PROJECT FINAL REPORT

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1.1. Executive summary.

The SITOGA project addresses the **integration of transition metal oxides (TMO) materials in silicon photonics technology** for the first time in a European-scale research initiative. TMO materials comprise a very diverse and fascinating class of compounds with properties that can be tailored for a wide variety of applications. SITOGA has focused on two disruptive TMO materials, **barium titanate ($BaTiO_3$) and vanadium dioxide (VO_2)**, for enabling breakthrough electro-optical functionalities due to their unique material properties not present in pure silicon. The figure below summarized the project concept.

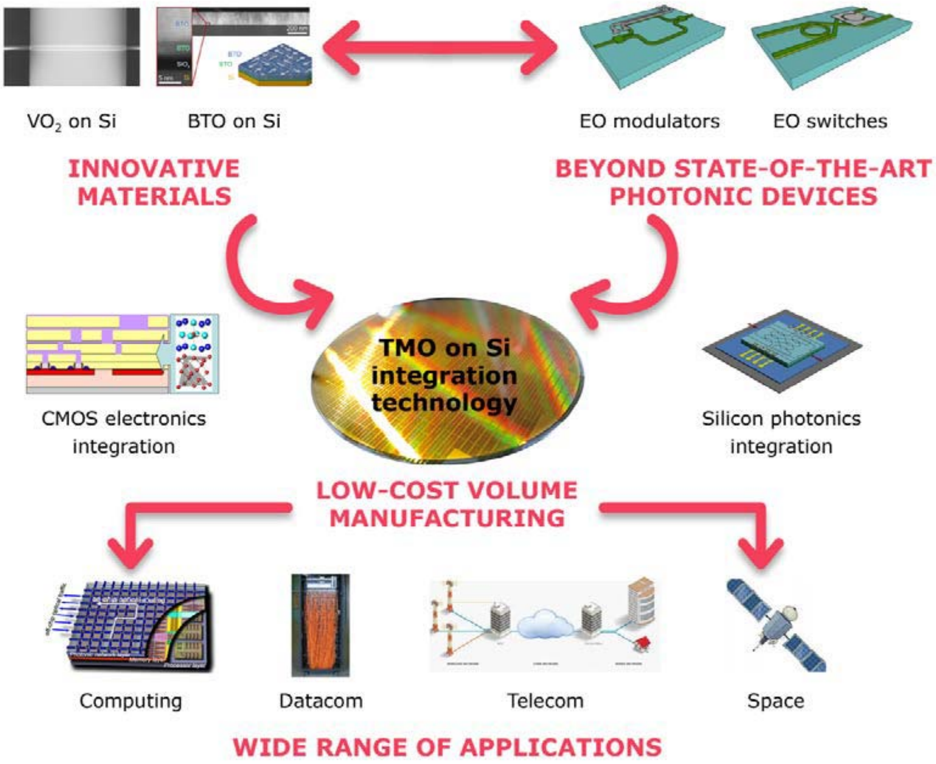


Figure 1.- SITOGA project conception.

Within the SITOGA project, we have successfully demonstrated the integration of $BaTiO_3$ and VO_2 technology on silicon devices with beyond state-of-the art performance. **Electro-optical modulators** based on the developed $BaTiO_3$/Si technology have been for the first time demonstrated with modulation bandwidths up to 30GHz and digital data rates up to 40Gbps. **Electro-optical switching devices** with ultra-short active lengths based on the developed VO_2/Si technology have been successfully demonstrated with data transmission capabilities up to 40 Gbps. Strategies to minimize power consumption have been thoroughly analyzed and experimentally validated. The integration of the developed technology on the **IHP's silicon photonics platform (BiCMOS photonics)** has also been addressed and the roadmap beyond the project has been established. The materials technology integration into the silicon platform combined with the development of beyond state-of-the art photonic devices is expected to pave the way towards a wide range of photonic applications. Therefore, the **exploitation of the technology** has been figured out in the context of evolving systems' requirements in telecom, datacom, spacecom and sensing markets.

1.2. Project context and objectives.

High performance information and communication (ICT) technologies, supported by strong progress in electronics, 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 big investment of the electronics industry on the silicon CMOS technology which has been translated in an impressive and continuous improvement in performance without penalizing the cost.

By contrast, 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. At this point is where silicon photonics technology comes into play. Silicon photonics technology, also referred to as **CMOS photonics**, is currently one of the most promising platforms 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. 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.

The SITOGA project has addressed the integration of **transition metal oxides (TMO) materials** in the silicon photonics platform 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** is expected to pave the way towards a wide range of photonic applications.

TMOs comprise a very diverse and fascinating class of compounds with properties that can be tailored for a wide variety of applications. Many transition metal oxides 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.

In the SITOGA project, we have focused on two disruptive TMO materials, **barium titanate (BaTiO3) and vanadium oxide (VO_2)**, as the best approaches for enabling electro-optical modulation and switching functionalities with beyond state-of-the art performance. While $BaTiO_3$ is interesting for its electro-optical activity, VO_2 is being actively investigated due to the ultra-large change in refractive index which follows the electrically-driven metal-insulator-transition (MIT). Table 1 summarizes the materials properties and key enhanced capabilities offered to the silicon platform.

	Material unique properties at 1550nm optical wavelengths	**Key enhanced capabilities offered to the silicon platform**
$BaTiO_3$	▪ Ultra-high Pockels coefficient ▪ Low optical losses ▪ High refractive index ▪ Bistable performance via ferroelectric domain switching.	▪ Ultra-fast and linear optical phase modulation ▪ CMOS compatible drive voltages with low insertion losses ▪ Electro-optical bistable performance for non-volatile photonic devices
VO_2	▪ Metal-insulator-transition induced thermally, electrically or optically ▪ Ultra large change of refractive index ▪ Bistable performance via phase transition triggering.	▪ Ultra-small footprint ▪ Low power consumption ▪ Electro-optical bistable performance for non-volatile photonic devices

Table 1.- Materials targeted in the SITOGA project.

SITOGA has addressed objectives that combine material technology, advanced development of complex photonic components and manufacturing of functional demonstrators for high-impact applications. In addition, exploratory research for enabling novel functionalities have also been investigated to exploit the unique material properties and developed technology. The main objections of the SITOGA project have been the following:

- Develop the **technology** (deposition pathways and processing) of two innovative transition metal oxides (TMO) materials, **$BaTiO_3$ and VO_2**, with unique properties for boosting photonic integration in silicon CMOS.
- Demonstrate **beyond state-of-the art electro-optical modulation and switching photonic components** and develop novel electro-optical functionalities.
- **Integrate the developed material technology on the silicon CMOS platform** for large-scale manufacturing of highly integrated and complex photonic devices.
- 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 **SITOGA consortium** was selected to cover the whole technology development chain from material technology to manufacturing of demonstrators driven by industrial requirements. The consortium was composed by six partners: 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.

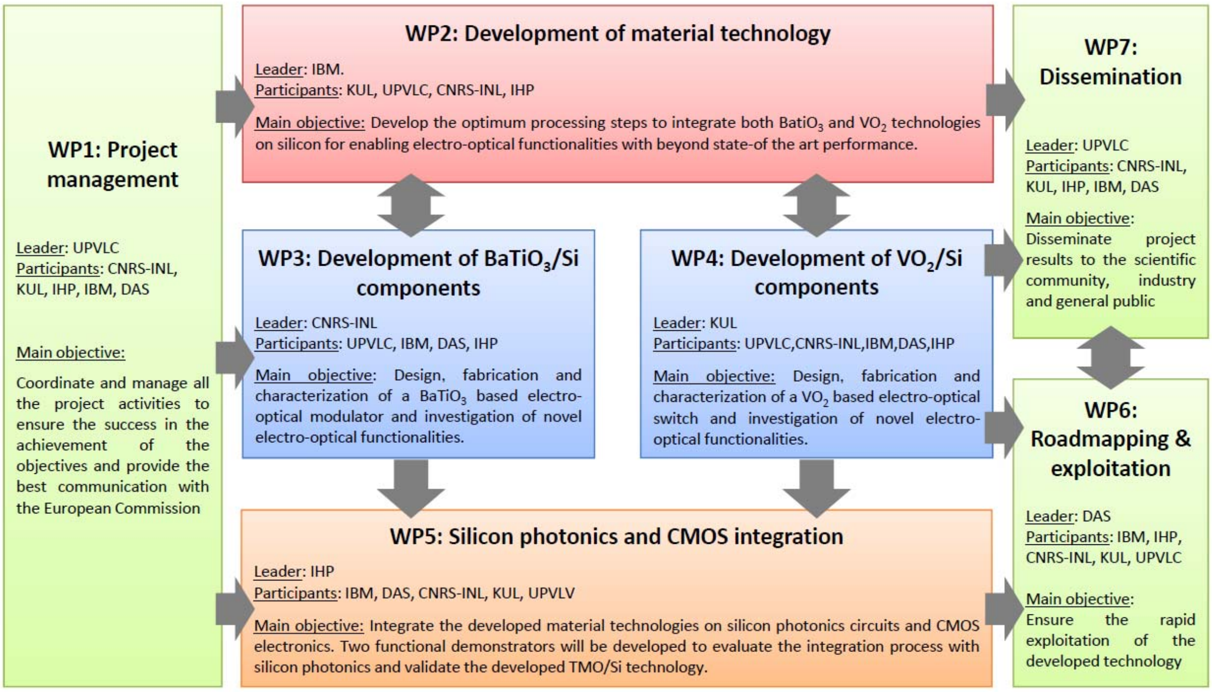
IHP is one of the main players in Europe in the CMOS manufacturing of silicon photonics devices and reference microelectronics research institute with a strong industrial commitment. Therefore, one of the main goals of the project has been the **integration of the developed material technology in IHP's existing photonic SG25_H4 BiCMOS line** to establish a clear path towards exploitation of the developed technology. With this approach, affordable access to the developed technology would be available for prototyping purposes, especially in the case of fabless SMEs, and the route for industrialization in a commercial foundry would be possible.

1.3. Main S&T results/foreground.

The **work plan of the SITOGA project has been organized into six intercorrelated work packages** (WPs) which follows the logical phases to achieve the project goals by means of a bottom-up approach.

- **WP1**: Project management.
- **WP2**: Development of material technology.
- **WP3**: Development of $BaTiO_3$/Si components.
- **WP4**: Development of VO_2/Si components.
- **WP5**: Silicon photonics and CMOS integration.
- **WP6**: Roadmapping and exploitation.
- **WP7**: Dissemination.

Figure 2 describes the interdependencies between the different WPs as well as the leader, participants and main objective of each WP. The main S&T achievements in the technological WPs (WP2-WP5) are summarized below.



WP1: Project management

Leader: UPVLC
Participants: CNRS-INL, KUL, IHP, IBM, DAS

Main objective:
Coordinate and manage all the project activities to ensure the success in the achievement of the objectives and provide the best communication with the European Commission

WP2: Development of material technology

Leader: IBM.
Participants: KUL, UPVLC, CNRS-INL, IHP

Main objective: Develop the optimum processing steps to integrate both $BatiO_3$ and VO_2 technologies on silicon for enabling electro-optical functionalities with beyond state-of the art performance.

WP3: Development of $BaTiO_3$/Si components

Leader: CNRS-INL
Participants: UPVLC, IBM, DAS, IHP

Main objective: Design, fabrication and characterization of a $BaTiO_3$ based electro-optical modulator and investigation of novel electro-optical functionalities.

WP4: Development of VO_2/Si components

Leader: KUL
Participants: UPVLC,CNRS-INL,IBM,DAS,IHP

Main objective: Design, fabrication and characterization of a VO_2 based electro-optical switch and investigation of novel electro-optical functionalities.

WP5: Silicon photonics and CMOS integration

Leader: IHP
Participants: IBM, DAS, CNRS-INL, KUL, UPVLV

Main objective: Integrate the developed material technologies on silicon photonics circuits and CMOS electronics. Two functional demonstrators will be developed to evaluate the integration process with silicon photonics and validate the developed TMO/Si technology.

WP7: Dissemination

Leader: UPVLC
Participants: CNRS-INL, KUL, IHP, IBM, DAS

Main objective:
Disseminate project results to the scientific community, industry and general public

WP6: Roadmapping & exploitation

Leader: DAS
Participants: IBM, IHP, CNRS-INL, KUL, UPVLC

Main objective:
Ensure the rapid exploitation of the developed technology

Figure 2.- Workpackage structure of SITOGA.

WP2. Development of material technology

The two material technologies, $BaTiO_3$ and VO_2, have been developed in this WP to fabricate the electro-optical modulator and switching device structures for WP3 and WP4 as well as the functional demonstrators for WP5.

Processes to grow $BaTiO_3$ (BTO) and VO_2 layers on top of SOI substrates have been successfully developed. BTO has been grown by using thin (3-4 nm thick) $SrTiO_3$ (STO) buffers in order to ensure good crystallinity and optimal structural quality. Molecular beam epitaxy (MBE) of STO and BTO was developed both at IBM (on 2” and 200 mm wafers) and INL (on max. 2” wafers). Furthermore, INL developed BTO growth by RF sputtering, and IBM compared BTO growth using four different deposition techniques (MBE, PVD, CVD and PLD).

Epitaxial growth of **high crystalline quality BTO thin films** has been demonstrated. The crystal quality measured via the FWHM of the rocking curve exceeds the goals set for the project (FWHM of the BTO (002) reflexion < 0.7°, see Figure 3(a)), and the surface roughness of the films (RMS ~0.3-0.5nm) is also significantly below the requirements (1nm). Furthermore, ferroelectricity has been demonstrated, and strategies, based on the control of the STO buffer thickness or on post-growth annealing, have been investigated to control the BTO ferroelectric orientation (a-axis or c-axis). Effective Pockels coefficients up to 120 pm/V have been demonstrated. The consortium has also faced up with high optical losses of more than 100dB/cm. The origin of such high optical losses has been thoroughly analyzed and several approaches have been successfully developed to reduce them to below 5dB/cm. Overall, minimization of the optical losses and control of the BTO ferroelectric domain structure remain as the main challenges to exploit the developed technology.

The growth of **high quality VO_2 films** has also been demonstrated. The deposition of VO_2 thin films was optimized following a two-step process. An amorphous vanadium oxide (VO_x) film was first deposited by MBE at room temperature and then transformed into polycrystalline VO_2 by an ex-situ annealing at moderate temperatures. Significant efforts have been devoted to optimize the annealing process to maximize the resistance change across the metal-insulator transition (MIT) and reduce the transition temperature to improve the power consumption. The growth and annealing methods developed within the project have resulted in VO_2 films with optical constants similar to the values reported in literature. Finally, doping of VO_2 with Mg has been also investigated. In this case, a decrease of the transition temperature has been observed. Remarkably, even if the change in resistance between the insulating and the metallic state is reduced as compared with the undoped case, the change in refractive index between the two phases remains considerable large.

In parallel to the optimization of the deposition processes, the process flow to fabricate the target devices has been defined and optimized by combining the facilities of the different partners (INL, KUL, IBM, UPVLC and IHP) to achieve a fast delivery time and thus increase the number of design-fabrication-characterization cycles. Concerning **BTO/Si technology**, an etching process has been developed for efficiently patterning thin BTO films thus enabling the fabrication of fully etched optical waveguides (see Figure 3(c)). Furthermore, the integration of amorphous silicon (a-Si) layer on top of BTO thin films has also been developed. UPVLC and INL have optimized two PECVD processes (based on Ar and H_2) to grow a-Si with a refractive index value close to 3.47, optical losses below 10 dB/cm and reduced stress to avoid the delamination from the BTO layer. Different techniques have been investigated to ensure a good adhesion between the a-Si and BTO layers. Concerning **VO_2/Si technology**, VO_2 etching has been successfully demonstrated by reactive ion etching. However, for the waveguide devices, a lift-process has been finally chosen and developed, which simplifies the fabrication.

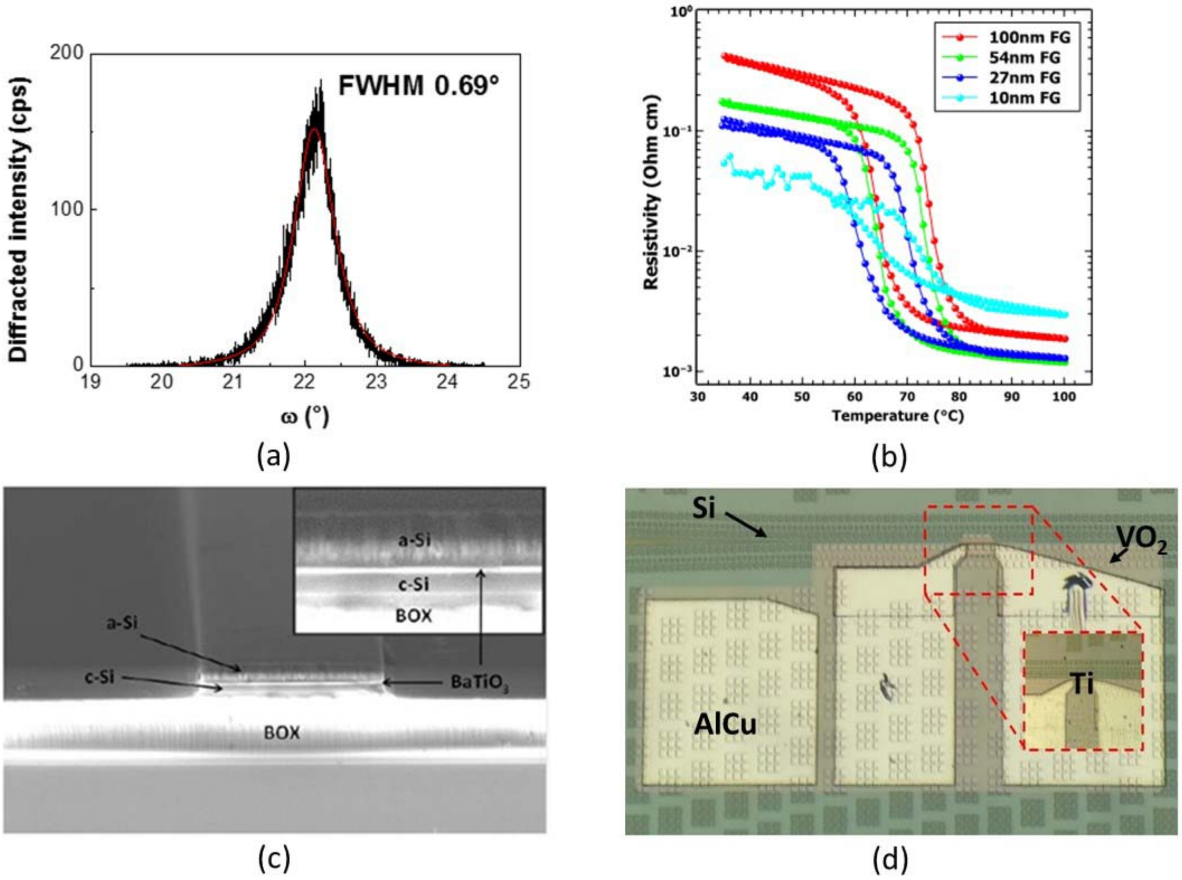


Figure 3.- (a) X-ray rocking around the [002] reflection recorded on a 50 nm thick $BaTiO_3$ layer grown by MBE on $SrTiO_3$/SOI. (b) Resistivity vs temperature characteristics recorded on VO_2 films with various thicknesses annealed in forming gas. (c) SEM cross-sectional view of a fully etched a-Si/BTO/SOI waveguide, where the developed recipe was used to etch the BTO layer. (d) Electrode with double metallization based onTi and Al/Cu developed for thermo-optical switching the VO_2.

Finally, processes to fabricate electrodes have been developed for both BTO and VO_2 material technologies. Concerning **BTO/Si technology**, a method to estimate the relative permittivity of thin BTO films from experimental measurements has been developed. High values between 800 and 1600 have been estimated at 20 GHz. Furthermore, no substantial difference has been obtained by using BTO grown by molecular beam epitaxy and sputtering. The obtained permittivity has been used to properly design the RF electrodes for high speed modulation in hybrid BTO/Si devices. Coplanar strip-line electrodes have been fabricated and the possibility of achieving modulation bandwidths up to 40 GHz has been demonstrated. The bandwidth is limited by the microwave propagation losses and, in this case, lower losses have been obtained for BTO grown by MBE as compared to BTO grown by RF sputtering which suggest that process conditions could be optimized to minimize the dielectric losses of the BTO layer.

Concerning to the **VO_2 technology**, metallic electrodes have been deposited on top of the VO_2 film by using a lift-off process. Several electrodes configuration have been investigated to reduce the power consumption. Furthermore, an electrode with double metallization based on titanium and Al/Cu, shown in Figure 3(d), has been developed for thermo-optical switching the VO_2 in the fabricated devices.

In summary, the main results that have been achieved in WP2 are:

- Demonstration of epitaxial growth of high crystalline quality thin $BaTiO_3$ films on silicon and SOI substrates with very low surface roughness.
- Demonstration of the metal-to-insulator transition (MIT) response in VO_2 layers grown on silicon.
- Demonstration of an efficient $BaTiO_3$ etching process for thin films on silicon.
- Development of amorphous silicon technology with low optical losses, targeted refractive index and low stress.
- Development of a multi-line method to estimate the relative permittivity of thin $BaTiO_3$ films at RF frequencies.
- Demonstration of low loss RF travelling-wave electrodes in hybrid $BaTiO_3$/Si devices for high-speed modulation.

WP3. Development of $BaTiO_3$/Si components

The main goal of this WP has been the development of a hybrid BTO/Si electro-optical modulator device with a bandwidth above 40GHz, drive voltage below 2V, modulation length below 2 mm and insertion losses below 5dB.

The optimum **waveguide structure** to implement the proposed BTO/Si modulator was first designed and experimentally demonstrated. The half-etched waveguide structure shown in Figure 4 was chosen. A non-standard SOI substrate having 100 nm thick silicon layer was used as the optimum substrate. This geometry is more favourable since it allows achieving single mode operation and higher optical confinement than the standard 220nm thickness.

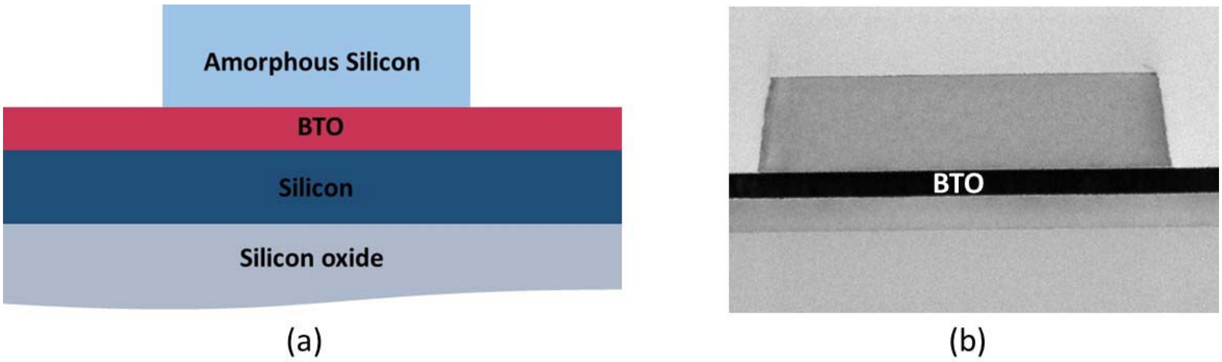


Figure 4. (a) Proposed $BaTiO_3$/Si waveguide structure and (b) TEM image of fabricated waveguide.

The BTO/Si electro-optical modulator based on a Mach-Zehnder (MZ) interferometer structure was then designed to meet the project specifications. The design has been focused on optimizing the V_π voltage but ensuring that propagation losses induced by the electrodes are negligible. Furthermore, the influence of BTO ferroelectric domain orientation on the electro-optical performance has also been extensively analyzed. Analytic expressions to calculate the V_π voltage have been derived for both BTO orientations and light polarizations and confirmed by simulations.

A **$V_\pi L$ as low as 0.27 V·cm has been achieved in simulations** 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. Moreover, such study was later extended and the influence of multi-domain structure was analyzed. 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 in WP2 to achieve such control. Basic building blocks, such as multimode interference couplers (MMIs) and grating couplers, were also designed. Finally, coplanar strip-line electrodes were designed for high speed modulation beyond 40GHz and impedance matching to 50Ω based on the estimations of the relative permittivity of BTO.

The designed hybrid BTO/Si waveguide has been initially fabricated and characterized. However, unexpected high propagation losses were measured which significantly delayed the progress of the modulator fabrication. We were able to identify the sources of the losses and reduce them significantly to <5 dB/cm. Actives devices were also fabricated and characterized. Several effects such as high BTO leakage and long-term drift responses were observed and investigated at DC and low modulation frequencies. Nevertheless, in the last phase of the project, we have been able to successfully demonstrate **electro-optical modulation at a very high-speed of 30GHz and data rate of 10Gbps**, and verify several key properties of the Pockels effect.

Lower efforts have been devoted to the exploratory research on **novel electro-optical functionalities**. Nevertheless, we have investigated the possibility of using the ferroelectric behaviour of BTO to fabricate non-volatile electro-optical devices. The idea is that if convenient built in electrical field is applied to the oxide layer, for instance by using asymmetric electrodes of doped substrates, the two polarization states that can be written remanently in the material by applying voltage pulses correspond to different refractive indices, so that the device can be switched in a non-volatile manner. We fully designed a non-volatile add-drop filter using this work principle, and we were able to demonstrate a hysteretic optical response of a ring resonator, unambiguously showing that the fabrication of a non-volatile electro-optical device is feasible. The last step towards its fabrication is the onset of a built-in electrical field in the oxide layer. In the end, we explored by simulation the contribution of piezoelectricity to modulation in MZM devices, which mainly contributes because it causes a change of the waveguide thickness and hence of the effective propagation index.

In summary, the main results that have been achieved in WP3 are:

- Identify the sources of high propagation losses in $BaTiO_3$/Si waveguides and reduce them significantly to <5 dB/cm.
- Design of a hybrid $BaTiO_3$/Si electro-optical MZ modulator with the target specifications.
- Demonstration of the designed $BaTiO_3$/Si waveguide with low optical losses.
- Demonstration of the designed $BaTiO_3$/Si MZ modulator with RF modulation up to 30GHz and digital data modulation up to 10 Gbps with a modulation length of only 1mm.
- Observation of the hysteretic optical response of $BaTiO_3$ based device, as a very last crucial stage before the fabrication of non-volatile electro-optical devices.

WP4. Development of VO_2/Si components

The main goal of this WP has been the development of a hybrid VO_2/Si electro-optical 2x2 switch device with a switching time below 1ns, power consumption below 1µW, footprint below 50 μm^2 and insertion losses below 1dB.

As in WP3, the optimum waveguide structure to implement the VO_2/Si switch was first chosen, designed and experimentally demonstrated. The structure, shown in Figure 5, 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 targeted **electro-optical 2x2 switch** has been based on an add drop microring resonator structure to achieve the target footprint. 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 below 1.8 dB and crosstalk values above 12 dB has been achieved with a hybrid VO_2/Si waveguide of only 2.8 µm-length and TE polarization. Lower insertion losses are only possible if the imaginary part of the VO_2 refractive index in the insulating state is lowered. The optical bandwidth of the design switch is around 3.8nm that will allow a data throughput rate higher than 500Gbps. Furthermore, the throughput can be increased beyond Tbps operation by using a WDM optical signal with a wavelength spacing matched with the free spectral range of the ring resonances to simultaneously switch on and off a large number of wavelength channels.

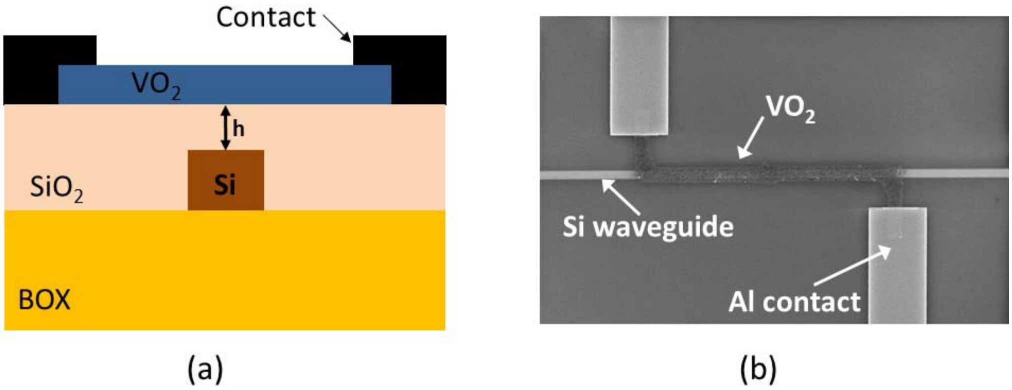


Figure 5. (a) Proposed VO_2/Si waveguide structure and (b) SEM image of one of the first fabricated devices.

The proposed hybrid VO_2/Si switching device has been successfully fabricated and characterized. We have been able to **demonstrate the metal-insulator (MIT) transition at room temperature**. The power consumption has been analyzed by using two approaches for changing the VO_2 state: electrical excitation and thermal heating. The minimum power consumption is in the mW range basically because the VO_2 becomes highly conductive in its metallic phase and an electrical current of the order of few mA is necessary to induce the phase transition. Therefore, the measured switching time is also in the µs range. Nevertheless, an **electrode based on a double metallization** has been developed and successfully demonstrated to minimize the power consumption by thermo-optical excitation. The hysteresis of the thermo-optical response has been characterized for both TE and TM polarization. A variation of optical losses above 30dB for applied electrical powers of 30mW has been demonstrated with a hybrid Si/VO_2 waveguide of only 20µm length and TM polarization.

The **influence of an external resistance** on the electro-optical switching performance has also been analyzed and experimentally characterized in devices based on switching the VO_2 by means of an electrical voltage applied between two electrodes (electrical excitation). Our results indicate that the external resistance plays a key role in the switching power consumption showing an optimum value, which depends on the dimensions of the VO_2 region between the electrodes. Therefore, **a power consumption reduction between 50% and 90%** has been demonstrated with the selection of the optimum value for the external resistance.

Finally, **novel electro-optical functionalities** have been investigated by exploiting the ultra large change of the VO_2 refractive index across the MIT. Tunable TE and TM pass polarizers based on a hybrid VO_2/Si waveguide structure have been achieved with insertion losses below 3dB. Ultra-compact electro-absorption modulators have also been proposed and designed. Furthermore, a novel modulation device with TM to TE polarization conversion has been achieved. The proposed device operates in a broadband wavelength range of 60nm with insertion losses below 0.5dB and modulation extinction ratios above 10dB. The possibility of implementing optical memories or multi-stable optical systems based on the VO_2 hysteretic performance has also been investigated.

In summary, the main results that have been achieved in WP4 are:

- Design of a 2x2 electro-optical switch based on an ultra-short VO_2/Si waveguide with insertion losses below 1.8dB, optical bandwidth of 3.8nm and footprint below 50 μm^2
- Design of ultra-compact and tunable polarizers based on VO_2/Si waveguides.
- Design of a novel VO_2/Si modulation device with TM to TE polarization conversion.
- Demonstration of the metal-insulator (MIT) transition at room temperature in VO_2/Si devices by electrical excitation
- Demonstration of electro-optical switching in hybrid VO_2/Si waveguides and add-drop ring resonators by thermo-optical excitation
- Demonstration of novel approaches to minimize the power consumption

WP5. Silicon photonics and CMOS integration

The main goal of this WPs has been twofold. On one hand, the optimum integration route of the developed material technology on the silicon BiCMOS platform of IHP has been addressed. On the other hand, the target functional demonstrators have been developed.

Figure 6(a) shows a cross-section of the SG25_H4 BiCMOS technology of IHP with the possible **integration routes** of the transition metal oxides (TMO) technology. The main integration effort has been dedicated to the integration of the BTO technology. The integration of VO_2 devices has not specifically been studied due to the low temperature deposition process, which is compatible with the thermal budget in the BEOL of the BiCMOS process. The integration route of the BTO modulator has been defined and successfully proven. A more versatile integration route has also been identified that would enable the BTO integration in the lower backend. Several delays occurred during the fabrication of the silicon photonics/CMOS chips due to issues when bonding oxide layers at IBM on top of test wafers provided by IHP. Dealing with these difficulties required that partners IBM and IHP had to iteratively adjust their fabrication and bonding processes. However, the main origin of the low bonding yield was identified and the fabrication of the BTO demonstrator was finally achieved.

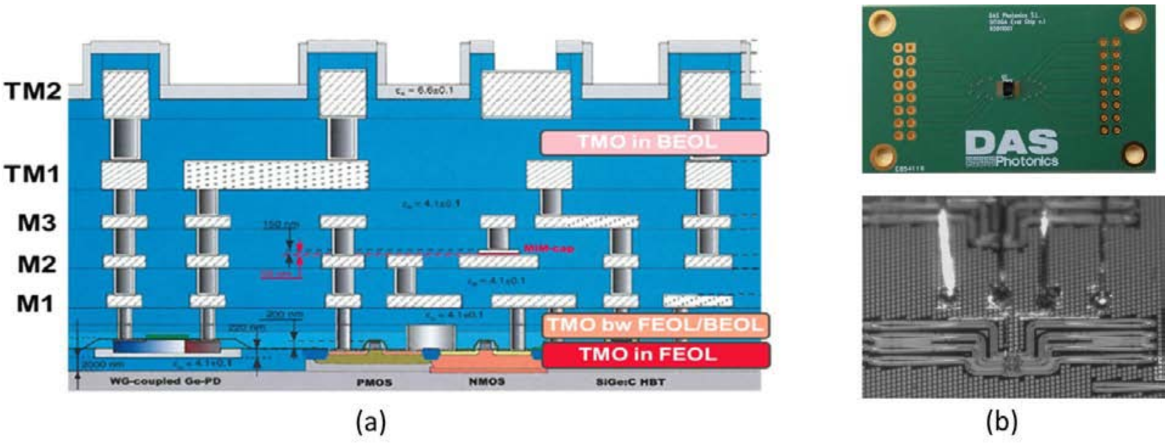


Figure 6. (a) Cross-section of the SG25_H4 BiCMOS technology of IHP with the possible integration routes. (b) Optical images of the 4x4 switching matrix interconnected to the control board by wire bonding.

The **two target demonstrators** have been (i) a 40Gbit/s DPSK transceiver with error-free performance and on-chip insertion losses below 5dB based on the BTO/Si technology and (i) a 8x8 switching matrix with 100Gbit/s throughput and a total footprint below 3500μm^2 based on the VO_2/Si technology. The two demonstrators have been designed, fabricated, and characterized. Although we could not achieve the specifications, we could show major achievements in the experimental realization of the devices.

For the **BTO/Si technology**, a working integration concept of functional BTO layers on wafers with CMOS circuitry has been developed. Electro-optical switching in BTO/Si waveguides based on the identical waveguide geometry as targeted for the demonstrator has been achieved. We successfully demonstrated modulation speeds up to 40Gbps in racetrack modulator which supposes a significant milestone for the SITOGA project. The demonstrator was also fabricated but the electro-optical characterization of the MZM transmitter was not possible due to issues in the circuit design.

For the **VO_2 technology**, we designed and fabricated 2x2, 4x4, and 8x8 switching matrices. An electronic board was also designed and fabricated to feed the switching matrix. Furthermore, the integration via wire bonding was developed. Electro-optical switching has been successfully demonstrated in the 2x2 and 4x4 matrices using the thermo-optic heater-based switching concept with a power consumption of 8mW. Furthermore, digital data transmission up to 40Gbps (limited by the available measurement set-up) has also been demonstrated in the 4x4 matrix.

In summary, the main results that have been achieved in WP5 are:

- Definition and demonstration of the optimum integration route of BTO and VO_2 materials in the SG25_H4 BiCMOS technology of IHP.
- Fabrication of the BTO/Si demonstrator and demonstration of digital modulation speeds up to 40Gbps in racetrack modulators.
- Demonstration of the routing capability of the 4x4 switching matrix based on the developed hybrid VO_2/Si optical switches with a data throughput up to 40Gbps and power consumption of 8mW.

1.4. Potential Impact

The increasing ubiquitous demand for high data rates is constantly pushing ICT technologies to their limit. Photonics has become the unique key enabler for the forecasted global data rate demand that will exceed 2.3 zettabytes/year in 2020, of which 20% correspond to mobile data, with an astounding CAGR of 22%[1]. This has an enormous business impact in photonic devices, components and system vendors in the different application areas concerned, such as telecom (from long-haul to access) or datacom. In telecom, the trend is to increase the number of wavelengths employing DWDM schemes, but the more the wavelengths used, the higher the impact on consumption, footprint, complexity of the network and operating costs. This is also the case for datacom, where for large scale data centres and high-performance computing (HPC), power consumption is now one of the biggest concerns.

Advances in optical interconnects and active optical cables (AOC) through enhanced integration and parallelisation, as well as increasing the line rate to 100 Gb/s and above, as projected by various roadmaps such as the IEEE P802.3bs 400 GbE Task Force and the Infiniband Roadmap (IBTA), are required to cope with that massive data transmission rate demand. This global trend will have a direct impact in the global Silicon Photonics Market, which revenue is expected to grow up to $1,078.9 million in 2022 at a CAGR of 22.1%, being APAC and Europe the fastest growing regions, with expected CAGRs of 27.4% and 26.1%[2], respectively. Therefore, it is clear that the technology developed in SITOGA may have a high potential impact on the silicon photonics market by offering access to electro-optical functionalities with improved performance.

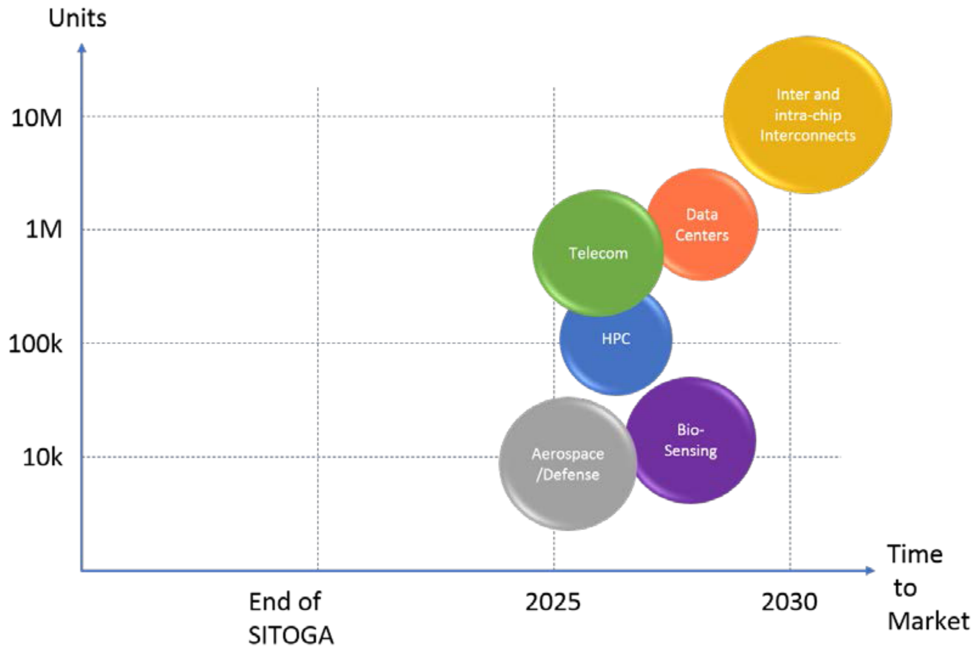


Figure 7. Markets' volume of silicon photonics for different applications that could be impacted by SITOGA technology.

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[1] CISCO VNI Forecast and Methodology, 2015-2010, http://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/complete-white-paper-c11-481360.html

[2] Silicon Photonics Market by Component, Application and Geography – Global Forecast to 2022", Markets and Markets

Besides telecom and datacom segments, significant economic impact can be generated in the satcom market, with a global revenue exceeding 100B$/year and a CARG of 5-10% from 2010-2012. In the EU, the satcom manufacturing industry represents 50% of the space industry turnover with around 35.000 workforce. Overall, according to Euroconsult[3], an average of 145 satellites with mass over 50 kg (over USD 250B market) will be launched in the period 2015-2025, and up to 900/year including planned small satellite mega-constellations. For this reason, the building blocks demonstrated could be used in the development of novel photonic based payloads. Partner DAS is pioneering the development of photonic payloads for SATCOM under ESA, EC4 and industrial contracts[5].

In this framework, SITOGA is expected to reinforce EU's photonic industry competitiveness and leadership in photonic market sectors such as telecom, datacom and satcom, and to seize new opportunities by exploiting a novel and advantageous fabrication platform. The availability of the TMO/Si technology will strengthen and differentiate EU manufacturing base in photonics, contributing to foster innovation and creating value and jobs.

Other industrial sectors, such as health and well-being, energy efficiency or safety could also leverage on SITOGA technology to solve current technological hurdles present in the fabrication of devices and components. The global market for biosensors had a volume of 8,5 B $ in 2012 and is expected to reach 16,8 B $ in 2018, with an annual growth rate of 9,6. Medical applications of biosensors, including 'Point-of-Care' and 'Home Diagnostics' represent the largest share of the market, estimated 66,5% in 2012, equivalent to 5,6 B $ in the year. These applications are expected to maintain their first position, reaching 10,8 B $ in 2018.

The outcomes of SITOGA are fully in line with the current industry and EC diagnosis of what is required to strengthen the position of EU Photonics Industry, as described in ECSEL-JU “Multi-Annual Strategic Plan – Part B “Essential Capabilities - 1. Semiconductor Process, Equipment and Materials”6 and Photonics 21 “Multi-Annual Strategic Roadmap 2014-2020”, as SITOGA contributes to 1) Photonic integration, by developing a generic integration platform and foundry model, 2) Integration of photonics with microelectronics at the chip, board and system levels, 3) Technologies for cost-effective manufacturing of components and subsystems.

SITOGA has been driven by the exploitation plans of the participating members, and the intention of the partners is to transform the achievement of the project objectives in a commercial success beyond the project. However, given the early TRL of the project, commercialization is not an immediate outcome and further developments need to be carried out. High economic impact can be predicted after the demonstration of SITOGA fabrication processes and components in high added-value applications, keeping competitive costs. Considering the maturity level of the technology developed, each partner will exploit it in a different way. The exploitation activities have been focused on a realistic and application-oriented framework for SITOGA activities to ensure the shortest time to market.

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[3] http://www.euroconsult-ec.com/13_September_2016

[4] The first photonic downconverter will be flying in HISPASAT H1F in 2017

[5] H2020 project OPTIMA[5] “Towards demonstration of photonic payload for Telecom Satellites” http://cordis.europa.eu/project/rcn/206265_en.html

[6] http://www.ecsel-ju.eu/web/JU/ECSEL%20Work%20Plan.php

During the project, the consortium has also made an extensive effort to disseminate the outcomes of the project. In the scientific scope, we have published 18 papers in scientific publications and 32 contributions to scientific conferences and workshops, some of them as invited talks. Additionally, 6 PhDs and 6 MSc have been carried out in the framework of the project. We have also organized two workshops and a session in a conference, and supported one international symposium.

We have also participated in an industry oriented post-ECOC workshop during 2016, with the participation of several members of the consortium. To maximize the dissemination impact of the developed technology, we have created a section in the website dedicated to Innovation & Technology where we have included several white papers that have been created and uploaded in the project website for free download.

Several activities have also been carried out to disseminate the project to the general public. Two press releases have been launched, one at the beginning of the project and one at the end. We have also created a LinkedIn group and IBM released a video for the Day of Photonics that had more than 550 visits[7].

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[7] www.youtube.com/watch?v=zC3knz_WY2c

1.5. Contact.

Project’s website: http://sitoga.eu/

Logo:

Sitoga

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