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XXXVI Cycle

3D multiphysics modeling of *pin* Ge-on-Si waveguide photodetectors

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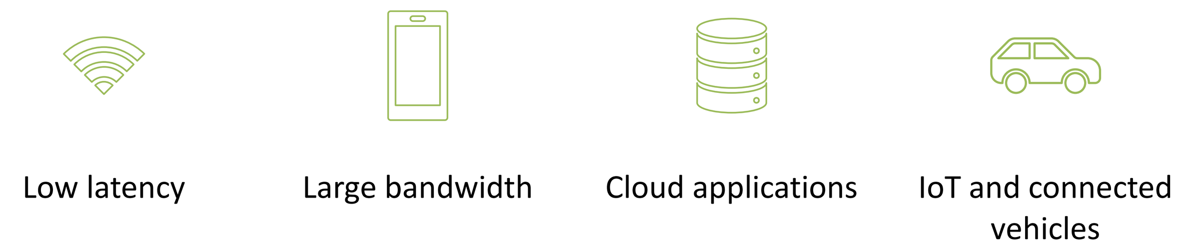
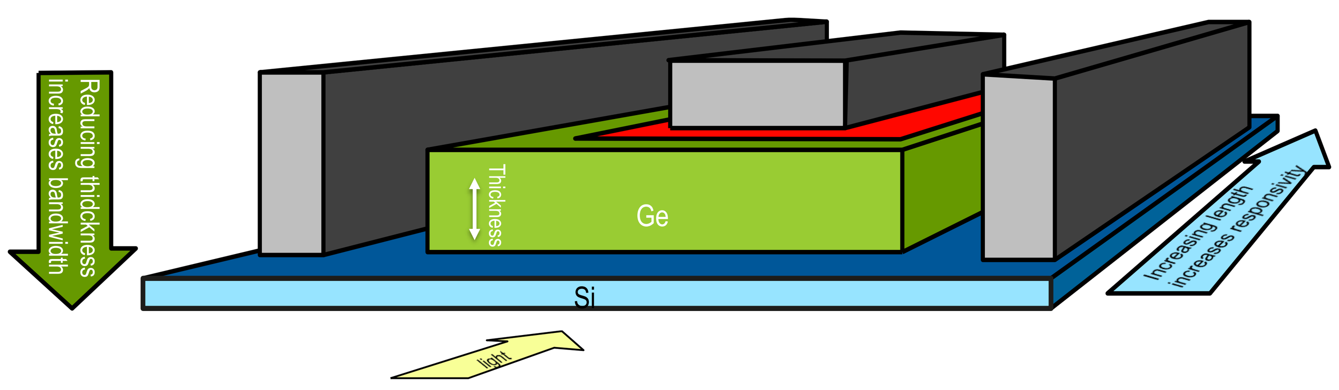
Research context and motivation

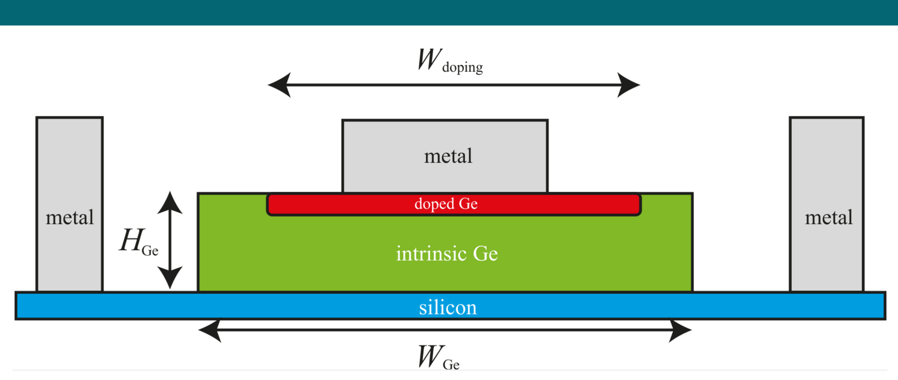
- IoT (internet of things), connected vehicles, sustainable data centers etc. require a high bitrate and large bandwidth infrastructure capable of tens of Gbit/s with few ms latencies.



- Therefore, optical links – historically confined to long-distance telecommunications – are now increasingly used in datacom interconnects and other short-haul applications.
- Key to this expansion is the low-cost deployment of silicon-based optoelectronic technology – usually called ***silicon photonics***: existing fabrication techniques for silicon-based integrated circuits are adapted to include hybrid or monolithic optical components onto a single microchip.
- Among all the building blocks of a silicon photonic system (lasers, optical modulators, passive devices such as couplers and splitters, etc.), the focus of my research has been on ***waveguide photodetectors (PDs)***.
- The most promising PD structures include a ***germanium*** absorption region (ideal for operation in the O and C bands of the near-infrared spectrum, i.e., 1.31 and 1.55 μm) and are ***waveguide***-integrated (which allows the independent optimization of *responsivity* and *bandwidth*)

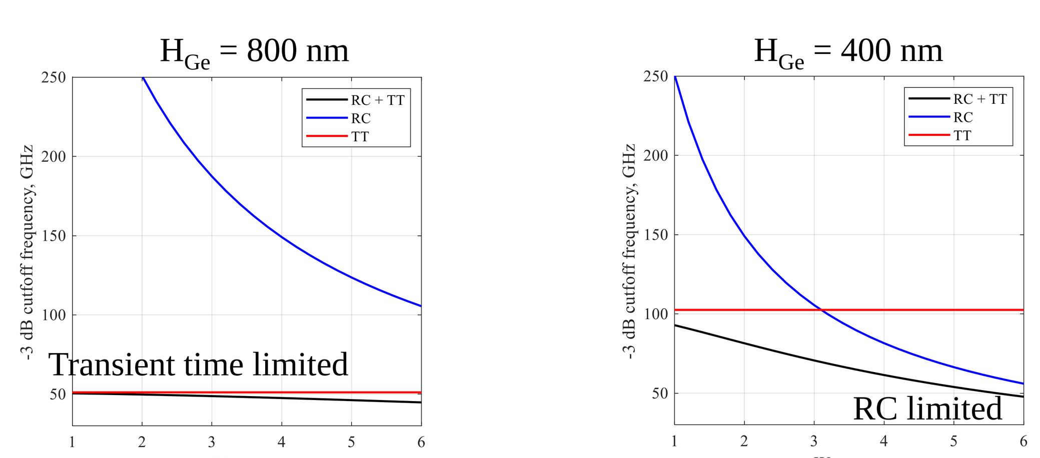


Addressed research questions/problems



H_{Ge}	W_{Ge}	L_{Ge}	W_{doping}
800 nm	4 μm	15 μm	3 μm

- The goals of my work are to set up a multiphysics modeling approach for Ge-on-Si butt-coupled waveguide PDs, to validate it against experimental measurements provided by Cisco Systems on several families of devices at different bias voltages, and to suggest ways to increase both **responsivity** and **bandwidth**.
- Bandwidth optimization means RC and transit time optimization, keeping responsivity constant

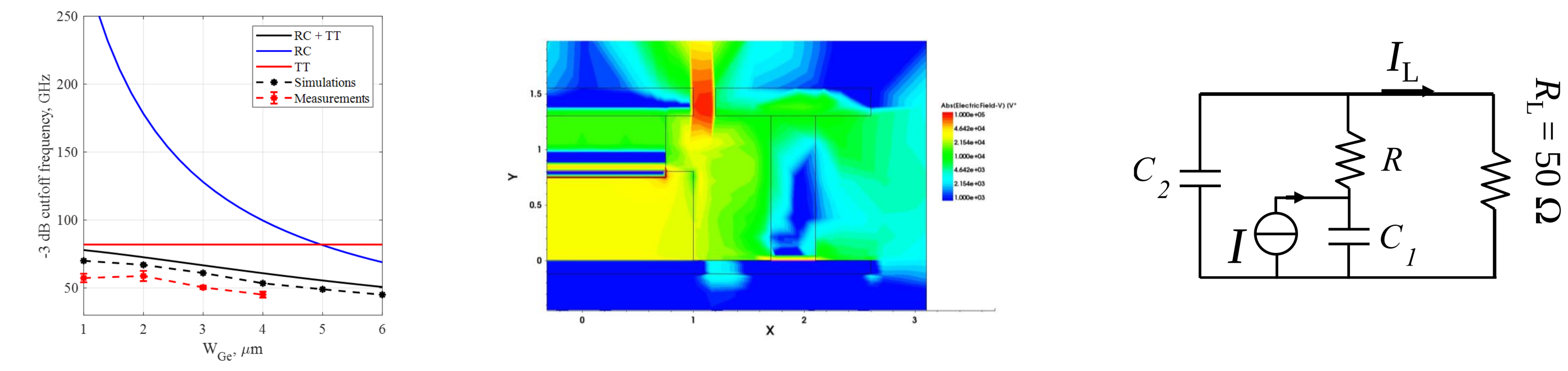


Submitted and published works

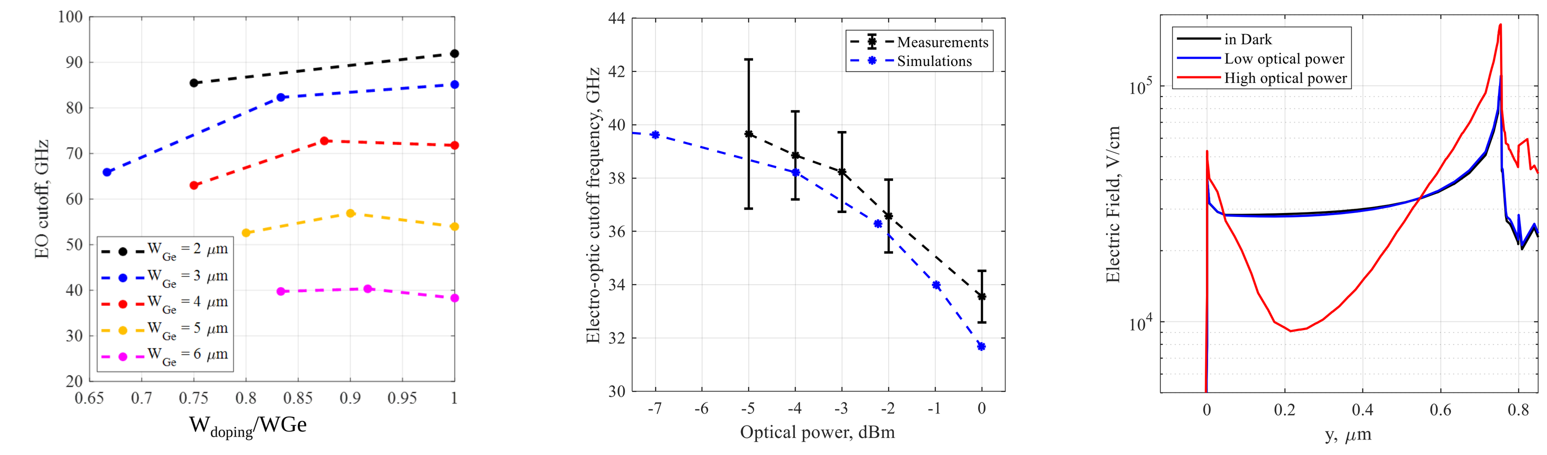
- Tibaldi, A., Montoya, J. A. G., Alasio, M. G., Gullino, A., Larsson, A., Debernardi, P., ... & Bertazzi, F. (2020). Analysis of carrier transport in tunnel-junction vertical-cavity surface-emitting lasers by a coupled nonequilibrium Green's function–drift-diffusion approach. *Physical Review Applied*, 14(2), 024037.
- Alasio, M. G. C., Franco P, Tibaldi, A., Bertazzi, F., Namnabat, S., Adams, D., ... & Goano, M. (2022, September). 3D multiphysics transient modeling of vertical Ge-on-Si pin waveguide photodetectors. NUSOD 2022, IEEE.
- Alasio, M. G. C., Vallone, M., Tibaldi, A., Bertazzi, F., Namnabat, S., Adams, D., ... & Goano, M. (2022, May). Modeling the frequency response of vertical and lateral Ge-on-Si waveguide photodetectors: Is 3D simulation unavoidable? CLEO 2022. Optica Publishing Group.
- Alasio, M. G., Goano, M., Tibaldi, A., Bertazzi, F., Namnabat, S., Adams, D., ... & Vallone, M. (2021, October). Bias effects on the electro-optic response of Ge-on-Si waveguide photodetectors. In 2021 IEEE Photonics Conference. IEEE.
- Alasio, M. G., Goano, M., Tibaldi, A., Bertazzi, F., Namnabat, S., Adams, D., ... & Vallone, M. (2021, September). Ge-on-Si waveguide photodetectors: multiphysics modeling and experimental validation. NUSOD 2021. IEEE.
- Tibaldi, A., Gullino, A., Montoya, J. G., Alasio, M., Larsson, A., Debernardi, P., ... & Bertazzi, F. (2020, September). Modeling Tunnel Junctions for VCSELs: A Self-Consistent NEGF-DD Approach. NUSOD 2020. IEEE.
- Palmieri, A., Shafiee, A., Alasio, M. G. C., Tibaldi, A., Ghione, G., Bertazzi, F., ... & Vallone, M. (2020, September). Enhanced dynamic properties of Ge-on-Si mode-evolution waveguide photodetectors. NUSOD 2020. IEEE.
- Vallone, M., Tibaldi, A., Bertazzi, F., Palmieri, A., Alasio, M. G., Hanna, S., ... & Goano, M. (2020). Next-generation long-wavelength infrared detector arrays: competing technologies and modeling challenges. In *Integrated Optics: Characterization, devices, and applications*, Vol. 2, Ch. 9, pp. 265-294.

Novel contributions

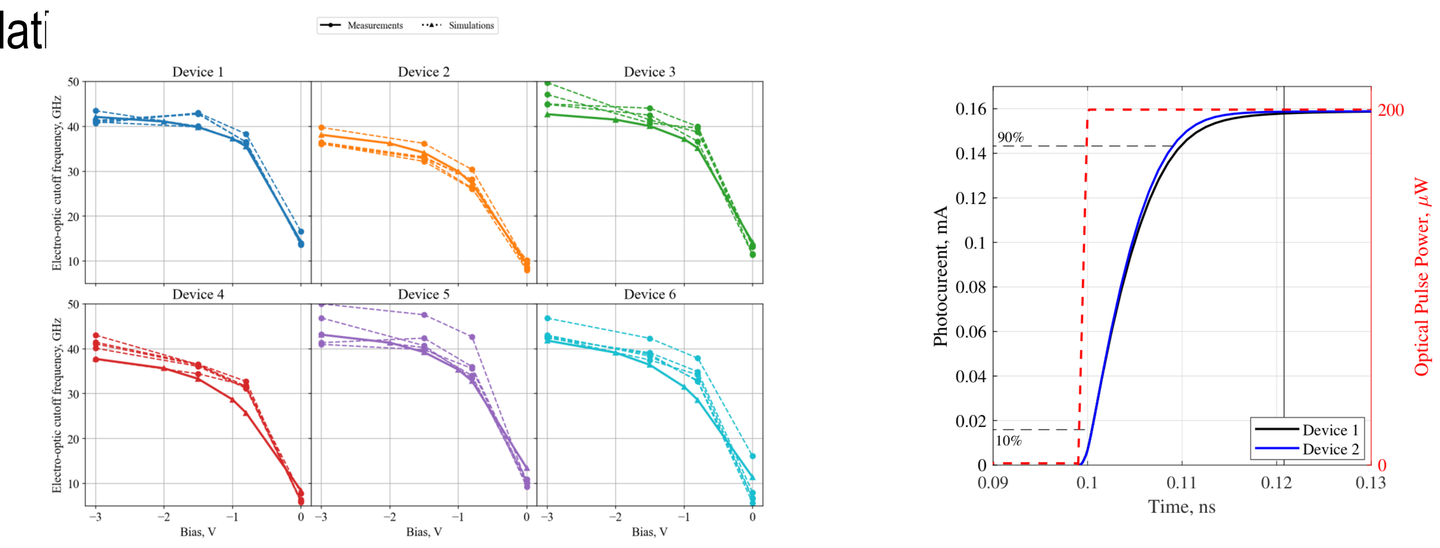
- Bandwidth optimization, taking into account both transit-time and RC contributions
- Model validation against measurements provided by Cisco Systems



- Minimization of the sensitivity of the frequency response to the input optical power

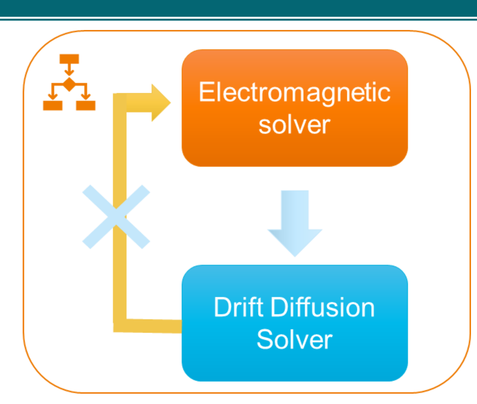


- Extension to large-optical-power applications based on **time-domain** multiphysics simulati



Adopted methodologies

- Multiphysics simulations: finite-difference time-domain (FDTD) for the electromagnetic problem, and drift-diffusion (DD) for the carrier transport problem
- The multiphysics coupling is unidirectional, i.e., the FDTD solution is used as a generation term in the DD equations, without any self-consistent loop.



$$\frac{\partial D}{\partial t} = \nabla \times H - J \qquad \nabla \cdot B = 0 \qquad H = \frac{1}{\mu_r \mu_0} B$$
$$\frac{\partial B}{\partial t} = -\nabla \times E \qquad \nabla \cdot D = 0 \qquad D = \varepsilon_r \varepsilon_0 E$$

G_{opt} →

$$\nabla^2 \phi = -\frac{q}{\varepsilon}\rho \qquad \rho = (+q\, N_D^+) + (-q\, N_A^-) + (+qp) + (-qn)$$
$$\frac{\partial p}{\partial t} + \frac{1}{q}\nabla \cdot J_p + U_p = 0 \qquad J_n = J_{n,t} + J_{n,d} = -qn\mu_n \nabla\phi + qD_n \nabla n$$
$$\frac{\partial n}{\partial t} - \frac{1}{q}\nabla \cdot J_n + U_n = 0 \qquad J_p = J_{p,t} + J_{p,d} = -qp\mu_p \nabla\phi - qD_p \nabla p$$

- The simulation software used is a set of commercial CAD suites by Synopsys:
  - Synopsys RSoft FullWave: FDTD solver
  - Synopsys TCAD Sentaurus: mesh generation, DD solver

Future work

- Extending the model validation against additional experiments should allow the extraction of relevant microscopic quantities (e.g., saturation velocities of carriers) for new designs
- The time domain analysis may directly provide the **eye diagrams** starting from a physics-based approach
- This work could be instrumental for next-generation *pin* photodetectors with focus on high bandwidth, low-bias and low-power application

List of attended classes

- 01UMNRV - Advanced deep Learning (didattica di eccellenza) (15/06/2021, 6)
- 01TUFRV - All you need to know about research data management and open access publishing (08/04/2021, 3)
- 01UNRRV - Entrepreneurship and start-up creation (31/05/2021, 8)
- 01PJMRV - Etica informatica (03/05/2021, 4)
- 01MNFIU - Parallel and distributed computing (26/07/2021, 5)
- 01TCTRV - Photonext: Hands on course on Photonics for Fiber Transmission (13/09/2021, 6)
- 01QFDRV - Photonics: a key enabling technology for engineering applications (15/07/2021, 5)
- 02SFURV - Programmazione scientifica avanzata in matlab (27/04/2021, 6)
- 01DNYRV - Semiconductor light sources for engineers (12/09/2022, 4)
- 02QUBRS - Statistical data processing (04/02/2021, 4)
- 01MMRRV - Tecniche numeriche avanzate per l'analisi ed il progetto di antenne (09/06/2021, 4)
- 01QORRV - Writing Scientific P+apers in English (20/05/2021, 3)

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