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# Silicon CMOS Compatible Transition Metal Dioxide Technology for Boosting Highly Integrated Photonic Devices with Disruptive Performance

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**ABSTRACT**

In this work we will present the objectives and last results of the FP7-ICT-2013-11-619456 SITOGA project. The SITOGA project will address the integration of transition metal dioxides (TMO) materials in silicon photonics and CMOS electronics. TMOs have unique electro-optical properties that will offer unprecedented and novel capabilities to the silicon platform. SITOGA will focus on two disruptive TMO materials, barium titanate ($BaTiO_3$) and vanadium didioxide ($VO_2$), for developing advanced photonic integrated devices for a wide range of applications. Innovative integration processes with silicon photonics circuits and CMOS electronics will be developed. The whole technology chain will be validated by two functional demonstrators: a 40 Gbit/s DPSK transceiver and an 8×8 switching matrix with 100 Gbit/s throughput.

**Keywords**: photonic integrated circuits, silicon photonics, transition metal dioxides, modulation, switching.

## 1. INTRODUCTION

High performance computing and communication technologies have proven as pervasive, driving forces in the world economy over the past two decades. They affect nearly every aspect of life: education, entertainment, transportation, workplace and personal communication to the basic infrastructures of our economy and society at large. One of the main driving forces behind these advances has been the continuously progress in photonics technologies. However, until recent years, the photonic industry has been focused on different material technologies to optimize individual photonic devices: III-V compounds for lasers, lithium niobate for modulators, germanium for photodetectors or doped silica for passive optical devices. Nowadays, it is clear that a common technological platform is a must to integrate all the above functionalities into a single photonic device. Furthermore, a platform that uses most or all fabrication facilities used in CMOS electronics would facilitate the integration with the required electronics circuitry and reduce the cost for mass-manufacturing.

Silicon photonics technology, also referred to as CMOS photonics, is currently one of the most promising platforms for enabling mass-manufacturing of highly integrated and complex photonic circuits mainly because the fabrication processing steps have been developed using standard CMOS fabrication infrastructure [1]. The development of individual components has been the subject of intense research during the last decade. More recently, significant efforts have also been devoted towards photonic integration. However, despite the high potential of silicon photonics, several challenges need still to be addressed for enabling the fully exploiting the technology. One of the main challenges is still related to improve the performance metrics of key photonic components, in particular active components. The silicon material itself imposes barriers to the ultimate active performance that can be achieved and therefore the integration of new materials on silicon is emerging as an active field in silicon photonics.

Transition metal dioxides (TMO) comprise a very diverse and fascinating class of compounds with properties that can be tailored for a wide variety of applications. Many transition metal dioxides have been prepared in bulk form or as thin films in the past several decades. However, obtaining single crystalline and high quality photonic waveguides has been a long-standing issue. The difficulty is largely related to the complex composition of TMOs, and most synthetic techniques developed in the past for nanophotonic waveguides cannot be simply applied. In fact, the benefit of using such materials is directly related to the structural quality of the crystal, so that a high quality fabrication process is a must for producing single crystal thin film. Recent significant progress in deposition tools and methods has enabled the growth of single crystal dioxide layers onto low-cost large-size silicon substrates which has substantially lowered the barrier to integrate TMO materials on silicon photonics.

Two promising TMO materials are barium titanate ($BaTiO_3$) and vanadium didioxide ($VO_2$). While $BaTiO_3$ is interesting for its high electro-optical Pockels effect [2], $VO_2$ is being actively investigated due to the ultra-large change in refractive index which follows the electrically-driven metal-insulator-transition (MIT) [3]. Therefore, such materials offer a unique opportunity for enabling breakthrough electro-optical modulation and switching functionalities. Up to now, the main approach followed for enabling these functionalities has been based on a pure silicon solution by means of the plasma dispersion effect [4]. However, despite the impressive results reported during the last years, there is still challenging to achieve high modulation speed with high extinction ratio together with CMOS-compatible drive voltages and low insertion loss. Table 1 summarizes $BaTiO_3$ and $VO_2$ unique properties at 1550 nm optical wavelengths and the key enhanced capabilities that could be offered to the silicon platform.

*Table 1. Barium titanate ($BaTiO_3$) and vanadium didioxide ($VO_2$) properties and key enhanced capabilities that could be offered to the silicon platform.*

| | **Material unique properties at 1550 nm optical wavelengths** | **Key enhanced capabilities offered to the silicon platform** |
|---|---|---|
| **$BaTiO_3$** | ▪ Ultra-high Pockels coefficient (up to five times larger than in lithium niobate).<br>▪ Very low optical losses (<0.5 dB/cm).<br>▪ High refractive index ($n_o = 2.44$ and $n_e = 2.36$).<br>▪ Bistable performance via ferroelectric domain switching. | ▪ Ultra-fast and linear optical phase modulation.<br>▪ CMOS compatible drive voltages with low insertion losses.<br>▪ Electro-optical bistable performance for non-volatile photonic devices. |
| **$VO_2$** | ▪ Metal-insulator-transition induced thermally, electrically or optically.<br>▪ Ultra large change of the complex refractive index.<br>▪ Ultra-fast time response (in the sub-nanosecond range).<br>▪ Bistable performance via phase transition triggering. | ▪ Ultra-small footprint.<br>▪ Ultra-low power consumption.<br>▪ Very low insertion losses.<br>▪ Electro-optical bistable performance for non-volatile photonic devices. |

## 2. BARIUM TITANATE ($BaTiO_3$) ON SILICON TECHNOLOGY

The outstanding electro-optical properties of ferroelectric dioxides have been known for long and the possibility of fabricating optical devices using these materials has been first proposed in the late 80's. The most known ferroelectric dioxide is lithium niobate ($LiNbO_3$) that is currently used in commercial electro-optical modulators. However, though different attempts have been investigated, the integration as high-quality films on silicon has only been achieved via complex and costly layer-bonding approaches [5]. On the other hand, $BaTiO_3$ have also been the subject of an intense research in the last decade due its ultra-large linear electro-optical coefficients. $BaTiO_3$ bulk single crystals exhibit a Pockels coefficient with $r_{42}$ > 1000 pm/V at a wavelength of 1500 nm which is more than 20 times higher than $LiNbO_3$ single crystals.

Magnesium dioxide (MgO) has been so far the main substrate of choice for $BaTiO_3$ due to its lower refractive index and optical transparency. However, the advance in silicon photonics has recently pushed the development of integrating such material directly on silicon. Since the first methods to epitaxially deposit perovskite dioxide thin films on silicon were established, the growth process has been carefully optimized and single crystalline layers have been fabricated even on large-scale 8" substrates [6]. Recently, the integration of a ferroelectric $BaTiO_3$ film on silicon exhibiting a strong linear electro-optic effect with an effective Pockels coefficient of $r_{eff}$ = 148 pm/V has been demonstrated [7,8]. This value exceeds previous data reported for integrated $LiNbO_3$ by at least a factor of five, and for strained Si by a factor of 100. In the context of the SITOGA project, recent results on the integration of $BaTiO_3$ on silicon by molecular beam epitaxy (MBE) are shown on Fig. 1(a). The high resolution dark-field TEM image shows that the $BaTiO_3$ layer is of excellent crystalline quality up to its top surface.

The integration of $BaTiO_3$ on silicon will be exploited to demonstrate beyond state-of-the art electro-optical modulation. To enhance the modulation efficiency, we propose to use a photonic waveguiding structure based on a horizontal slot configuration with the $BaTiO_3$ located in the slot region. Figure 1(b) shows the designed waveguide structure, initially considered meanwhile the process for $BaTiO_3$ etching is developed. A similar structure has also been recently reported showing a modulation bandwidth up to 4.9 GHz [9]. Figure 1(c) shows a scanning electron microscope (SEM) image of the fabricated structure. Hydrogenated amorphous silicon (a-Si:H) layer was deposited by plasma-enhanced chemical vapour deposition (PECVD) and a post growth anneal was used to eliminate residual oxygen vacancies in the $BaTiO_3$. The device was patterned by RIE-ICP and a 1 µm $SiO_2$ upper cladding was deposited by PECVD. The lateral bubbles are due to the BHF etch used to remove the $SiO_2$ for better seeing the SEM image.

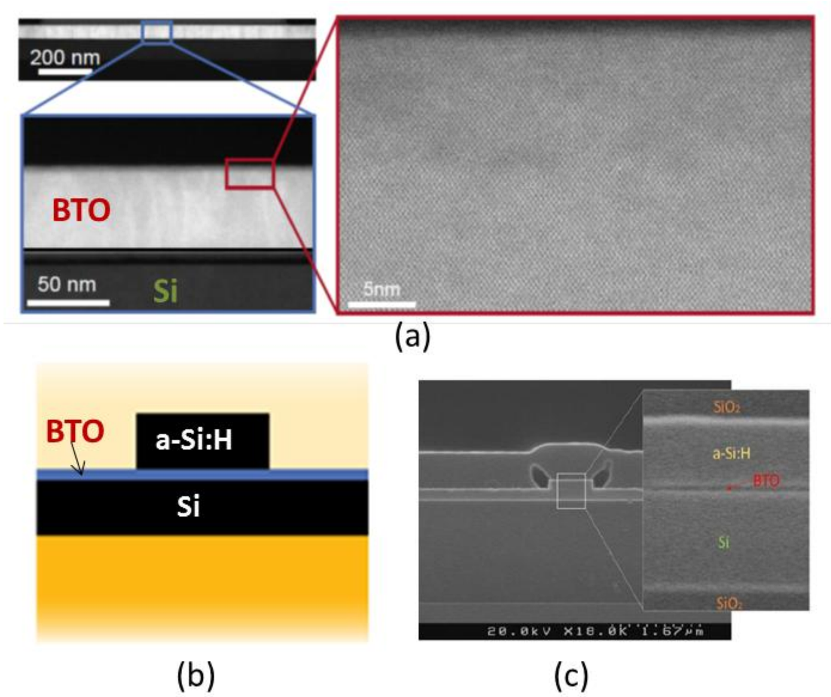


*Figure 1: (a) Results on the integration of 50 nm $BaTiO_3$ on Si by molecular beam epitaxy (MBE); (b) Schematic and (c) SEM image of the slot $BaTiO_3$/Si waveguide.*

## 3. VANADIUM DIOXIDE ($VO_2$) ON SILICON TECHNOLOGY

Metal-insulator transition (MIT) in dioxides has been a topic of long-standing interest in condensed matter materials sciences. Among the different TMO materials with MIT, particular emphasis is placed on emerging research devices operable near room temperature wherein the phase transition can be triggered by small thermal, electrical, or optical perturbations. This is the case of vanadium dioxide ($VO_2$) with a MIT of about 340 °K in bulk crystals. This unique property, coupled with an impressive five-order-of-magnitude resistance change in single crystals across the transition, makes $VO_2$ a compelling candidate for enabling photonic devices with breakthrough performance.

The integration of $VO_2$ with silicon photonic devices has been demonstrated in different works for enabling modulation and switching [10-12]. However, one of the remaining challenges, which will be targeted in the SITOGA project, is to trigger the phase transition in the $VO_2$ material integrated with silicon photonic waveguides by an external electric field instead of thermally, which has already been demonstrated and investigated for high speed electronics [13], to benefit from the ultrafast response inherent to the MIT effect. While some authors estimate that the thermal contribution is not high enough to explain the MIT under applied electrical field, others believe that the electrically driven transition in $VO_2$ contains a thermal component. This means that the current flowing through the $VO_2$ layer most probably does not only modify the carrier density locally but also increases the temperature of the layer, bringing the system closer to the thermal MIT transition. Since heat dissipation is slow, this may hamper a fast return to the insulating state upon cooling. Therefore, the target will be to work in the window for which small changes in the external parameters will lead to a significant change in refractive index while minimizing thermal changes [14]. This will allow high speed operation in the sub-nanosecond regime.

The integration of $VO_2$ on silicon will be exploited to demonstrate beyond state-of-the art electro-optical switching performance. The current process for the growth of $VO_2$ films is based on a recipe for the growth of $V_2O_3$. The direct growth of $VO_2$ under MBE conditions requires too high oxygen partial pressure which is detrimental to the MBE operation. As a first step we have taken our standard $V_2O_3$ thin films and investigated the conversion from $V_2O_3$ to $VO_2$ using a high temperature annealing process. Figure 2 shows the high angle X-ray diffraction (XRD) spectra of one sample at three different stages. First the black curve shows the data as grown and a clear peak with finite size oscillations is shown. Next the sample is annealed at 450 °C – corresponding to the blue curve and a shift of main peak position is observed. Finally the sample is annealed at 500 °C – the red curve – and a further shift is observed towards the value of the bulk $VO_2$ (002) peak.

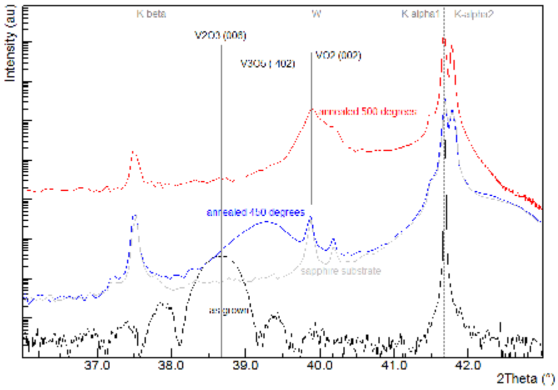


*Figure 2. High angle X-ray diffraction (XRD) spectra results of fabricated samples.*

## 4. CONCLUSIONS

The technology developed in the context of the SITOGA project will be useful for a wide-range of applications, especially in the telecom and datacom markets but also open opportunities in other high impact markets. The integration of such innovative materials will offer enhanced capabilities to the silicon photonics platform by offering unprecedented performance for electro-optic functionalities in terms of operation speed, power consumption, losses and footprint. Access to novel functionalities, such as electro-optical non-volatility (bistability) performance, will also be explored to make them available for the first time in the silicon platform.


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