PhD proposal for 2020

Centre de Nanosciences et de Nanotechnologies
CNRS & Université Paris-Sud, UMR 9001
Université Paris-Saclay
C2N, 10, Boulevard Thomas Gobert
91120 Palaiseau, France

Contact: Philippe Dollfus
Research Director, CNRS
Center for Nanoscience and Nanotechnology (C2N)
Phone: +33 (0)1 70 27 04 09
Website: http://computational-electronics.ief.u-psud.fr/
E-mail: philippe.dollfus@u-psud.fr

Fields: Nanoelectronics, Optoelectronics, Computational Electronics

Modelling and optimization of Si and Ge-based Single Photon Avalanche Diodes for Lidar and fast movement detection

Scientific Context

Advanced optoelectronic devices such as the single-photon avalanche diode (SPAD) are now widely employed in the fields of 3D imaging, camera assist, laser ranging and proximity [1]. Next generation of SPAD will be devoted to time-of-flight 3D ranging and fast movement detection, notably for long LiDaR used in autonomous driving cars, collision avoidance, seeing round corners. To achieve these new technological challenges, it is required to design efficient devices of reduced dimensions with photon detection probability (PDP) as high as 10 times the present values. A crucial and not trivial issue is to obtain larger PDP without increasing the obscurity signal detection or dark count rate (DCR), but also the time distribution response to the reflected light pulses (jitter) [2].

Methodology and objectives

The PhD work will consist in developing and exploiting two different and complementary home-made simulators. These state-of-the-art codes will provide reliable and predictive simulations able to reach a deep understanding of the device physics. The ultimate goal of this PhD will be to propose original design options based on scaled nanostructures such as thin semiconductor films and nanowires. This study will allow us to optimize existing optoelectronic devices, as well as to test new device based on unexplored working principles.

First, by using 3D particle Monte Carlo simulation [3,4] for solving the Boltzmann transport equation, the time behavior of different designs of Si-SPAD devices will be statistically analyzed in order to reduce the jitter and to enhance the photon detection probability. The MC technique is a unique tool to analyze single particle trajectories as well as the time evolution of terminal currents and voltages (see Figs 1 and 2).

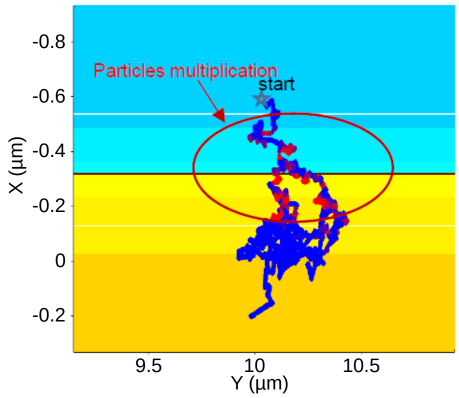

Fig. 1. Particle trajectories in a SPAD and multiplication (Monte Carlo simulation)

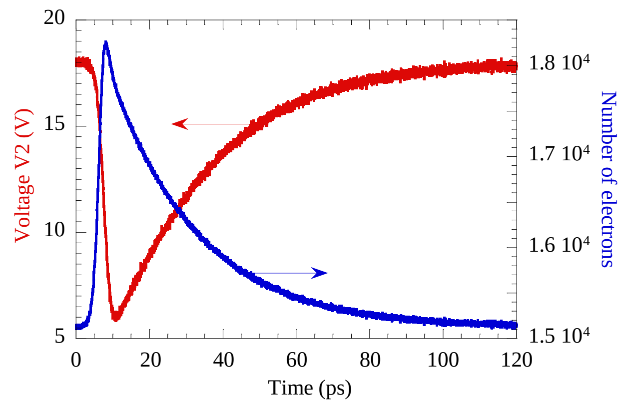

Fig. 2. Time evolution of output voltage and number of electrons in a SPAD after avalanche (MC simulation).

The analysis will be made also in terms of ionization events and internal quantities such as carrier density and electric field distribution. Germanium-based SPADs, better suited for detection of large wavelength photons (≈ 1500 nm) will be investigated too, which will first require the implementation of impact ionization rates for this material.

In the second part, the PhD student will investigate the relevance of non-local effects related to quantum confinement and quantum correlations between carriers and photons and phonons on the electric performance and on the signal-to-noise ratio of SPADs. To this purpose, quantum transport will be addressed by using the Non-equilibrium Green's function method, which will allow us to include also the inelastic electron-photon and electron-phonon interactions [5]. Full band effects will be also considered thanks to the use of empirical pseudopotential models [6, 7] since high-energy carriers are involved during the occurrence of impact ionization in SPADs. The role played by trap assisted tunneling in determining the noise of such devices will be also simulated using a full-quantum approach [8].

Importantly, within a collaborative project, all simulations and physical models will be validated by comparing numerical results with experimental data supplied by STMicroelectronics, which is a world-leader company in the field of single-photon detectors [9].

The final objective of this theoretical work is threefold: (i) understanding the optical and electronic properties of SPAD devices by means of a both semi-classical and full-quantum approaches, (ii) suggesting design options to improve the performance of this type of device and (iii) eventually propose new efficient optoelectronic devices for applications in autonomous cars and gesture detection.

Skills learned

The student will acquire a broad range of skills: in solid-state and device physics (band structure, electronic transport, impact ionization, optoelectronic devices), and scientific programming (Fortran, Matlab).

Candidate's Profile

The candidate should have an MSc in Physics, Electronics, Materials Science or related topics, with a good knowledge of electronic structure of solids, electronic transport phenomena, and semiconductor devices, together with a good basis in quantum mechanics. We are seeking a creative person highly motivated by scientific research and well trained. Scientific programming experience (Matlab, C, Fortran) is also desirable, but not mandatory.

Please join a CV, a list of courses that you have followed and results of exams in the framework of your master program, and any other information that you consider useful.

References:

[1] D. Bronzi et al., "100 000 frames/s 64× 32 single-photon detector array for 2-D imaging and 3-D ranging", IEEE J. Sel. Top. Quantum Electron. 20, 3804310 (2014).

[2] Y. Xu, P. Xiang, X. Xie and Y. Huang, "A new modeling and simulation method for important statistical performance prediction of single photon avalanche diode detectors", Semicond. Sci. Technol. 31, 065024 (2016).

[3] D. Querlioz, J. Saint-Martin, K. Huet, A. Bournel, V. Aubry-Fortuna, C. Chassat, S. Galdin-Retailleau, P. Dollfus, "On the ability of the particle Monte Carlo technique to include quantum effects in nano-MOSFET simulation", IEEE Trans. Electron Devices 54, 2232-2242 (2007).

[4] T. T. Trang Nghiêm, J. Saint-Martin, P. Dollfus, "Electro-thermal simulation based on coupled Boltzmann transport equations for electrons and phonons", J. Appl. Phys. 116, 074514 (2014).

[5] G. Mahan, Many-Particle Physics, Plenum Press, New York, (1990).

[6] M. Cohen and J.R. Chelikowsky, Electronic structure and optical properties of semiconductors, Springer, (2012).

[7] M. G. Pala, O. Badami, D. Esseni, "NEGF based transport modelling with a full-band, pseudopotential Hamiltonian: Theory, implementation and full device simulations", 2017 IEEE International Electron Devices Meeting (IEDM), 31.5.1 (2017).

[8] M.G. Pala and D. Esseni, IEEE Trans. Electron Devices, "Interface Traps in InAs Nanowire Tunnel-FETs and MOSFETs—Part I: Model Description and Single Trap Analysis in Tunnel-FETs", 60, 2795-2801 (2013).

[9] http://www.st.com/en/imaging-and-photonics-solutions/proximity-sensors.html