Ph.D. in Information Technology:

Acconcia, Buttafava, Calandri, Lussana, and Sanzaro Final Dissertations

DEIB Conference Room

February 17th, 2017

09.00 am

First Ph.D. presentation and discussion:

Giulia ACCONCIA – XXIX Cycle

"High-performance integrated electronics for high-throughput Time Correlated Single Photon Counting"

Advisor: Prof. **Ivan Rech**

Abstract:

The analysis of optical signals by means of Single Photon Avalanche Diodes (SPADs) has been subject to a widespread and steadily increasing interest in recent years, driven by the need for ultimate sensitivity in various scientific and industrial applications such as Fluorescence Lifetime Imaging (FLIM) and Förster Resonance Energy Transfer (FRET) in life sciences, Laser Imaging Detection and Ranging (LIDAR) in remote objects sensing and Quantum Key Distribution (QKD) in cryptography and communication. In particular, the use of fluorescence lifetime spectroscopy as both analytical and research tool has increased markedly in recent years with remarkable applications in chemistry, biochemistry and biology. The Time Correlated Single Photon Counting (TCSPC) technique is a powerful tool by which fluorescence-lifetime measurements are carried out.

In the complex environment of living cells, for instance, the study of the composite interactions between proteins and other cellular components is extremely challenging due to the reactions and uncertainties that mainly affect the intensity of the stimulated fluorescence emission. Nevertheless, a deep understanding of these processes is paramount for a better understanding of the (patho)physiology of tissues and organisms and gives a base for gaining a better insight into key medical issues, such as the origin and growth mechanisms of tumors. In this case the exploitation of a TCSPC-based lifetime imaging technique makes it possible to overcome many issues, since it relies on phenomena that, unlike intensity, are mostly

independent from probe concentration and all other parameters that cannot be easily controlled during cellular experiments.

Although TCSPC is a very effective and well-established technique, it can have a few drawbacks: the repetitive nature of this measurement, for example, makes the acquisition time intrinsically long. The need to speed up the acquisition time - in order to exploit this technique in all those applications where the duration of the measurement is crucial for example - has been driving the development of multichannel acquisition systems featuring a steadily increasing number of channels operating in parallel.

Concerning the detector, to date best results have been obtained resorting to technologies specifically dedicated and optimized for the fabrication of the SPAD, usually known as custom technologies. Taking advantage of the remarkable features of custom technology SPAD devices in real acquisition systems, though, requires complex front end and processing electronics designed on purpose. In this work, I designed three integrated circuits that open the way to the development of a high performance TCSPC acquisition system. The approach I followed in this work is completely orthogonal to what other researchers currently pursue, both in terms of the technologies and of the architecture adopted. High-performance, fully-integrated readout and processing electronics has been developed using two different technologies, each of them optimally suited for a single part of the system, targeting the exploitation of dense arrays of high-performance custom technology SPAD detectors combined with the electronics in a 3-D stacked architecture.

Second Ph.D. presentation and discussion:

Mauro BUTTAFAVA – XXIX Cycle

“Time-gated single-photon counting instrumentation and applications”

Advisor: Prof. **Alberto Tosi**

Abstract:

In the last years, an increasing number of applications require the use of photodetectors able to acquire fast and weak light signals, down to the single-photon level. For this purpose, Single-Photon Avalanche Diodes (SPADs) can be successfully employed, achieving high detection efficiency with low noise and high timing resolution. Another advantage of a SPAD detector is the possibility of turning it ON and OFF very quickly and efficiently. This gating technique is useful to perform a time selection of incoming photons, for example in cases where a filtering based on light wavelength or polarization is not possible. Moreover, the gated-mode operation can also be used to reduce the effect of Dark Count Rate (DCR) and afterpulsing contributions, improving the signal-to-noise ratio of the measurement.

The PhD research activity aimed to develop new electronic instrumentation for time-gating SPAD detectors, starting from a single-pixel photon counting module with gating transitions shorter than 200 ps and repetition rates up to 100 MHz and moving towards more advanced systems. The developed instruments were exploited in different applications, like time-resolved diffuse optical spectroscopy, fluorescence life-time microscopy and ultrafast time-of-flight imaging. These exploitations were carried on in collaboration with world-leader research groups, looking for new application-specific improvements in order to achieve the best performance from time-gated SPAD instruments.

Third Ph.D. presentation and discussion:

Niccolo' CALANDRI – XXIX Cycle

"Advanced single-photon detectors in semiconductors and superconductors"

Advisor: Prof. **Alberto Tosi**

Abstract:

Nowadays many applications of various scientific fields (such as physics, biomedicine, electronics, etc.) need to detect very faint and fast light signals, down to the single-photon level. Different kinds of single-photon detectors have been developed in the past, but solid-state detectors have the advantage of high reliability and robustness, thus enabling the development of very compact and portable modulus, while superconductive cryogenic detectors show the best performances achieved for a single-photon detector but within bulky cryostats.

The present Ph.D. dissertation is focused on the design, development, characterization and modeling of novel near-infrared single-photon detectors and the associated readout architectures. An extensive characterization of different single-photon detectors is proposed, new structures are presented proving outstanding performance. New physical models are envisioned and validated, guaranteeing new interpretations for phenomena often unclear. Thank to successful international collaboration with other research groups, new detectors and read-out circuits are developed, enabling measurements previously considered unfeasible.

Fourth Ph.D. presentation and discussion:

Rudi LUSSANA – XXIX Cycle

"Time-of-flight CMOS single-photon cameras for high frame rate 2D imaging and 3D ranging"

Advisor: Prof. **Franco Zappa**

Abstract:

In the last decade, the ability to acquire high frame-rate (higher than standard video-rate) two- and three-dimensional videos of scenes with very faint illumination has become more and more important in many fields, such as ambient surveillance, road safety, identification of people and objects, gaming, biomedical imaging, and studies on materials physics. In particular, there is a growing interest in devices capable of acquiring high frame-rate 3D (i.e., distance-resolved) videos with measurement ranges up to some hundreds of meters, to be employed as sensors for completely autonomous vehicles.

My Ph.D. research aimed at developing high-end cameras able to acquire such videos, both in 2D and 3D modes, based on the "direct Time-of-Flight" (ToF) technique and to deploy them in real scientific applications. The cameras are based on SPAD (Single-Photon Avalanche Diode) detectors which, thanks to their extreme sensitivity, make it possible to achieve both relatively high frame-rates (higher than standard video rates) and long measurement ranges (up to 100 m). The single-photon sensitivity offered by SPAD detectors also makes it possible to count each incoming photon and also to measure each photon's ToF timing information, thus enabling the reconstruction of very faint and fast optical signals by means of the TCSPC (Time-Correlated Single-Photon Counting) technique, applied on each independent pixel. Such capability also allows to further exploit these SPAD cameras in different scientific fields, exploiting the utmost advantages of single-photon sensitivity, e.g. in all biological applications where low-power illumination is compulsory, in order not to damage the sample under study. Finally, these cameras have triggered important collaborations in quantum mechanics and quantum computing, thanks to the possibility to study the behavior of each individual detected photon in both 2D and time-domain with sub-nanosecond resolution.

Fifth Ph.D. presentation and discussion:

Mirko SANZARO – XXIX Cycle

"Near-Infrared Single-Photon Detectors in Emerging Technologies"

Advisor: Prof. **Alberto Tosi**

Abstract:

A growing number of applications rely on single-photon detectors with high detection efficiency in the near-infrared (NIR) range. In order to bring these applications out of the laboratories, single-photon detectors have to be compact, low power and rugged. Single-Photon Avalanche Diodes (SPADs), being solid-state devices, are the preferred solution for most applications. The aim of this doctoral work was to design novel NIR SPAD structures and to contribute to the advance of the state-of-the-art in the field.

In the past decade, owing to the increasing interest in quantum information applications, such as quantum computing and quantum cryptography, there has been considerable effort to improve InGaAs/InP SPADs. Even so, noise and afterpulsing are still strong limitations that impair their wide-spread exploitation. A primary objective of my Ph.D. research was the development of low noise InGaAs/InP SPAD detectors and the reduction of afterpulsing effects through a novel mixed-quenching approach based on a monolithically integrated resistor.

CMOS SPADs have recently become an emerging imaging technology for applications requiring both high sensitivity and high frame-rate in the visible and NIR range. However, a higher PDE, particularly in the NIR, is highly desirable for many growing markets, such as eye-safe time-of-flight laser ranging (LIDAR) and three dimensional imaging. The second research topic of this Ph.D. work was to design, in collaboration with STMicroelectronics, the first SPADs fabricated in a BCD technology and to use the BCD platform to develop device solutions with the purpose of overcoming the intrinsic photon detection efficiency limitations of typical CMOS SPADs.

PhD Committee:

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