Ph.D. in Information Technology
Thesis Defenses

February 9th, 2022
at 14:00
Room Conferenze "Emilio Gatti"

Klaus PASQUINELLI – XXXIV Cycle

Advanced instrumentation for time-resolved single- and multi-photon counting applications

Supervisor: Prof. **Franco Zappa**

Abstract:

Many high-end applications require very sensitive photodetectors and imagers able to measure very faint and very fast optical signals. Examples of such applications are distance ranging by measuring photons' time-of-flight (TOF), fluorescence lifetime imaging, and quantum communications. While some photon-starved applications require Single-Photon Avalanche Diode (SPAD) arrays thanks to their single-photon sensitivity, others must operate with either a few or even many photons per event, so Silicon Photomultipliers (SiPM) or alike should be preferred.

My PhD research aims at developing advanced electronic instrumentation based on multi-pixels photon detectors and imagers, able to measure the intensity of light events by counting the number of incoming photons, record the time-resolved optical waveform through the measurement of the photons' arrival time, and detect coincidences in the arrival time across the SPAD array sensors. To ensure optimal performance in ToF applications, both practical and theoretical studies about the photodetector choice will be provided. Starting from the results obtained in previous photodetector modeling, this research will study in depth the performance achievable with both avalanche photodiodes (APD), SPAD and SiPM, with a variable number of cells. Furthermore, a dedicated hardware with field programmable gate array (FPGA) to detect photon coincidences will be designed. This will pave the way to a new instrument based on "programmable" SiPMs, able to detect photon arrival coincidences with variable photon thresholds, to be adjusted based on the operating conditions.

An introduction of the background of LiDAR measurement systems will be presented, from the first historical mechanical example to the modern system based on electromagnetic waves and image sensor. After a brief overview on the various modern techniques, the photodetector used for LiDAR systems will be presented and then the state of the art will be discussed. The main part of the thesis will be about the modeling of photodetectors. After a description of the characterization of the detectors, a mathematical model will be presented for avalanche photodiode (APD), single-photon avalanche diode (SPAD), and for the silicon photomultiplier (SiPM). These models will lead to a performance comparison among the detectors through a nomograph. Given these results a prototype of single-pixel time of flight (TOF) 5 × 5 SPAD camera will be presented. Chip, system, and measurements will be discussed. From this prototype digital and analog methods to reject the

background light will be proposed and analyzed, so to increase the signal to noise ratio. Various algorithm and architectures will be proposed for single-shot and multi-shot applications. Eventually one of these methods will be used in a prototype chip for industrial applications. System and measurements will be shown.
Eventually, the last part presents the simulations and the modeling of a new type of hybrid digital and analog SiPM with on-chip background rejection circuitry. In the first phase, performances, with the given parameters will be shown and then, improvements will be added so to adapt parameters to the target specifications to reach better performances. Eventually, system prototype and achievements will be shown and compared to the predicted one.

Fabio SEVERINI – XXXIV Cycle

Single Photon Avalanche Diode Arrays for Quantum Applications

Supervisor: Prof. **Federica Villa**

Abstract:

Quantum imaging exploits quantum correlations to image objects at low light (single-photon) regime, with unprecedented vertical dimension sensitivities (a few atomic layers) and very large field-of-view (tens of mm2), surpassing the limits imposed by the laws of classical optics.
Single Photon Avalanche Diodes (SPADs) are the forefront detectors for this application, thanks to their single-photon sensitivity, good detection efficiency, relatively low voltage operation, sharp timing resolution, room temperature operation, and compatibility with standard CMOS microelectronic processes. Thus, high performing sensors are obtained by the monolithic integration of high detection efficiency and low noise SPADs along with their sensing circuits, and suitably designed processing digital electronics.
The main goal of this presentation is to illustrate the design, characterization and testing of a pioneering SPAD imager targeting quantum imaging applications. Indeed, the design of this SPAD imager was achieved within the framework of the European Horizon 2020 FET project “Q-MIC”, whose final target was the development of a microscope with unprecedented phase resolution capabilities, by exploiting quantum sources and single-photon detectors. The detector, manufactured in a 0.16 µm BCD (Bipolar – CMOS – DMOS) technology, has been conceived targeting all the features of the ideal quantum imager, i.e., photon coincidence detection capability, high-pixel count, event-driven readout, and spatial resolution.
This presentation will also include the design of a multi-channel SPAD chip to be integrated along with silicon photonics, as part of the Horizon 2020 FET project “UNIQORN”, and the testing of SPAD pixels with extremely short dead times, enabling giga count per second applications.

Fabio SIGNORELLI – XXXIV Cycle

Single-Photon Avalanche Diodes in InGaAs/InP and micro-crystal heterostructures

Supervisor: Prof. **Alberto Tosi**

Abstract:

In the last years, with the so-called "second quantum revolution", single photon detection in the short-wavelength infrared (SWIR) range is receiving more and more interest for applications such as quantum key distribution, quantum computing, and eye-safe three-dimensional imaging with light detection and ranging (LIDAR) or non-line-of-sight (NLOS) techniques. The aim of this Ph.D. work was to develop new single-photon avalanche diodes (SPADs) for SWIR single-photon detection with improved performance, by following two approaches: i) a groundbreaking novel heteroepitaxy, exploited for developing Si-on-Si or Ge-on-Si microSPAD structures; ii) a more established, yet under development, InGaAs/InP technology.

The first microSiPM prototypes were designed as proofs of concept of micro-crystals working as SPADs. Electrical and optical TCAD simulations shows that a very high PDE (>75% at 600 nm) can be achieved. The experimental characterization of single micro-crystals shows a clear SPAD behavior, and an additional implanted top contact helps reducing the dark count rate that, however, is still high even at very low temperatures. Moreover, photoresponsivity of the micro-crystals is good (up to 0.1 A/W), despite the top contact is not transparent. According to TCAD simulations, Ge-on-Si micro-crystals can achieve a PDE higher than 50% with few µm-thick Ge layer. A first experimental characterization of planar Ge-on-Si SPADs, aimed at assessing the quality of the germanium epitaxy, shows results comparable with state-of-the-art devices.

The developed InGaAs/InP SPADs demonstrated to successfully compare to the best ones ever reported in the literature. The zinc diffusion and the charge layer thickness have been optimized to lower the noise of the detector. A different structure with a thicker absorption layer, aimed at enhancing the PDE, has also been designed. The developed SPADs achieve low dark count rate of 1 kcps and 4 kcps at 225 K and 5 V excess bias for 10 µm and 25 µm diameter devices, respectively. Both devices also show a high photon detection efficiency, being 33% at 1064 nm and 25% at 1550 nm. The efficiency-enhanced detector achieves a PDE up to 50% at 1550 nm, with a dark count rate of 20 kcps and a timing jitter of ~ 70 ps (FWHM) at 225 K. Timing jitter is comparable to previous-generation devices. Ultimately, when combined with a custom integrated circuit, afterpulsing probability is as low as few percent with a gating frequency of 1 MHz and hold-off time of few microseconds at 225 K, allowing to achieve a count rate of almost 1 Mcps.

PhD Committee

Prof. **Angelo Gulinatti**, Politecnico di Milano

Prof. **Gian Franco Dalla Betta**, Universita' di Trento

Prof. **Ivo Degiovanni**, INRIM - Istituto Nazionale di Ricerca Metrologica