PROJECT PERIODIC REPORT

Grant Agreement number: 619456

Project acronym:	SITOGA
Project title:	Silicon CMOS compatible transition metal oxide technology for boosting highly integrated photonic devices with disruptive performance
Funding Scheme:	Collaborative Project
Date of Annex I:	17/09/2013
Periodic report:	**1st** X **2nd** ☐
Period covered:	from 1st December 2013 to 31st May 2015
Project's coordinator:	Dr. Pablo Sanchis-Kilders. Universitat Politècnica de València
Tel:	+34963879736
Fax:	+34963872778
E-mail:	pabsanki@dcom.upv.es
Project website address:	https://www.upv.es/
	http://www.ntc.upv.es/

1. Publishable Summary

The SITOGA project addresses the **integration of transition metal oxides (TMO) materials in silicon photonics technology** for offering breakthrough electro-optical functionalities due to their unique properties not present in pure silicon. Such integration combined with the development of beyond state-of-the art photonic devices will pave the way towards a wide range of photonic applications. Figure 1 summarizes the SITOGA project concept. The consortium of the project is composed by the Universitat Politecnica de Valencia (UPVLC) in Spain, which is the coordinator, the Centre National de la Recherche Scientifique-Institut des Nanotechnologies de Lyon (CNRS-INL) in France, the Katholieke Universiteit Leuven (KUL) in Belgium, the Leibniz Institute for Innovative Microelectronics (IHP) in Germany, IBM Research GmbH in Switzerland and DAS Photonics in Spain.

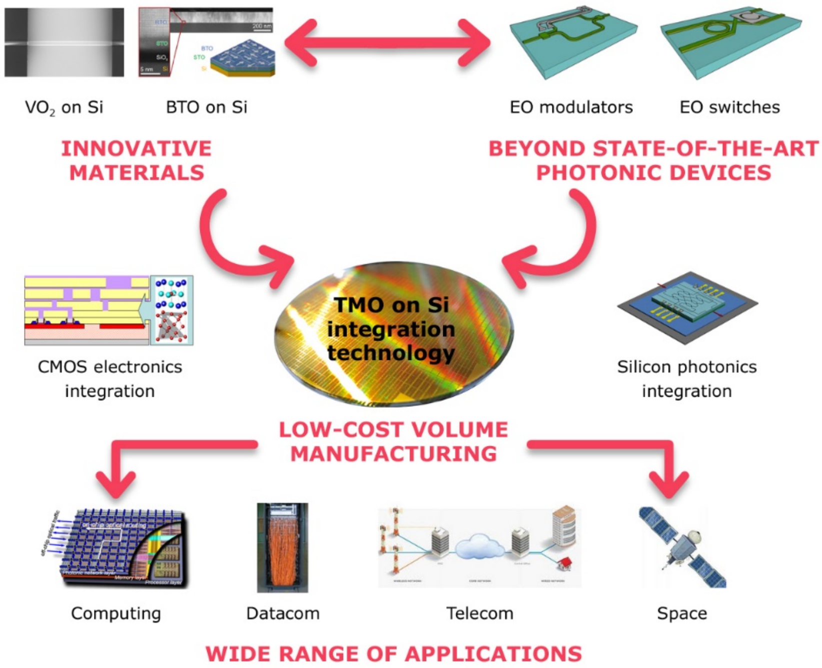


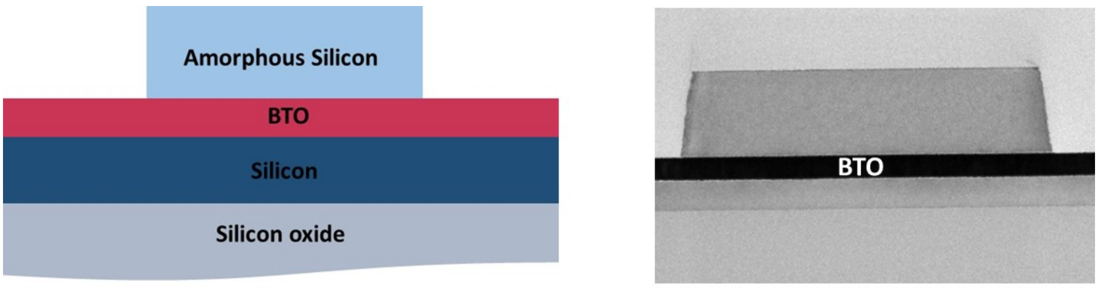
Figure 1. SITOGA project concept.

Silicon photonics technology is currently the most promising platform for enabling automated, low-cost volume manufacturing of highly integrated and complex photonic circuits mainly because the fabrication processing steps have been developed using standard CMOS fabrication infrastructure. 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, several challenges need still to be addressed for enabling the full development of commercial products. 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 with the potential to generate technology breakthroughs leading to novel markets and applications. Clear examples of that are III-V compounds that have been widely investigated for solving the lack of an on-chip light source in silicon due to their well-proven lasing properties or Germanium that is the best approach for enabling photodetection in silicon at 1550 nm optical wavelengths due to its excellent properties for light absorption in the near infrared and CMOS compatibility.

SITOGA addresses the combination of material technology, advanced development of complex photonic components and manufacturing of functional demonstrators for high-impact applications. The main objectives of the project are:

- To develop the technology (deposition pathways and processing) of two **innovative transition metal oxide materials**, **$BaTiO_3$ and VO_2**, with unique properties for boosting photonic integration in silicon CMOS.
- To demonstrate **beyond state-of-the art** electro-optical modulation and switching photonic components and develop **novel electro-optical functionalities**.
- To integrate the developed material technology on the silicon CMOS platform for **large-scale manufacturing** of highly integrated and complex photonic devices.
- To validate the enhanced capabilities provided to the silicon platform by means of two **functional demonstrators** and define **the roadmap for the exploitation** of the developed technology.

The main integration route of the **$BaTiO_3$ material**, also referred as BTO, on silicon is based on molecular beam epitaxy (MBE) though other deposition methods such as sputtering and pulsed laser deposition (PLD) have also been investigated. Epitaxial growth of high crystalline quality thin films has been demonstrated with a FWHM of the rocking curve below 0.5º and very low surface roughness (~0.3-0.5nm rms). Furthermore, ferroelectricity has been shown and the ferroelectric domain structure can be controlled to a certain extent. On the other hand, an etching process for thin film $BaTiO_3$ layers has also been successfully developed.



(a) (b)

Figure 2. (a) Proposed $BaTiO_3$/Si waveguide structure and (b) TEM image of fabricated waveguide cross-section.

The optimum waveguide structure for $BaTiO_3$/Si electro-optical modulation has been designed in parallel with the material technology development. Different waveguide structures have been thoroughly analyzed in terms of expected performance and fabrication complexity. The proposed waveguide structure is shown in Figure 2. A SOI substrate having 100 nm thick silicon layer has been chosen as the optimum substrate. The $BaTiO_3$ thickness has been fixed to 50nm to increase the optical confinement. The optimum amorphous silicon layer thickness and waveguide width depend on the electro-optical performance. The waveguide structure has been successfully fabricated, as it can be seen in Figure 2, and **low optical losses around 10dB/cm have been recently demonstrated for both TE and TM light polarizations**. To achieve this goal, amorphous silicon technology with low optical losses and good adhesion to the $BaTiO_3$ layer was previously developed within the project.
The targeted electro-optical modulator is based on a Mach-Zehnder interferometer structure. The optimum electro-optical performance has been designed with the aim of minimizing the V_π voltage. In this context, the influence of $BaTiO_3$ ferroelectric domain orientation has been extensively analyzed. Analytic expressions to calculate the V_π voltage have been derived for both $BaTiO_3$

orientations and light polarizations and confirmed by simulations. A **$V_{\pi}L$ as low as 0.27 V·cm has been designed** for a-axis oriented $BaTiO_3$ and by conveniently rotating the waveguide in the horizontal plane at an optimum angle of 55º for which the electro-optical coefficient is maximized. The control of the ferroelectric polarization orientation is therefore crucial and several fabrication approaches based on a post-deposition annealing process and the control of the $SrTiO_3$ buffer layer have been investigated to achieve such control.

The different fabrication steps are now ready for the fabrication of the modulator device which is currently on progress. Basic building blocks, such as multimode interference couplers (MMIs) and grating couplers, have also been designed. In the latter, coupling losses below 7dB have been recently obtained by means of 3D-FDTD simulations for both TE and TM polarizations. From the material side, **effective Pockels coefficients up to 120 pm/V have been measured** in 80nm-thick $BaTiO_3$ layers with a-axis orientation, which is an encouraging step towards the objective of the project (>300 pm/V).

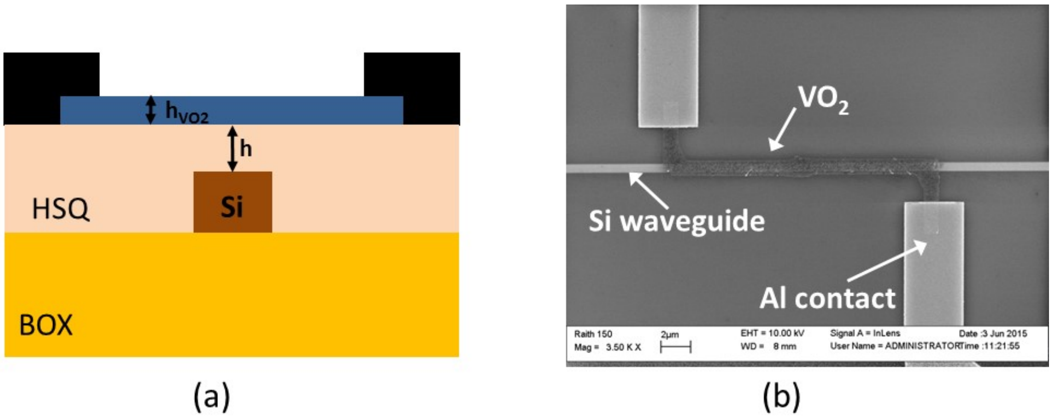


Figure 3. (a) Proposed VO_2/Si waveguide structure and (b) SEM image of fabricated device.

The main integration route of the **VO_2 material** on silicon is also based on molecular beam epitaxy followed by a post-deposition annealing process step. The annealing process has been optimized to obtain more reproducible results and the temperature has been lowered to make all the processing CMOS compatible. A change of resistance as a function of temperature of more than one order of magnitude together with a hysteresis performance has been successfully demonstrated in VO_2/Si substrates showing a **clear signature of the metal-insulator transition** (MIT). The change in resistance when applying an electric field and the role of the thermal component in the switching mechanism have also been investigated. There are two main challenges when switching by an electric field: (i) the largest effect is observed close to the transition temperature (T~60C) and (ii) the switching from the insulating to the metallic state is not completely reversible. Several approaches are currently being analyzed to address these issues.

The optimum waveguide structure for VO_2/Si electro-optical switching is shown in Figure 3(a). The structure is based on a fully etched silicon waveguide with a VO_2 film on top and it has been chosen to minimize propagation losses due to the high absorption in the VO_2 material while having enough optical confinement to achieve ultra-compact active lengths. The design of the waveguide has been carried out taking into account both TE and TM polarizations. All the process steps were carefully designed and optimized before successfully fabricating the structure, as it can be seen in Figure 3(b). A planarization process was developed prior to the VO_2 deposition. VO_2 pattering was carried out by a lift-off process. **Propagation losses in very good agreement with simulations have been demonstrated**.

The targeted electro-optical 2x2 switch is based on an add drop microring resonator structure. The device switches between the bar and cross states by exploiting the ultra large change of the VO_2 complex refractive index. Insertion losses is the most critical parameter as VO_2 has high absorption losses even in the insulating state. The design of the microring switch based on the VO_2/Si waveguide structure has been carried out by simultaneously optimizing the absorption loss and phase shift variation in the VO_2. In such way, **insertion losses as low as 1.5dB** and crosstalk values above 10dB have been obtained. Lower insertion losses are only possible if the imaginary part of the VO_2 refractive index in the insulating state is lowered. Therefore, doping of the VO_2 film is currently being investigated to analyze if it is feasible to achieve such reduction.

The VO_2/Si waveguide structure with electrodes has also been successfully fabricated and characterized. Metallic contacts are based on Aluminium and have been fabricated by a lift-off process. Different types of electrodes have been analyzed to enhance the electro-optical performance. A variation of the absorption as a function of the applied voltage has been demonstrated in the designed VO_2/Si waveguides. Furthermore, microring resonator structures have been fabricated to evaluate the phase shift induced by the change of the VO_2 refractive index. A performance in agreement with simulations has been measured. A non-volatile switching performance has also been observed and is currently under investigation.

Finally, the **optimum integration route of TMO materials with silicon photonics circuits** has also been addressed. The transfer of the MBE deposition process from 2'' to 8'' substrates and the bonding process are being developed for efficient integration. The optical connection based on interlayer coupling by means of grating couplers has also been designed and several experimental demonstrations have been attempted.

The expected final **project results and their potential impact** can be summarized as:

- The developed technology 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 such as space.
- 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.
- A clear path towards exploitation of the developed technology will be pursued by evaluating the integration of TMO/Si technology in the BiCMOS pilot line of IHP partner to extend its technology portfolio.

The address of the project public website is **www.sitoga.eu**.