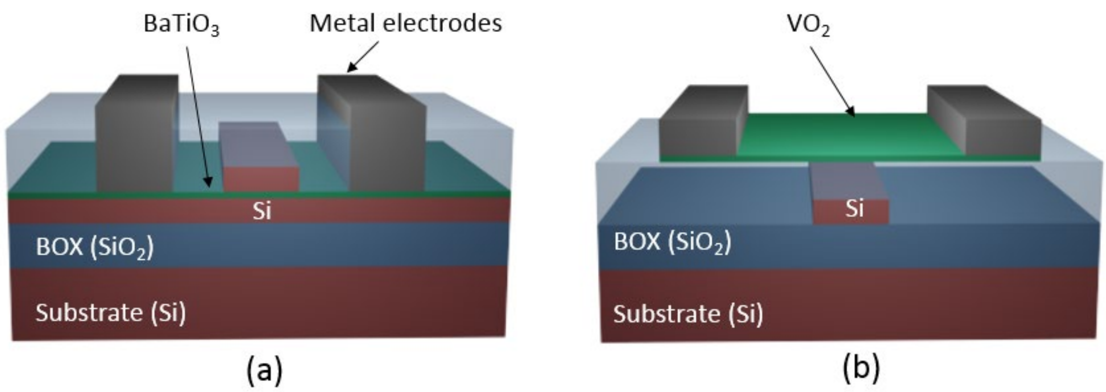


**Fig. 2**. Examples of Si-compatible (a) $BaTiO_3$ and (b) $VO_2$ waveguides.

More recently, barium titanate ($BaTiO_3$) has appeared as a promising alternative to $LiNbO_3$ [Ab13]. Indeed, the Pockels coefficient in bulk $BaTiO_3$ crystals ($r_{BTO}$> 1000 $pm \cdot V^{-1}$) is several orders of magnitude higher than $LiNbO_3$ ($r_{LiNbO3} \approx$ 30 $pm \cdot V^{-1}$) [9]. These interesting properties have stimulated the analysis of $BaTiO_3$-based photonic devices. Along this line, Mach-Zehnder modulators with Si-compatible $BaTiO_3$ waveguides, shown in Fig. 2(b), have predicted values of $V_\pi L$ as low as 0.27 V·cm for *a*-axis oriented $BaTiO_3$ and TE polarization by rotating the optical waveguide to an optimum angle [10]. The reality, however, is that the experimental values of the Pockels coefficients measured in thin films are much smaller than those reported for bulk crystals [11]. Among the highest recorded values, electro-optical modulation based on a hybrid $BaTiO_3$/Si waveguide structure has been experimentally reported with an estimated effective Pockels coefficient up to 213 $pm \cdot V^{-1}$, voltage length product of $V_\pi L$ = 1.5 V·cm, and modulation bandwidths in the gigahertz regime but large propagation losses of 44 dB/cm [12], much larger than the propagation losses below 2 dB/cm of state-of-the-art silicon waveguides.

We see, therefore, that the measured voltage length product $V_{\pi}L$ is within the range of commercial modulators, but the appearance of high propagation losses is a serious drawback that needs to be tackled. Fortunately, recent studies show that optical losses depend strongly on the material processing and appropriate CMOS-compatible procedures can be developed to obtain low-loss waveguide structures with absorption losses around 6 dB/cm, which are much closer to the standards of silicon photonics (~2dB/cm) [13].

On the other hand, as aforementioned, there is still a large room to improve the optical properties of Si-integrated thin films and, in particular, the electro-optic coefficients. In this respect, a key aspect is to have an accurate and reproducible control of the ferroelectric domain orientation during the film growth, since it has been demonstrated that domain orientation has a strong impact on the modulation performance [10, 14]. Additionally, a comprehensive recent study has shown the strong dependence of the Pockels effect in $BaTiO_3$ thin films on the microstructure [11]. More specifically, the main aspects that have been identified as essential to maximize the electro-optic response are related to the reduction of the film porosity, which reduces the effective electric field inside the ferroelectric layer and the increase of tetragonality $c/a$, where $c$ and $a$ are the lattice parameters, which is generally used as an indicator of symmetry breaking. A reduction of tetragonality may be caused by defects that restore locally centrosymmetricity or to the formation of multidomains with random orientations. Therefore, achieving dense, tetragonal, epitaxial films remains the big challenge for the next future to enhance the electro-optic properties towards bulk values [11]. Alternatively, novel concepts may yield new perspectives and developments, as in the recent demonstration of an ultra-compact $BaTiO_3$/Si plasmonic modulator operating up to 72 Gbit/s data rates [15].

*Metal-insulator transitions in oxides*. Because of the metal-to-insulator transition, vanadium dioxide ($VO_2$) has raised recently the interest for plasmonics, metamaterials, and reconfigurable photonics. The most significant characteristic is the large modulation of the complex refractive index, particularly at telecommunication wavelengths [16], which allows the design of ultra-compact devices. Hybrid $VO_2$/Si photonic waveguide structures have been successfully demonstrated mainly with one input/one output (1x1) configuration and exploiting the change in the imaginary part of the refractive index [17]. Electro-absorption modulation with large extinction ratios above 10 dB have been achieved with astonishing active lengths of only 1 µm [18]. Such an ultra-small modulation device allows for scaling up the integration of modulators arrays and reduces the size mismatch between photonics and electronics. The main challenge is the ultimate modulation speed that can be achieved. The pure electronic process in the $VO_2$ phase transition is inherently very fast and switching times lower than 2 ns have been experimentally measured in $VO_2$/Si devices [19]. Nevertheless, a Joule based thermal process has been shown to be necessary for completing the transition, which is required to maximize the modulation depth but would prevent its use for high-speed modulation. Therefore, strategies to minimize the impact of the slow thermal component are mandatory for enabling practical modulating devices.

As mentioned in the introduction, a desirable target is to develop optical switches with low power consumption, low insertion losses and compact footprint as key parameters for scalability. Very recently, efforts in this direction have been investigated and 2×2 photonic switches have been designed using microring resonators based on the hybrid $VO_2$/Si waveguides depicted in Fig. 2(b), with footprint below 50 $\mu m^2$ and a high optical bandwidth that could support a data throughput above 500 Gbit/s [20]. However, insertion losses are too high (> 1 dB) for enabling large-scale switching matrices. The reduction of the imaginary part of the $VO_2$ refractive index at the insulating state or novel disruptive designs of the $VO_2$/Si photonic waveguide structure are potential approaches for minimizing insertion losses. On the other hand, the impact of the external circuitry on the power consumption when electrically switching the $VO_2$ has been proven critical and power consumption reductions up to 90% have been demonstrated reaching values around 5 mW [21].

The integration of $VO_2$ films on hybrid silicon waveguides faces also with material challenges. The most essential issue is related to the structural mismatches of $VO_2$ and Si, which can degrade the optical performance. Moreover, due to the multiplicity of valence states of vanadium, there are several stable oxides of different chemical composition, including $VO_2$ polymorphs, $V_2O_5$ and $V_2O_3$, among many other phases. This has stimulated the research of the optimum growth conditions for high optical performance of $VO_2$ films on silicon platforms, with promising results [22-23]. These encouraging perspectives may enable future devices based on $VO_2$ competitive with actual silicon photonic switches. Furthermore, the potential of hybrid $VO_2$/Si devices to operate as photodetectors with high sensitivity at telecom wavelengths has also been shown with responsivities in excess of 10 A/W [18].

*Transparent conducting oxides*. Several transparent conducting oxides, and in particular indium tin oxide (ITO), have gained an increased interest during the last years for pushing forward the limits of electro-optical functionalities. As with $VO_2$, the main outstanding property is the ability to achieve an ultra-large change of the complex refractive index ($\Delta n > 1$) but, in this case, by changing the carrier concentration under the application of an electric field [24]. Furthermore, an epsilon-near-zero (ENZ) regime at telecommunication wavelengths can be achieved and exploited to significantly enhance the variation of the optical mode properties. In the ENZ condition (i.e., permittivity $\varepsilon \approx 0$), the material undergoes a transition between a dielectric (low absorption) and a metallic response (high absorption). The electric field is largely enhanced with respect to the adjacent materials which improves the modulation efficiency when a high optical confinement across the ENZ material is also achieved [25].

Along this line, most of the proposed approaches for electro-optical modulation are based on the control of plasmonic modes through a charge-accumulation layer in metal-oxide-semiconductor (MOS) structures. High modulation depths (2.71 dB/μm) have been demonstrated [26]. However, a trade-off between modulation depth and insertion losses is still present due to the high losses inherent to plasmonic mode propagation. Therefore, pure dielectric approaches based on replacing metal layers by semiconductor dielectric materials, basically doped silicon, have also been designed with the aim of minimizing losses [27]. One of the main challenges is still to demonstrate high-speed modulation as an ultra-fast time dynamics linked to the carrier concentration effect is expected. Conversely, a non-expected resistive switching performance has been reported that would not be useful for implementing modulating devices but could open a new way for enabling optical switching with a bistable performance [28]. Additional transparent conducting oxides, such as those based on doped zinc oxide, are also being considered as an alternative to ITO.

## 3. Concluding Remarks

In the previous section, we have described the current status and future challenges on the research of some functional oxides and their integration into Si-photonic devices to achieve optical modulation, switching and even photodetection capabilities with unique performance. These devices could enable a transition to a new generation of optical interconnects for datacom applications but they could also expand applications in other fields, such as sensing or space. Furthermore, the demonstration of successful active photonic devices opens up fascinating novel avenues into other emergent fields, such as non-volatile optical memories, quantum photonics or neuromorphic computing.

For instance, the above-mentioned Mach-Zehnder interferometers (Fig. 1a) work by controlling the interference of beams travelling along waveguides, so that the relative amplitude and phase of the interfering beams in the output waveguides can be modulated. This process enables the possibility of controlling and programming the transmission response through a mesh of interconnected arrays of MZI nodes. This complex structure should allow developing a remarkably wide range of optical functionalities. Among the most interesting prospects, arrays of interconnected MZI modules can enable linear optical operations that can mimic neuromorphic operations using optical networks. An impressive step towards this paradigm has been realized recently in silicon integrated photonic meshes comprising hundreds of optical components in millimeter-sized chips, demonstrating key aspects of an optical neural network processing [29].

At this point is where some functional oxides may have a decisive role for further development of Si-integrated optical neuromorphic computing. In particular, it is known that brain-like computing requires highly connected networks of nonlinear elements that are “trained” to perform operations. For that purpose, integrating materials with non-volatile physical properties is an important advantage. In this line, recent research has shown the potential to reconfigure the strength of interconnected networks of oxide-based ferroelectric tunnel junctions [30]. Similarly, other oxides with non-volatile functionalities –as in ferroelectrics or resistive switching materials– may provide a playground to implement physically and modulate the connection strengths in a network. With this in mind, and given the impressive progress in the integration of electro-optic oxides into silicon platforms, the possibility of further development into optical neural networks is particularly enticing.


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