Ph.D. in Information Technology
Thesis Defenses

May 28th, 2024
at 14:30 p.m.
Room Alpha

Davide BERRETTA – XXXVI Cycle

HIGH PHOTON-RATE AND LOW CHARGE PER PULSE SPAD FRONT-END FOR HIGH-DENSITY IMAGERS

Supervisor: Prof. Federica Alberta Villa

Abstract:

Today, SPADs are widely used as imaging sensors, and in many applications, the trend is to continuously increase the number of pixels of the final chip array, thereby expanding the area leading to megapixel sensors. This incoming feature takes advantage of a larger effective area and a very large field of view, but at the same time, it bumps into an increasing amount of power consumption. In the case of limited current or other restrictions from surrounding electronic components, especially under high photon flux conditions, total power consumption may become an issue. For this reason my Ph. D. research, in collaboration with STMicroelectronics, looks into the power dissipation issues with the goal of minimizing the Charge Per Pulse (CPP), meanwhile continuing to maximize the pixel Max Count Rate (MCR).
Indeed, the workflow is to analyze and solve the problems starting from the device to the front-end circuit operation. First, the focus is to identify the main physical parameters that cause huge power demands, investigate their models, and introduce some innovations that can face or minimize their energy demands. In this part, the breakthroughs introduced involve mainly the device itself, specifically including parasites and components that have no direct effect on the detector behavior. Secondly, when the device is optimized, the front-end electronic should be designed to maximize the performance. A testchip has been designed with a state of the art technology based on a 3D-stacked structure (3D- stacked 28 nm FDSOI by STMicroelectronics). Finally, this research activity will also cover the evaluation and verification of the implemented solutions in a single pixel, to identify the final solution for the entire array.

Andrea BONZI – XXXVI Cycle

NEXT GENERATION SINGLE PHOTON AVALANCHE DIODES FOR HIGH-EFFICIENCY, NEAR-INFRARED PHOTON-TIMING

Supervisor: Prof. Angelo Gulinatti

Abstract:

Thanks to their high Photon Detection Efficiency (PDE), compactness, and reliability, Single Photon Avalanche Diodes (SPADs) are now profitably used from both the scientific and industrial communities in a wide range of applications that rely on single-photon detection. Light detection and ranging (LiDAR), diffuse optical tomography (DOT), and fluorescence lifetime imaging spectroscopy (FLIM) are just a few examples.

Among the many SPADs now available, silicon SPADs are the most widespread ones, because of their excellent performance in terms of Dark Count Rate (DCR), afterpulsing probability, and time resolution.
Despite the incredible steps forward of the last decade, already-existing detectors make not possible to envision a good combination of high detection efficiency and good timing resolution in the near-infrared spectrum (i.e. between 800 and 1000 nm of wavelength). The reason is an in intrinsic trade-off that plagues the current SPAD structures: as the detector is illuminated from the top, increasing the detection efficiency requires a thicker depletion region which results in a larger time jitter, owing to the dispersion of the carriers' transit times. For example, passing from a thin to a red-enhanced SPAD increases the PDE from about 10% to 30% at 850 nm, but simultaneously leads to a degradation of the time jitter from about 30 to 90 ps FWHM. Consequently, there is a wide variety of applications the potential of which cannot be fully satisfied by currently available detector structures, such as Quantum Key Distribution (QKD), Quantum Information Processing (QIP), etc. My doctoral work aims at developing SPADs that overcome the trade-offs between detection efficiency and timing jitter at near-infrared wavelengths.
First, with the goal of helping the growth and the validation of new and more accurate SPAD models, I developed an extraction technique able to provide accurate doping profiles along the depletion region of the measured SPADs. Indeed SPAD models, thanks to their ability in accurately forecasting detectors' metrics, play a key role in the evolution of SPAD technology. However, to verify the effectiveness of these models, a thorough and extensive validation against experimental data is required. To this aim, being most physical phenomena that determine detector performance strongly dependent on the electric field, accurate doping profiles are mandatory. Unfortunately, widely-adopted profiling techniques provide results which are not precise enough for SPAD modeling. Starting from an initial, approximate, doping profile provided by process simulations and/or Secondary Ion Mass Spectroscopy (SIMS) measurements, the technique I developed refines it up to an accuracy level high enough to correctly predict SPAD metrics. To do this, I adopted an inverse scheme in which the doping profile is continuously corrected until a close matching is obtained between electrical simulations and experimental capacitance-vs-voltage (C-V) measurements. To verify the method, I applied the technique to several real SPADs with different internal structures and different doping profiles and used the obtained results to compute their breakdown voltage. Calculated outcomes in good accordance with experimental data were obtained, providing a convincing validation of the proposed method.
Second, with the aim to push farther the boundaries set by the trade-off between PDE and timing jitter, a side-illumination approach, in which the light propagates transversally, has been proposed. This way, the absorption efficiency can be improved by acting on the detector length, rather than its thickness, thus decoupling light absorption from avalanche multiplication. This way, the detector thickness can be reduced to the values typical of the thin SPADs, allowing a potential time jitter of about 30 ps FWHM. To do this, the SPAD will be embedded in a silicon-waveguide structure and the photons, generated externally, will be coupled into the detector through an optical fiber. An upper electrode and a silicon contact region present on one side of the guide are necessary for biasing the structure and having along the device thickness the typical electric field profile of the detector. As a first step, an optical analysis has been conducted in order both to size the main parameters of the waveguide structure and to verify the robustness of the system. Afterwards, a simplified but realistic fabrication process was devised and simulated in order to investigate the electrical properties of the detector. The simulations I performed confirmed that this solution is very promising and that non idealities, such as the surface roughness of the guide or a small misalignment or tilt between the detector and the input optical fiber, have only a minimal impact on the detector performance.
Third, in order to overcome SPAD limitations within existing detector structures (thin and red-enhanced SPADs in particular), the following two technological solutions have been explored: back-illumination technology and resonant cavity integration. Indeed, despite the promising results predicted for the side-illumination approach, a waveguide-SPAD is not suitable for a number of applications. For example, a waveguide-integrated SPAD cannot be employed in a satellite-QKD system, as the light coming from the telescope requires large active area diameter (i.e. between 100 - 150 μm). Simulation results allowed me to conclude that impressive improvements may be attained in terms of both detection efficiency and time response through the aforementioned solutions, either singularly or in combination. For instance, PDE as high as 77% are predicted at 850 nm of wavelength from a red-enhanced SPAD structure, together with timing jitters and diffusion time constants in the order of few hundreds of picoseconds. As another example, detection efficiency from about 51% to 64% are expected from both front- and back-illuminated resonant cavity enhanced thin SPADs, along with time jitter of $\approx$ 32 ps and diffusion time constant no longer than 0.19 ns. Calculations I performed highlighted a pivotal role may be played by such structures for high-rate QKD via satellites.

Lastly, as there are still a large number of applications for which red-enhanced SPADs may be suitable, the final part of my Ph.D. work was dedicated to this class of detectors. Modifications have been applied to the RE-SPADs' fabrication process in order to satisfy a series of requirements, such as a lower junction depth, an improved compactness, and a reduced thermal budget. With the goal of evaluating the effectiveness of all the modifications I applied, a simplified version of the fabrication process with a reduced manufacturing time was also devised to produce test devices. In addition, to be able to extract the boron profiles from the wafers where the RE-SPADs will be manufactured, the potential and the feasibility of different Metal-Oxide-Semiconductor (MOS) structures have been investigated. Simulation results demonstrated that it is possible to obtain valuable information about the doping profile in some critical regions of the detector, provided that appropriate measures are adopted in the design of the test structures.

Serena FARINA – XXXVI Cycle

TOWARD ENHANCED TIME-CORRELATED SINGLE-PHOTON COUNTING SYSTEMS: FROM THEORETICAL STUDIES TO FIELD APPLICATIONS

Supervisor: Prof. Ivan Rech

Abstract:

In the last decades, a growing interest has emerged in the use of light sensing for both research and industry purposes. The possible applications span, indeed, a wide range of activities: for instance, biological and medical imaging, laser ranging and imaging in harsh environments, quantum cryptography, and communications are all fields where light sensing is acting as an enabling technology. In this context, an important role is not only played by the possibility of detecting macroscopic light signals, but even more by the capability of distinguishing the smallest light particle, i.e. the single photon. More precisely, a sophisticated and widespread methodology for low-light sensing consists of time-correlated single-photon counting (TCSPC), an acquisition technique where the time of arrival of single photons is recorded with respect to a reference stimulation. In this framework, this Ph.D. thesis attempts to find possible answers to the following research question: "Can current TCSPC systems be improved as to meet the requirements of future light-sensing applications?". In particular, along the thesis work, the question is addressed from various perspectives, reflecting the different figures of merit that are, from time to time, important for different types of scientific applications.

Fabio TELESCA– XXXVI Cycle

SINGLE-PHOTON AVALANCHE DIODES IN III-V COMPOUND SEMICONDUCTOR FOR NEAR-INFRARED APPLICATIONS

Supervisor: Prof. Alberto Tosi

Abstract:

There are many cutting-edge applications that require manipulation and sensing of single-photons in the short-wave infrared range (SWIR). From quantum computing to quantum optics experiments, from quantum communication to quantum metrology, there is a strong need for detecting single-photons at 1550 nm wavelength, typically travelling in optical fibers. Similarly, innovative imaging applications, such as ghost imaging, non-line-of-sight imaging and low-power LiDAR, all require eye-safe sources and the typical

wavelength of choice is 1550 nm. Also, biomedical applications, such as near-infrared spectroscopy (NIRS) and diffuse correlation spectroscopy (DCS), are extending their range beyond 1.1 µm. This drive from application requirements led to the development of single-photon detectors (SPDs) implemented with innovative technologies and materials capable of detecting NIR single-photons. Among them, the most prominent devices nowadays are superconductive nanowire single-photon detectors (SNSPDs) and single-photon avalanche diodes (SPADs). While the former are capable of photon detection efficiency (PDE) above 90% at selected wavelengths, with dark counts as low as few cps, their main disadvantage is the requirement of bulky and expensive cooling systems to operate the detectors at cryogenic temperatures. SPADs, on the other hand, and specifically InGaAs/InP SPADs, can be integrated in compact, portable systems and, at a temperature of about 230 K, reachable with a small, three-stage thermoelectric cooler, have overall good performance in terms of both PDE and noise. The goal of this Ph.D. work is to push the development of InGaAs/InP SPADs in an effort to optimize the main trade-offs, with the goal of: enhancing the PDE, while keeping DCR as low as possible, and enabling the possibility of operating InGaAs/InP SPADs at higher temperatures and higher photon count-rates.

PhD Committee

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