Ph.D. in Information Technology: Thesis Defenses

February 23rd, 2018

DEIB Conference Room "Emilio Gatti" (building 20) - 09.30 am

Francesco CECCARELLI – XXX Cycle

"Development of custom-technology single-photon avalanche diode arrays for high-performance applications"

Advisor: Prof. **Angelo Gulinatti**

Abstract:

Recent years have seen the rise of Single-Photon Avalanche Diodes (SPADs) as the solid-state alternative to Photo Multiplier Tubes (PMTs) in many Single-Photon Counting (SPC) and Time-Correlated Single-Photon Counting (TCSPC) applications: high Photon Detection Efficiency (PDE), compactness, high reliability and the compatibility with the fabrication of detector arrays are just few of the main advantages of SPADs. Furthermore, silicon custom technologies have widely contributed to obtain large-area detectors, with excellent performance in terms of Dark Count Rate (DCR), afterpulsing probability, time jitter and detection efficiency over the visible range and up to 1- m wavelength. In particular, a significant breakthrough was the introduction of the Red-Enhanced SPAD (RE-SPAD), the first SPAD able to attain a remarkable PDE in the near infrared range (e.g. 40% at a wavelength of 800 nm), while maintaining a good time jitter of less than 100 ps FWHM. These features have been already proven to be crucial in single-photon applications like single-molecule Forster Resonant Energy Transfer (smFRET), a powerful tool used to study the conformation of diverse biomolecules, like proteins, nucleic acids, etc. Nevertheless, this application suffers from long measurement times, strongly limiting the time scale on which the biological phenomena can be observed. Multi-spot excitation/detection schemes are a promising way to increase the throughput of single-molecule analysis, but this requires the use of a complex setup in which a suitable SPAD array has to be employed. The main focus of this doctoral work was the development of high-performance RE-SPAD arrays, using silicon custom technologies. The first prototypes of RE-SPAD arrays (Fig. 1) have been fabricated at the Cornell Nanoscale Science and Technology Facility (CNF) and part of my work was focused on the experimental characterization of these devices, aimed both at quantifying their performance and at understanding their behaviour. This led to some significant results. In particular, with the new experimental set-ups (both wafer-level and chip-level) that I designed I was able to demonstrate that the electrical isolation has been fully

recovered by means of deep trenches, with no detrimental effect on the detector DCR. Furthermore, I showed also that additional n+ structures implemented in the deep trenches are sufficient to inhibit the direct optical crosstalk between pixels. Therefore, deep Phosphorus diffusion are no longer needed, with obvious advantages in terms of compactness and thermal budget. Overall, these results demonstrate that RE-SPAD arrays can be employed in photon counting applications with the same performance of single-pixel devices. A 32x1 RE-SPAD array has been exploited in the development of the first complete RE photon detection module, able to attain a PDE as high as 70% at 650 nm; this module is currently employed in a multi-spot smFRET set-up, in the context of a fruitful collaboration with the University of California, Los Angeles (UCLA).

Even though the attained results are remarkable, the current design suffers some important limitations. Indeed, the onset of the edge breakdown strongly limits the applicable excess bias and, in order to overcome this, a guard ring structure is present in each pixel. Unfortunately, the possibility to increase the operating overvoltage comes at the expenses of an increased complexity in the biasing of the device and in a reduction of the attainable fill factor. Both these limitations prevent the fabrication of dense arrays and completely preclude the scaling toward arrays with thousands of pixels. Therefore, with my PhD work I propose a new design, that resorts to a high-energy Boron implantation to obtain at the same time a fully optimized electric field profile and a higher edge-breakdown voltage. Furthermore, I also show how both standard and RE detectors can greatly benefit from the use of a standard Phosphorus implantation instead of a predeposition, both in terms of PDE and temporal response. Detectors with the new design will be fabricated and experimentally investigated in the next months, in order to verify the predicted results and to exclude any detrimental effect on the device noise of both the new technological approaches.

A second important contribution that I gave was on the experimental characterization of standard SPADs belonging to the previous generation and fabricated by the National Research Council of Italy - Institute for Microelectronics and Microsystems (IMM-CNR sez. Bologna). These devices allowed me to participate in the development of a complete detection module based on a 8x8 standard SPAD array, getting acquainted also with the issues that are typical of the system integration. In particular, the module has been envisioned also for use in an alternative operating mode, that combines the output coming from the 64 pixels in order to enhance the maximum count rate to more than 2 Gcps, to provide photon-number resolving capabilities and to extend the dynamic range to 141 dB, a value higher than reported so far in literature. In particular, this value is currently limited by the speed at which the Active Quenching Circuits (AQCs) can be operated and by the presence of some high-DCR SPADs in the array. To the aim of investigating the future perspective of the 8x8 array, I also developed a detection head based on a low-noise, single-pixel SPAD, operated with a new AQC able to attain a dead time as low as 8.3 ns. The result was the best dynamic range ever reported for a SPAD: 152 dB, that can become even higher if this configuration is employed in a parallel module like the aforementioned one. Furthermore, I studied also the effect of the introduction of a n-epitaxial layer on timing performance: thanks to the reduction of the parasitic elements, the jitter shows a strong reduction of the dependence on the detection threshold. This opens new prospects in the design of high-threshold detection systems with a high number of pixels and reduced electrical crosstalk among them.

Nicola LUSARDI – XXX Cycle

"Advanced Methods Techniques and Digital Architectures for High Performance Timing of Events"

Advisor: Prof. **Angelo Geraci**

Abstract:

The precise measurement of time intervals is a primary goal in a growing number of applications and the challenge to achieve increasingly higher resolutions than ever is a main topic of research. In this sense, Time-of-Flight measurements and Time-Correlated Photon Counting are two milestones. Since the intrinsic resolution of the sensors used today is in the order of tens of picoseconds, the measurement systems must guarantee performance at least of this order.

The choice of making digital a part or the totality of the measurement electronic systems exploits well-known advantages from the adaptivity, to the versatile calibration, to the easiness of implementation of powerful processing algorithms with lower power consumption, and area occupation with respect to the equivalent analog solutions.

The last generation of digital programmable devices as Field Programmable Gate Arrays (FPGAs) and System-of-Chips (SoCs) has made possible the implementation of high-accuracy TDC architectures on programmable logic with performance comparable with ASIC realizations. In this way, all the well-known advantages of using programmable devices are exploited, such as totally tunable characteristics, easiness of portability, reduced time-to-market, lower migration cost from one generation of technology to another, just to name a few. This has to be done always keeping on foreground the maximum functional performance. The dissertation focuses on the maximization of sets of figures of merit single such as precision, resolution, full-scale range, power consumption, area occupancy, acquisition rate, depending on the target application. This is accomplished through measurement techniques like Nutt-interpolation and sub-interpolation algorithms, among which a high-performance totally new solution is presented in this dissertation.

In particular, state-of-the-art of multi-channels sub-interpolated TDCs based on Tapped Delay-Line (TDL) and Nutt-interpolation are considered, both in terms of ideal and real features. Consequence of that is the introduction of a mathematical theory, new in literature, which explains and quantifies advantages and limits of this solution.

Moreover, all investigated issues have been simulated and experimentally validated on a wide spectrum of devices from the Xilinx and Altera manufacturers. In this regard, the issue of migrating firmware between different devices has been studied by providing precise guidelines for the realization of TDC IP-Cores with timing performance comparable with ASIC solutions in the same technological node designed for being migrated between devices from the same or different manufacturers.

As reference case study, is presented the implementation of a very high-performance (high-range, high-resolution and high-precision) multi-channel TDL-TDC (i.e. smart triggering of events, 16 channels, 12ps r.m.s. precision, 9.45s full-scale range with a resolution of 250fs) in devices of different manufacturers (i.e. Altera and Xilinx), paying particular attention to the migration of architectures in structurally very different devices This instrument is being used in several national (2) and international (5) research activities, among which a review of some as examples is presented. Moreover, the most significant achievements accomplished during the activity are attested by 39 international publications (8 on journal), of which 13 as first author and 1 single name submission.

Pietro PERONIO – XXX Cycle

"Time-Correlated-Single-Photon-Counting Systems: Challenging the Limits"

Advisor: Prof. **Ivan Rech**

Abstract:

Time-Correlated Single Photon Counting (TCSPC) is an effective technique for measuring fast and weak optical signals, thanks to the achievable high temporal resolution and single photon sensitivity. These features make it suitable for a huge variety of applications, especially those related to life science, where the maximum power of the laser has to be limited in order not to damage the sample. On the other hand, the main drawback of this technique is the intrinsic long acquisition time, which has constantly fostered the development of faster and faster TCSPC systems. In recent years, the increase of the parallelism level has been the main trend followed by the development of TCSPC system, which feature higher and higher count rate capabilities, but with timing performance not even comparable with the best state-of-the-art single channel systems. I decided to follow an orthogonal approach to break the existing trade-off, by first defining the maximum throughput that the data link toward the PC can sustain (about 10Gbps) and then tailoring the number of acquisition chains to saturate it. Since in advanced TCSPC system the ASIC and system designs are strongly connected to get the desired performance, I contributed to the development of an innovative routing architecture and a fast TAC (F-TAC). When operating together, the router and the F-TAC generate a data throughput of several Gbps that has to be properly managed in order not to lose information and impair

the measurement speed. To this aim, I designed and developed hardware and firmware solutions to manage the throughput on board and to transfer the huge amount of data to the PC at a rate up to 10Gbps. Besides exploiting several detectors in parallel to reduce the measurement time, advanced TCSPC systems can interface with microscopes to perform a scan of the sample. To this aim, I developed a general-purpose firmware interface to manage the synchronization signals and divide the acquisition into pixels and frames. I implemented some of the developed solutions on a 32-channel complete TCSPC system to test and validate them. The instrument, which features state-of-the-art performance, has been employed on a research project to distinguish various stages of aggregation of alpha synuclein (aSyn) in cells, which is a small, natively unstructured protein that can aggregate into insoluble structures that are toxic to neurons, a phenomenon closely linked to the pathology of Parkinson's disease. The results obtained from the testing of the 32-channel system were state of the art and showed that a break of the trade-off was effectively feasible. These premises pushed me toward the design of advanced TCSPC systems that could feature a higher and higher number of channels. As a first technological step on this way, I worked on a 32x32 instrument whose main core is a SPAD array developed exploiting a custom technology. The main goal of this work was to analyze the main issues that affect the design of large TCSPC instruments in order to find possible solutions. This system is meant to fully exploit the bandwidth of the data link toward the PC and maximize the utilization of the acquisition chains. The designed instrument is only a technological step toward the development of large multichannel TCSPC system.

PhD Committee:

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