

# Functional oxides on Silicon and Sapphire substrates for photonic applications

Guillaume Marcaud, Sylvia Matzen, Carlos Alonso-Ramos, Xavier Le Roux, Mathias Berciano, Valérie Pillard, Pedro Damas, Thomas Maroutian, Guillaume Agnus, Ludovic Largeau, Eric Cassan, Delphine Marris-Morini, Philippe Lecoer, Laurent Vivien  
C2N- Centre for Nanoscience and Nanotechnology  
University of Paris-Sud, University of Paris Saclay  
Building 220, rue André Ampère 91405 Orsay cedex, France  
[guillaume.marcaud@c2n.upsaclay.fr](mailto:guillaume.marcaud@c2n.upsaclay.fr)

Silicon photonics is expected to allow the implementation of a wide range of applications including sensing, datacom and security with the potential to leverage the already existing CMOS fabrication facilities for cost-effective and large production. Among the building blocks to develop, optical modulator is considered as a key device for integrated circuits. The main physical effect to perform optical modulation in silicon is based on plasma dispersion effect. However the maximum modulation speed achievable with this approach is limited by the mobility and recombination time of the carriers. Furthermore, these types of modulators face some limitations in terms of power consumption, chirp and loss that may compromise their future integration in circuits.

Our work focuses on the integration of Yttria-Stabilized Zirconia (YSZ) functional oxide on sapphire substrates and on silicon. The common aim for both integrations is to induce nonlinear optical effects at the wavelength around 1550nm, thanks to strain tuning in full oxide- or in hybrid oxide/Si-photonic structures.

Indeed, we explore an alternative approach, based on the use of the Pockels effect for optical modulation [1]. Such an effect, commonly used in Lithium-Niobate, allows high speed and low power consumption optical modulation [2]. Unfortunately silicon is a centro-symmetric crystal leading to a vanishing of the second order nonlinear coefficient, i.e. no Pockels effect. To overcome this limitation, it is possible to break the crystal symmetry by straining the silicon lattice [3]. The new approach developed here is to generate strain by the epitaxial growth of crystalline functional oxides, which exhibit more appropriate strain-induced characteristics than the use of silicon nitride with lower defect concentration at the Si/oxide interface. Indeed, these functional oxides are deposited by epitaxial growth at high temperature with pulsed-laser deposition [4], [5]. The induced strain due to lattice parameter mismatch and the difference in the thermal expansion coefficients between oxides and silicon are strong. Furthermore, functional oxides exhibit very interesting multiferroicity and piezoelectricity properties that pave the way

to a new route to implement silicon photonic circuits with unprecedented functionalities.

Our study includes:

- Epitaxial growth of YSZ functional oxide by pulsed-laser deposition and material characterizations with several complementary techniques such as X-ray diffraction, atomic-force (AFM) and electronic microscopies (SEM and TEM).
- Fabrication processes with electronic lithography and different etching techniques which allow us to fabricate photonic structures such as gratings coupler, strip or sub-wavelength waveguides on full oxide- and hybrid oxide/Si chips and their optical characterisation around 1550 nm.
- Micro-Raman spectroscopy used to provide information about strain in silicon or YSZ structures throughout the processes [6].

Last results about full oxide- and hybrid oxide/Si- photonic structures will be presented and discussed.

- [1] Pedro Damas, Xavier Le Roux, David Le Bourdais, Eric Cassan, Delphine Marris-Morini, Nicolas Izard, Thomas Maroutian, Philippe Lecoer, and Laurent Vivien. Wavelength dependence of pockels effect in strained silicon waveguides. *Optics Express*, 22(18):22095, September 2014.
- [2] S. Abel, T. Stoferle, C. Marchiori, D. Caimi, L. Czornomaz, M. Stuckelberger, M. Sousa, B. J. O rein, and J. Fompeyrine. A hybrid barium titanate silicon photonics platform for ultraefficient electro optic tuning. *Journal of Lightwave Technology*, 34(8):1688, April 2016.
- [3] Massimo Cazzanelli and Joerg Schilling. Second order optical nonlinearity in silicon by symmetry breaking. *Applied Physics Reviews*, 3(1):011104, March 2016.
- [4] J. Y. Dai, H. C. Ong, and R. P. H. Chang. Structural Properties of Yttria stabilized Zirconia Thin Films Grown by Pulsed Laser Deposition. *Journal of Materials Research*, 14(04):1329, 1999.
- [5] S. J. Wang and C. K. Ong. Epitaxial growth of Yttria stabilized Zirconia films on silicon. Dynamic growth process and interface structure. *Applied Physics Letters*, 80(14):2541, April 2002.
- [6] Ingrid De Wolf. Microraman spectroscopy to study local mechanical stress in silicon integrated circuits. *Semiconductor Science and Technology*, 11(2):139, 1996