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XXXII Cycle

Physics-based modelling of optoelectronic devices and materials

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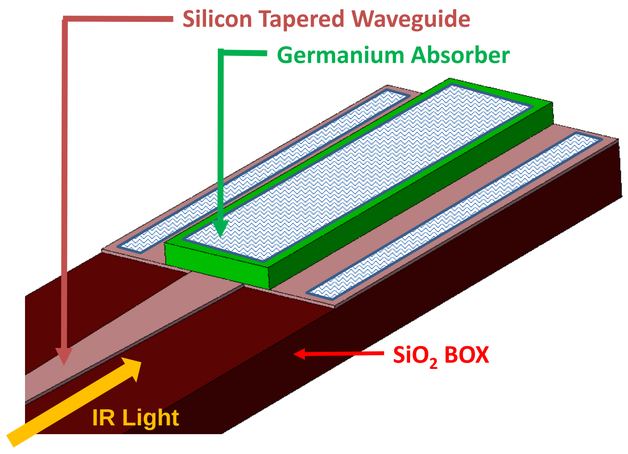
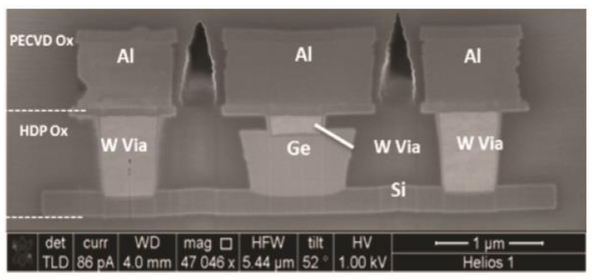
Research context and motivation

- Silicon photonics is one of the most attractive technological solutions when it comes to the realization of effective, low-cost integration of optical and electrical subsystems.
- Being transparent at standard telecom wavelengths (i.e. 1.31 um, 1.55 um), we exploit Si as optical guiding medium for our photonic integrated circuits; on the other hand, we leverage on the astounding capabilities of CMOS fabrication to monolithically integrate on wafer light modulators and waveguide-coupled photodetectors together with the control and driving electronics.



Left: 3D model of the *pin* design under study
Bottom: SEM cross-section of a waveguide *pin* from Sandia National Lab (C.T. DeRose et al., Opt. Expr. 19 (2011) 24897)



- Several factors make Ge appealing for the realization of integrated photodetectors: the availability of Ge-on-Si heteroepitaxy (potentially less expensive than III-V/Si integration), a strong absorption at telecom wavelengths and the possibility to play with strain and Ge-based alloy (e.g. GeSn).
- Moreover, it is possible to integrate external light modulator in the photonic platform through multi-quantum well Ge/SiGe electro-absorption modulator or carrier dispersion effects in Si-based electro-refraction modulators

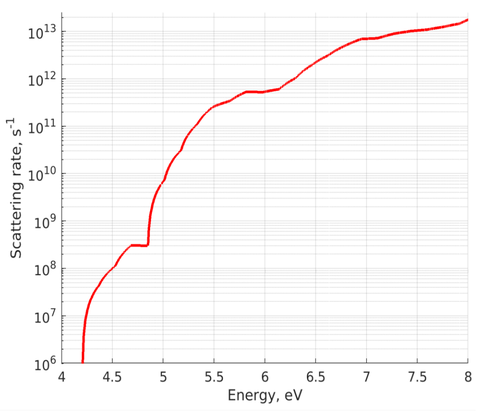
Adopted methodologies

- Optical model: ***finite differences time domain (FDTD)*** and ***eigen-mode expansion (EME)*** techniques are employed to obtain the electro-magnetic fields and the absorbed photon density distribution.
- Electrical model: a TCAD commercial software is used to solve the ***drift-diffusion (DD) equations***. A carrier generation term driven by the photon density distribution from the electromagnetic simulator couples the two models in a multiphysics approach.

External research activity

- In my stay at the 'Computational Electronics Laboratory' led by prof. Enrico Bellotti at Boston University, I worked on the transport and avalanche properties of GaN and its ternary alloys (i.e. $Al_{1-x}Ga_xN$, $In_{1-x}Ga_xN$) for high-power devices using a Monte Carlo technique.

Right: Impact ionization scattering rate for electrons in GaN obtained from a full-band Monte Carlo simulation



Submitted and published works

- M. Vallone, A. Palmieri, M. Calciati, F. Bertazzi, F. Cappelluti, G. Ghione, M. Goano, M. Bahl, E. Heller, R. Scarmozzino, S. Hanna, D. Eich, H. Figgemeier, *"Non-monochromatic 3D optical simulation of HgCdTe focal plane arrays"*, Journal of Electronic Materials, Oct. 2018, vol. 47, iss. 10, pp. 5742-5751, DOI:10.1007/s11664-018-6424-1
- A. Palmieri, M. Vallone, M. Calciati, A. Tibaldi, F. Bertazzi, G. Ghione, M. Goano, *"Heterostructure modeling considerations for Ge-on-Si waveguide photodetectors"*, Optical Quantum Electronics, Feb. 2018, vol. 50, pp. 71
- M. Vallone, A. Palmieri, M. Calciati, F. Bertazzi, F. Cappelluti, G. Ghione, M. Goano, R. Scarmozzino, E. Heller, M. Bahl, S. Hanna, H. Figgemeier, *"Non-monochromatic 3D optical simulation of HgCdTe focal plane arrays"*, The 2017 U.S. Workshop on the Physics and Chemistry of II-VI Materials, Chicago, IL, Oct. 2017
- A. Palmieri, M. Calciati, M. Vallone, G. Ghione, A. Tibaldi, F. Bertazzi, M. Goano, *"Energy balance modelling of Ge-on-Si waveguide photodetectors"*, 2017 International Conference on Numerical Simulation of Optoelectronic Devices (NUSOD), Copenhagen, Denmark, pp. 211-212, Jul. 2017, DOI:10.1109/NUSOD.2017.8010066
- M. Vallone, A. Palmieri, M. Calciati, F. Bertazzi, M. Goano, G. Ghione, F. Forghieri, *"3D physics-based modelling of Ge-on-Si waveguide p-i-n photodetectors"*, 2017 International Conference on Numerical Simulation of Optoelectronic Devices (NUSOD), Copenhagen, Denmark, pp. 207-208, Jul. 2017, DOI:10.1109/NUSOD.2017.8010064
- M. Vallone, A. Palmieri, M. Calciati, F. Bertazzi, F. Cappelluti, G. Ghione, M. Goano, S. Hanna, H. Figgemeier, R. Scarmozzino, E. Heller, M. Bahl, *"Broadband 3D optical modeling of HgCdTe infrared focal plane arrays"*, 2017 International Conference on Numerical Simulation of Optoelectronic Devices (NUSOD), Copenhagen, Denmark, pp. 205-206, Jul. 2017, DOI: 10.1109/NUSOD.2017.8010063
- A. Palmieri, M. Vallone, M. Calciati, F. Bertazzi, M. Goano, G. Ghione, *"Effect of Saturation Velocity in Germanium p-i-n Photodetectors"*, 2017 Fotonica AEIT Italian Conference on Photonics Technologies, Padova, Italy, May 2017

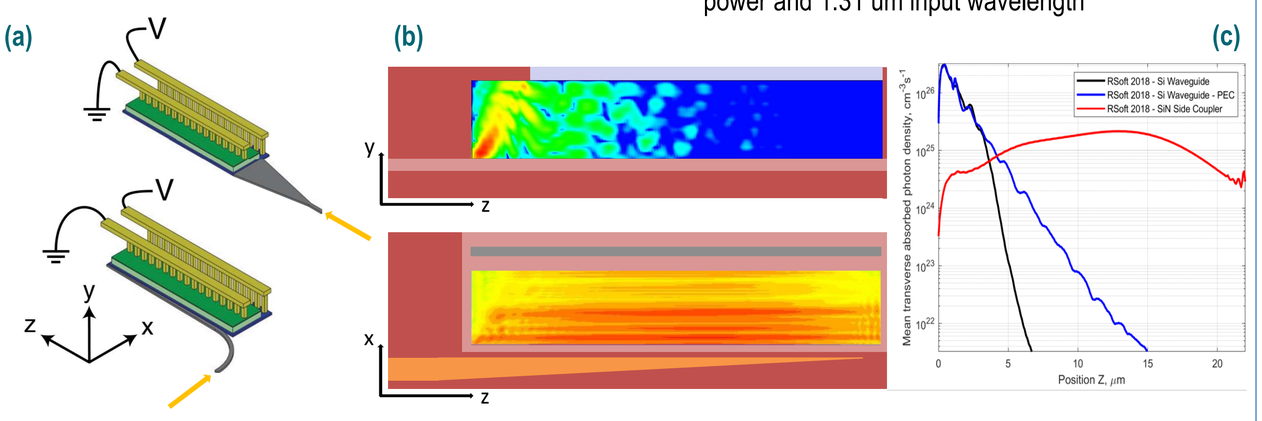
Addressed research questions/problems

1. Using a butt-coupled waveguide, much of the light fed to the Ge volume is absorbed in the first microns. For increasing levels of optical power, carrier photogeneration is strong enough to induce an electric field able to screen the one from the applied bias, resulting in lower responsivity and bandwidth → How to minimize the saturation effects?
2. High-capacity communications require optical modulators to be operated at the highest speed on the smallest footprint so that low-energy consumption and a much denser integration may be achieved → Is there any alternative to Si-based modulators?

Novel contributions

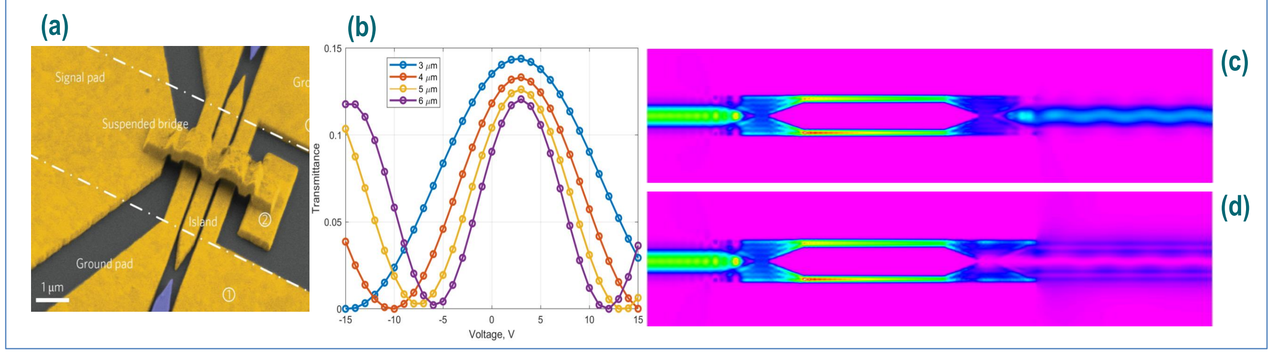
- Innovative coupling structures: inspired from literature (M. J. Byrd, Optics Letters 42 (2017) 851), we studied an asymmetric lateral tapered coupler in SiN. This new design produce a gradual release of the input optical power to the Ge detector, resulting in a more uniform distribution of the optical generation rate.

Left: 3D models of the *pin* photodetector butt-coupled (top) and of the evanescent coupler (bottom)
Center: absorbed photon density maps computed at 200 uW input optical power for a butt-coupled Si waveguide (a, side view) and a tapered SiN side coupler (b, top view)
Right: mean transverse absorbed photon density in the Ge region as a function of the propagation direction at 200 uW input optical power and 1.31 um input wavelength



- Plasmonic-organic hybrid modulators for SiPh: Mach-Zehnder interferometers realized from metallic slots exploiting linear electro-optic effects in poled organic polymers have recently emerged as a valid alternative to in terms of speed (> 100 GHz), footprint (length ~ 10 µm) and energy consumption per bit (tenths of fJ/bit)

Left: colorized SEM image of the plasmonic modulator under study (C. Haffner et al., Nat. Phot., vol. 9, pg. 525, 2015)
Center: static modulation characteristic obtained from 2D EME simulation for varying slot lengths
Right: colormap of the real part of the time-averaged Poynting vector in the on-state (top) and the off-state (bottom) from 2D EME simulations



Future work

- Use of high-order models for carrier transport, such as Monte Carlo to gain deeper insight on the avalanche ionization properties of Ge-based materials and optoelectronic devices.

List of attended classes

- 01QRQRV – Compressed sensing: theory and applications (20/07/2017, 4 CFU)
- 01NTUKG – Fisica dei sistemi mesoscopici (22/06/2017, 4 CFU)
- 01QSAIU – Heuristics and metaheuristics for problem solving (06/07/2017, 4 CFU)
- 02RHQRV – Intellectual Property Rights, Technology Transfer and Hi-tech Entrepreneurship (17/07/2017, 9 CFU)
- 01RZLKI – Nanometric dielectrics (01/06/2017, 4 CFU)
- 01MNFIU – Parallel and distributed computing (07/07/2017, 5 CFU)
- 02IUGKG – Metodo Monte Carlo (21/12/17, 6 CFU)
- 01SFURV – Programmazione scientifica avanzata in MATLAB (12/04/2018, 4 CFU)
- 01UGERO – Materials by design: how structure meets function (03/07/19, 4 CFU)
- 01SDDKI – Additive manufacturing polimerico (19/07/2019, 4 CFU)

- PhD Course "Organic electronics: principles, devices and applications" - Milano, 12-16/03/2018
- PhD School "SQUAD 2017: advanced school on quantum detectors" - Trento, 16-18/10/2017
- PhD School "GaN electronic and optoelectronic devices for increased energy efficiency" - Padova, 19-20/09/2017
- PhD School "ePIXfab 4th Silicon Photonics Summer School" - Pisa, 1-5/07/2019

POLITECNICO DI TORINO

PhD program in
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