PhD in Electrical, Electronics and Communication Engineering

Research Title: Development of Advanced Silicon Sensors for Big Science and Industrial applications

Development of Silicon Photomultipliers at FBK

Funded by	Fondazione Bruno Kessler, Trento, Italy

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Context of the research activity	Silicon Photomultipliers (SiPMs) are silicon photodetectors with internal signal amplification obtained by means of the impact ionization mechanism, operating in the so-called Geiger mode and achieving a gain in the order of a few millions per a single, photo-generated carrier. They are extremely fast and sensitive detector, having demonstrated the capability of detecting light down to the single photon level and with a Single Photon Time Resolution (SPTR) of 20 ps FWHM. Thanks to these exceptional characteristics, SiPMs are currently of great interest in several scientific and industrial applications. They are being considered for the detection of faint light signals in the large majority of big scientific experiments of the next generation, ranging from the HL-LHC upgrade to future Dark Matter and Neutrino experiments. For these experiments, SiPM technology needs to be developed further, to obtain, among other features, enhanced radiation hardness, effective operation at cryogenic temperatures and sensitivity to extremely low-wavelength photons down to 128 nm, for direct detection of LAr scintillation light. By overcoming such difficult challenges, SiPMs, will constitute an *enabling technology* for scientific research over the next decade. On the other hand, SiPMs have even more important industrial applications, with great potential to improve health and several aspects of people's lives. The most traditional industrial application is the use of SiPMs to build next-generation, Time-of-Flight Positron Emission Tomography machines (ToF-PET), which are used in neurology, cardiology, oncology, drug development, and in a number of other medical imaging use cases. Thanks to their excellent time resolution and

	sensitivity, SiPMs are currently the only technology of choice for the development of new ToF-PET machine designs. While the first ToF-enabled machines, with a time resolution of around 200 ps, have already hit the market, becoming the industry standard for performance and image quality, R&D activity is far from being finished. With the ultimate goal of winning the "10 ps challenge" (https://the10ps-challenge.org), next-generation SiPMs for ToF-PET will enable further, dramatic improvements in the field, providing non-incremental upgrades in future PET machines. An example of which improvements can be expected from the next-generation PET can be found in the experimental EXPLORER project (https://explorer.ucdavis.edu/). A second, extremely interesting SiPM application is LIDAR for automotive. Indeed, SiPMs are considered one of the most promising technology solutions to enable LIDAR sensors that will provide 3D vision to next-generation, autonomous driving systems (level 4 and above). As this is a field of huge industrial interest, for obvious reasons, all major players and OEMs are extremely active in research and development activities, including R&D on the sensors. As regards SiPMs, several technical challenges need to be solved, including the increase of sensitivity at 905 nm (the laser emission wavelength), for which absorption length in silicon is very large, the improvement of time resolution and time response of the detector in general and the reduction of its noise in the industrial temperature range. Such improvements are necessary to cope with the formidable challenge of detecting efficiently the laser echo from objects as far as 200 meters from the vehicle.

Objectives	In the context of SiPM developments, Fondazione Bruno Kessler (FBK, Trento) has been at the forefront of developments for more than ten years and is currently carrying out frontier R&D activities in all the fields mentioned in the previous section. FBK is currently collaborating with CERN and several other research institutions for the development of rad-hard SiPMs, which are required to withstand radiation doses in excess of 1e14 neq/cm^2. Considering cryogenic operation of SiPMs, R&D carried out by FBK for experiments such as DarkSide-20k (http://darkside.lngs.infn.it/), nEXO (https://nexo.llnl.gov/) and DUNE (https://www.dunescience.org/) has already achieved outstanding results, such as almost noiseless detector operation at 87 K (LAr temperature). On the other hand, research is still ongoing to improve detector characteristics cold temperatures, such as reducing afterpulsing, output capacitance and increasing photon detection efficiency (PDE). As regards PET, research is constantly needed to keep the performance of FBK SiPM competitive with or better than the competition, which is composed of big multinational companies. In particular, current important research goals are: (i) further increasing the PDE at 420 nm, corresponding to the peak light emission wavelength of the LYSO crystal used in PET (FBK SiPM PDE already has a record value of 60%). (ii) reducing correlated noise, which distorts the time of arrival statistics of the detected photons and limits the maximum bias that can be applied to the detector, ultimately, worsening timing performance. (iii) keeping the excellent SPTR of 20 ps FWHM already demonstrated. (iv) improving detector characteristics as regards its matching to the readout electronics, including reduction of output capacitance and choice of the best segmentation of the active area. Over the last few years, it has become evident that this last point is going to play a major role in performance improvement for PET over the next few years

	(https://doi.org/10.1088/1361-6560/aafd52). Finally, considering LIDAR applications, single-photon detectors with high sensitivity are strongly needed because, for eye-safety concerns, the peak emission power of the pulsed, laser source is severely reduced and the amount of photons in the laser echo, reaching the detector, is extremely limited. The main challenge in SiPM development is enhancing PDE at long wavelengths, for example at 905 nm, which is one of the typical laser emission wavelengths chosen by OEMs. Increasing PDE in this region of the spectrum is difficult, because SiPMs are built on an epitaxial layer, which is normally a few micrometers thick, while the light absorption length in silicon at 905 nm is around 30 um. It is thus necessary to increase the thickness of the active layer of the detector by a large amount, which, in turns, requires a considerable amount of redesign of the device structure. Backside-illuminated devices, which have become the industry standard in CMOS image sensors, are also being considered for the same purpose. A second, important improvement of the SiPMs for this application is the reduction of the delayed correlated noise, which can worsen performance in all applications, including LIDAR, in which a faint light signal needs to be detected after a very strong excitation pulse. All the characteristics and improvements mentioned above strongly depend on the design of the electric field inside the microcells (diodes), which are operated in reverse bias, above the breakdown voltage, and are connected in parallel to obtain the SiPM. Continuous research activity carried out at FBK over the years has been related to experimenting different positions, layouts, dimensions critical distances, number, depths, doses, fabrication processes of the dopant layers forming the junction and the virtual guards rings around it. The goal of these many changes and optimizations is to modify the SiPM characteristics, to improve them in general and to find the best trade-offs for any given, specific application. Such research activity will always be needed and will be an integral part of the studies carried out by the PhD Candidate. On the other hand, it has become clear over the years that a tight integration between sensor (SiPM) and readout electronics will be fundamental to keep the exciting pace of improvement demonstrated in the SiPM field over the last ten years. To this end, it will be necessary to design the SiPM taking into account the front-end, and vice versa, ultimately co-designing them. In addition, 3D integration techniques will be employed to stack and directly connect two different wafers, one containing the SiPMs and the other the CMOS front-end, allowing independent optimization of these two tiers and unprecedented integration between them. In this context, FBK is well positioned to play an important role, thanks to the recently-funded IPCEI project (https://ipcei-me.eu/), which will allow FBK to upgrade its clean-room, adding state-of-the-art 3D integration and BSI capabilities. Considering the importance of integration between sensor and front-end, the partnership between FBK, which develops SiPMs, and Politecnico di Torino and INFN, sezione di Torino, which are expert in CMOS ASIC design, is strategic. The PhD candidate will play an important role in this context, studying the interaction between sensor and readout electronics and developing next-generation sensors optimized for the integration with the front-end. More in detail, The PhD candidate will work in the IRIS research unit of FBK (https://iris.fbk.eu/), which is composed of approximately 20 people, mostly researchers and PhD students, working on SiPM, SPAD and CMOS image sensors development. Within IRIS, his/her research activity

	will be focused on the study and development of SiPMs built in custom technology in FBK clean-room, with special attention dedicated to the interaction between sensor and front end and to advanced 3D integrated and BSI SiPM structures. The PhD candidate will be inserted in a team of researchers developing word-class sensor technologies, with the purpose of becoming proficient in the field of instrumentation and, in particular, of silicon sensors and readout techniques. He/She will learn how to characterize and optimize the components of a photon or radiation detection system, taking into account the requirements of different scientific and industrial applications. The PhD candidate will dedicate his/her research to one or a few projects, selected together with his/her supervisor among the ones carried out by FBK and characterized by uniform technical challenges. At the beginning of the three-year studies, he/she will be focused on understanding the SiPM working principle and its main characteristics and on becoming expert in some of the different, advanced characterization setups and techniques employed at FBK. They include: semiconductor analyzers, high-speed digitizing oscilloscopes, ultra-fast laser sources, thermostatic chambers, a cryostat, instrument programming in Labview, digital data processing, data analysis, development of custom, front-end electronics, scintillating materials and radioactive gamma-ray sources. An important part of his/her activities will be constituted by the advanced characterization of different SiPM process and layout splits, which are usually included in R&D runs fabricated at FBK. Such activity will be aimed at understanding the features of the device, studying the different phenomena involved, evaluating the effectiveness of the technical solution implemented and proposing further developments of the sensor. After acquiring sufficient experience, towards the end of the PhD studies, it will be also possible for him/her to contribute to the design of new SiPM sensors. At the end of the PhD studies, the PhD candidate is expected to become proficient in the field of sensors, instrumentation and characterization setups. He/She will be able to start a career either in the scientific field, for example joining a large scientific collaboration, in which his/her competences are usually highly valued, or in the industrial sector, as an expert in detection systems.

Skills and competencies for the development of the activity	The ideal candidate will hold a Master Degree in Electronic Engineering, Physics, or neighboring fields. Attendance to courses on electronics, semiconductor devices, solid state physics and experience during the master degree thesis on electronics design, sensor characterization, TCAD simulations are preferred but not necessary. Indeed, all the relevant competences will be taught to the PhD candidate over the course of his/her studies. In addition, strong team work attitude, passion for research activities, precision and organization in carrying out experimental tasks and high motivation to develop next-generation light sensors for both science and industrial applications are required.