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Thesis title: **Fast-Gated Single-Photon Avalanche Diodes and Applications**

Advisor: **Franco Zappa**

Research area: **Sensors and instrumentation**

Thesis abstract:

The unceasing request of devices able to detect fast-changing ultra-faint light pulses has leaded to the development of detection systems based on both silicon and InGaAs/InP Single-Photon Avalanche Diodes (SPADs).
Some important applications require to avoid the detection of photons which arrive outside of a well-defined time slot. In that case, a time-gated detector is needed, enabled and disabled at a given delay with respect to the optical signal. Most of the single-photon detectors do not allow an efficient gated-mode operation. But, the possibility to gate-on and gate-off SPAD detectors in a fast and efficient way has opened the way to new applications. Unfortunately, some electronic issues arise from the fast-gated operation and the development of new detectors front-end electronics is required. During the Ph.D. research, the sensitivity, the time-resolution and the applicability of fast gated-mode techniques based on SPADs have been developed.
A first result is the development of new front-end circuits for gated-mode operation able to overcome limitations of traditional configurations. The circuitry is developed for fast (nanosecond switching time) and ultra-fast (hundreds of picoseconds or less) gated-mode operation of SPAD detectors and has been applied in different fields, obtaining scientific results in different applications.
In the field of time-resolved Near-InfraRed Spectroscopy (NIRS), the feasibility of the novel approach to photon migration based on time-resolved reflectance measurements performed at small or null source-detector distance has been demonstrated for the first time. Indeed, notwithstanding possible advantages in terms of contrast, spatial resolution and probing depth, this approach has resulted unfeasible for years from its theoretical formulation. The reason is that the strong presence of early-photons coming from the outer layers of the probing tissue, which forces one to reduce the optical power injected in order to avoid the saturation of the detection electronics. Thanks to ultra-fast gated operation of silicon SPADs, it has been possible to obtain a strong rejection of early-arriving photons, thus allowing the increase of the injected optical power.
Previous results have been attained also thanks to a close collaboration with the Dipartimento di Fisica of Politecnico di Milano, in the context of the "nEUROPt" European project for the non-invasive imaging of brain function and disease by pulsed near-infrared light. Moreover, it has been possible to perform the first in vivo measurement of brain activity by means of time-resolved reflectance detection at the small source-detector separation of 2 mm.

By means of the developed electronics, it has been also possible to demonstrate the usability of gated silicon SPADs in some applications at 1550-nm wavelength.
A wide range of applications needs to detect photons in the NIR range between 1.0 and 1.7 μm. Germanium SPADs and InGaAs/InP SPADs are among the candidates to fulfil such requirements. In particular, InGaAs/InP SPADs are the more promising, even if they are still in development and, therefore, accurate experimental characterizations are mandatory in order to understand the detector issues and to push forward the device design.
In the field of InGaAs/InP detectors, a detailed characterization of recently developed devices has pointed out the main detector issues. It has been possible to propose some device improvements, especially in order to reduce the detector noise (such as the afterpulsing phenomenon arising from a delayed release of carriers trapped during an avalanche ignition). A deep characterization of germanium detector has been also performed. Thanks to the new approach to gated-mode operation, it has also been possible to increase the photon timing resolution attainable from InGaAs/InP detector up to few tens of picoseconds.