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Development and characterization of Silicon Photomultipliers for cryogenic applications

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Abstract

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Development and characterization of Silicon Photomultipliers for cryogenic applications

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The addition of dark matter (DM) in the Universe can explain different cosmological and astrophysical phenomena, such as the motion of stars within galaxies, the dynamics of galaxy clusters, and the inhomogeneity on large scales of the Cosmic Microwave Background (CMB) radiation.

Currently, there is wide agreement in the scientific community that DM constitutes $\sim 85\%$ of matter in the Universe. Given its elusive nature DM must be non-baryonic and could be made of particles, that do not interact with the electromagnetic or strong forces. Weakly interacting massive particles (WIMPs) are well motivated candidates to explain the DM. The Standard Model (SM) does not include WIMPs, for which there is still no experimental evidence. However, some supersymmetric theories beyond the SM predict WIMP-like particles. Thus their discovery could open a new discovery frontier, in physics.

Experiments searching for WIMPs can be broadly divided in three categories:

- one can search for the production of new particles, in high-energy collisions, e.g. at the ATLAS and CMS experiments at the LHC (WIMP production).
- WIMPs could annihilate into ordinary particles (neutrinos, gamma-rays, electron-positron pairs, etc.). If this happens, these products coming from dense celestial objects can be detected by experiments such as the PAMELA, the Fermi Large Area Telescope, and AMS on the ISS (indirect detection).

- Finally, one can detect WIMPs by their interactions in the shielded underground detectors (direct detection). These have as common goal to achieve low-enough energy threshold to detect the recoils of nuclei scattered by WIMPs and sufficient radioactive background suppression to allow these extremely rare events to be observed. Direct detection experiments include a wide variety of technologies, such as cryogenic crystals (SuperCDMS, EDELWEISS), sodium/cesium iodide scintillator detectors (DAMA/LIBRA, COSINE-100), bubble chambers (PICASSO, COUPP), point contact germanium detectors (CoGeNT) and detectors using liquid xenon (XENON-100, PandaX, LUX) or argon (MiniCLEAN, DarkSide-50).

The DarkSide-20k (DS-20k) experiment is under development as the scaled-up successor of the currently operating DarkSide-50 experiment. DS-20k is a dual phase liquid argon (LAr) time projection chamber (TPC) with a total underground argon (UAr) mass of 50 tons. DS-20k detects two different signals: primary scintillation light produced by recoiling nuclei of argon (S1), and second scintillation light (S2) generated via ionizing radiation, such as electroluminescence by ionization drifted away from the primary interaction site and extracted into the high field gaseous argon. The isotropic scintillation 128 nm light is down-converted to 420 nm by a thin film of tetra-phenylbutadiene (TPB) that coats the inner surfaces of the TPC. The light shift is necessary to fit the responsivity of detectors used as photo-sensor of the TPC. The double S1-S2 signal enables 3D reconstruction of events and allows for a very efficient rejection of the background by pulse-shape discrimination (PSD). DS-20k will be run at the underground Laboratori Nazionali del Gran Sasso (LNGS, Italy) heavily shielded from cosmic rays background. The TPC will be inside an acrylic vessel immersed in a large LAr cryostat to reject and further reduce the background due to cosmic rays, material and environmental radioactivity. Furthermore, ultrapure argon (UAr) and low-radioactivity materials will be used for a background free design. Unlike the prior DS-50, DS-20k will not use photomultiplier tubes (PMTs) but will rely on silicon photomultipliers (SiPMs) which are emerging as major players in the next generation of noble liquid detectors for neutrino (DUNE, nEXO). This choice is motivated by several advantages over traditional PMTs: higher photon detection efficiency (PDE), better single photon resolution, and low bias operating voltage ($< 80\text{ V}$). The compactness of SiPMs facilitates their integration with the readout electronics. SiPMs can be arranged in high fill factor (FF) tiles for scalability of the active area (20.7 m^2 are required for DS-20k). Another important feature is their excellent radio-purity, much better than the best PMTs.

The main performance parameters of single SiPMs required by the experiment are:

- good functionality at liquid argon temperature (87 K)
- Photon detection efficiency (PDE) $\geq 45\%$ for 420 nm light

- individual device size greater than $5 \times 5 \text{ mm}^2$ to allow for practical integration into the arrays
- Dark count rate (DCR) $\leq 80 \text{ mHz/mm}^2$
- total correlated noise probability (TCNP), the combination of cross talk (CT) and after-pulsing (AP) probability, $\leq 60 \%$ at the operating voltage
- effective output capacity $\leq 50 \text{ pF/mm}^2$ to preserve adequate signal to noise ratio (SNR).

The Integrated Radiation and Image Sensors (IRIS) group of the Fondazione Bruno Kessler (FBK), member of the DS-20k collaboration, has developed three main SiPM technologies with high density (HD) single photon avalanche diodes (SPADs) and with maximum peak detection efficiency in the near ultraviolet (NUV). These are: NUV HD standard field (SF), NUV HD low field (LF) and NUV HD-Cryo. In this context, the aim of the mark described in this thesis is, on one hand, optimize and characterize SiPMs for the DS-20k experiment and, more generally, to develop experimental setups, analysis software, procedures and knowledge necessary to study SiPMs in a wide range of temperatures down to lower LAr temperature.

The main results from the last few years are discussed below, starting with the first two SiPM versions produced, NUV HD SF and NUV HD LF. In these, polysilicon quenching resistors (QR) with high temperature dependence were used to keep the AP rate under control. These QRs increase their resistance 65-fold from $1.8 \text{ M}\Omega$ up to $120 \text{ M}\Omega$, going from 290 K to 80 K . This solution was necessary because below 150 K the AP probability rapidly diverges with increasing voltage. Above this temperature the AP is practically negligible for both technologies. This phenomenon may be attributed to long average emission times of charge carriers, captured by trapping centers at low temperatures. A large QR allows to obtain an AP probability of 25% with a $25 \mu\text{m}$ cell size at 80 K and 5 V overvoltage (OV). This is at a cost of a microcell recharge time constant (RTC) of $3.5 \mu\text{s}$ instead of 80 ns at room temperature. The NUV HD LF has a lower peak value of the electric field in the high field region at breakdown voltage (V_{BD}) compared to the NUV HD SF thanks to a deeper high-energy n-type implant. The LF design displays an increase in the V_{BD} value (32.5 V instead of 26.5 V at 290 K), and a different temperature dependence (30 mV/K instead of 26 mV/K for $T > 100 \text{ K}$). The V_{BD} thus decreases with decreasing temperature (from 32.9 V down to 27.2 V going from 290 K to 80 K) because mean free path between scatterings of carriers in the high-field region grows. The main effect of LF technology is on the DCR. At room temperature, there is no significant difference of the DCR (100 kHz/mm^2) between SF and LF, while at temperatures lower than 150 K we observe a lower DCR with LF technology, with the difference below 100 K being 100-fold compared to SF technology at same conditions. The NUV HD LF DCR drops 7 order of magnitude between 290 K and 80 K , few mHz/mm^2 at 80 K . At high

temperatures, the DCR is dominated by field-enhanced thermal generation, where it is evident in DCR/temperature plots that the DCR has exponential dependence with increasing temperature. Below a certain temperature, band-to-band tunneling dominates. In this regime it depends on the silicon band gap and, weakly, on temperature, as shown by the plateau in DCR/temperature plots. Another benefit of the LF compared to the SF is the reduction of the AP probability by a factor ~ 2 at cryogenic temperatures.

The PDE as a function of incident wavelength shows a peak between 400 nm and 420 nm for both NUV HD LF and NUV HD SF technologies. They, however, differ in absolute value. The PDE is about 50 % for SF and 45 % for a LF with 35 μm cell size, 3 V OV, 410 nm incident wavelength at room temperature. The PDE is lower in NUV HD LF due to the lower electric field in the high-field region.

Another important parameter is the maximum operational overvoltage (OV_{MAX}) beyond which the correlated noise diverges because of AP, making the SiPM inoperable. OV_{MAX} can be measured with a current/voltage plot (IV). At room temperature the OV_{MAX} is ~ 20 V for both LF and SF technologies but at cryogenic temperature the OV_{MAX} drops to a few volts (it is worse for SF), reducing performance in working conditions. In addition, the high quenching resistor at cryogenic temperatures for a given electronic readout gives a long single cell response, reducing the peak amplitude and worsening the amplitude and charge SNR. These limitations are solved with the NUV HD-Cryo, which on the NUV HD LF in two ways: low Afterpulsing (LowAP) and low resistor/temperature variation technologies. Different NUV HD LF versions are produced: with standard and LowAP processes and different QR values. The results are very interesting: at cryogenic temperature, the LowAP process suppresses the AP probability by a factor 10 at same conditions compared to standard process. In addition, the LowAP process extends the OV_{MAX} beyond 20 V at 80 K. The suppression of the AP allows to use a smaller value of the quenching resistor at cryogenic temperature, which in turn yields a smaller variation of resistance with temperature, reduced by a factor of ~ 4 . The quenching resistor now varies from 1.6 M Ω to 6.5 M Ω between 290 K and 80 K; as a result, the microcell recharge time constant grows from 65 ns to 270 ns with a cell size of 30 μm and a 12 % AP probability at 5 V OV. The next step is to study how the PDE varies as a function of temperature between 300 nm and 700 nm.

In conclusion, the R&D program reported in this thesis has delivered the NUV HD-Cryo technology to the DS-20k experiment that represents the best cryogenic SiPM performance and fully satisfies the experiment requirements. These developments are relevant also to nEXO experiment and have attracted the attention of other large experiments, such as DUNE, which require large active areas of SiPMs operated in cryogenic noble liquids.

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Introduction

In this chapter, we will introduce the problem of Dark Matter (DM), which is one of the big unanswered questions of modern physics, and the main strategies to research it. Then we will focus on the DarkSide-20k experiment, an international project led by INFN for direct of dark matter search. In the end, we will describe the time projection chamber that is the core of the experiment. In particular, we will show the main features of the photoelectronic part of the experiment since the DarkSide collaboration wants to use for the first time a large SiPM area photodetector at liquid argon temperature.

0.1 Dark Matter

The Swiss astronomer Fritz Zwicky had been the first to propose the existence of large amount of non-luminous matter or dark matter. Between the 1970s and the 1980s, radial speed curves $v(r)$ of stars in various spiral galaxies were systematically observed which didn't follow the expected relation described by Kepler's law: $v(r) = \sqrt{GM(r)/r}$ [1] [2], where G =universal gravitational constant, r =galaxy radius and $M(r)$ =radial galaxy mass. The conclusion of these observations is that a dark matter halo must exist in order to explain the large difference from the predictions. Fig. 1 shows an example of radial speed curves of a disc galaxy.

One of the main evidences of dark matter existence is the gravitational lensing effect. It is similar to classical optical lensing and it is among the best probes to measure the mass and distribution of dark matter in specific regions of Universe. This happens because the light travels in a straight line but if gravity can bend space-time (Einstein's general relativity [4]) light curves with it. Therefore, gravitational lensing can be used to calculate the mass of the "lens" be it composed of luminous or dark matter [5] [6].

At the moment the most precise estimate of total DM amount in the Universe is given by Plank telescope measurement of Cosmic Microwave Background (CMB). From this measurement it is calculated the density parameter Ω . It is a parameter of the model currently accepted to describe universe dynamic given by Friedmann-Robertson-Walker metric that is a solution of Einstein's general relativity equation. $\Omega = \rho/\rho_C$, where ρ is the observed universe matter-energy density, while ρ_C is the critical universe matter-energy density that is defined by the relation [9]:

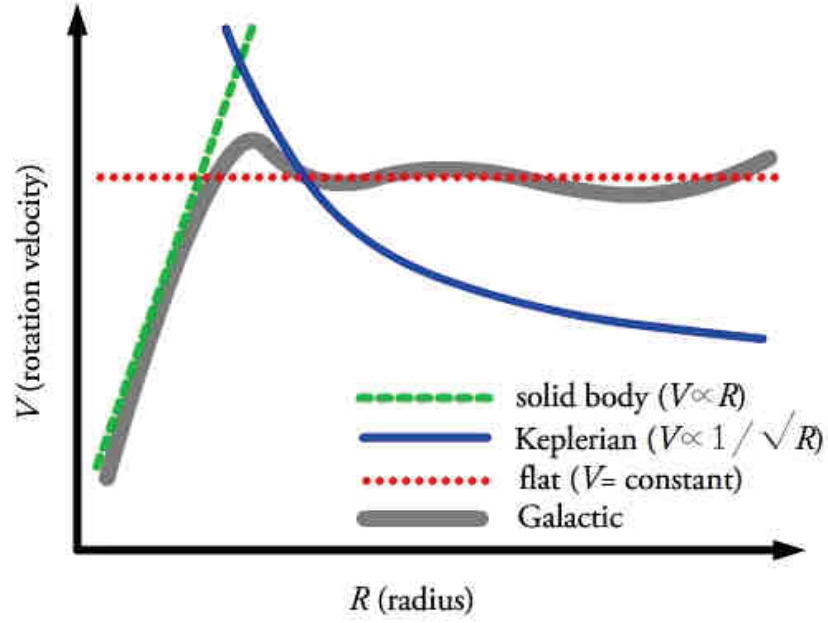


FIGURE 1: Keplerian prevision of radial speed (blue curve) compared to an experimental measurement (gray curve). Original figure taken from [3]



FIGURE 2: On the left, gravitational lensing mechanism. On the right, a composed picture of Einstein ring that is called "SDSS J103842.5948917.7" or "Cheshire Cat", composition of *Hubble* and *Chandra* telescopes. Original figures taken on [7] and on [8] respectively

$$\rho_C = \frac{3H_0^2}{8\pi G} \sim 8 \cdot 10^{-26} g/m^3 \quad (1)$$

where H_0 is the Hubble cosmological constant and G is the universal gravitational constant.

Planck measurement indicates that $\Omega = 1$. It means that the metric Universe is flat and it follows the Euclidean geometry. Moreover, it gives the estimate of the

matter-energy density components $\Omega = \Omega_B + \Omega_{DM} + \Omega_\Lambda$, where:

- $\Omega_B = 4.9\%$ [10] is the term due to all baryonic matter. It is composed by subatomic particles which contain an odd number of quarks (at least three quarks, as in the case of neutrons and protons) so they belong to the hadron family which consists of quark-based particles [11]. It can be split in baryonic luminous matter (stars) and in baryonic dark matter. The latter is a very small fraction of the dark matter [12] composed by: black holes, neutron stars, white dwarfs, very faint stars, planets and brown dwarfs.
- $\Omega_{DM} = 26.8\%$ [10] is the non-baryonic dark matter density component of the Universe. The DM does not seem to interact via strong and electromagnetic forces, while it interacts through gravity and it is thought that it should also act via weak interaction.

The DM can be split in hot dark matter (HDM) and cold dark matter (CDM). The HDM is composed by light mass particles that move relativistic speeds: the best candidates are currently neutrino particles ν . HDM can not be held by galaxies because they are too fast and moreover their contribution to the mass density is very small. In fact the current fossil density of neutrinos in the universe is expected to be $\sim 300\nu/m^3$ and if the neutrino mass will be $m_\nu \sim 0.1\text{ eV}$ the neutrino density is $\Omega_\nu \sim 0.002$ [13].

The CDM gives the main contribution in mass to the universe density ($\sim 84.5\%$ of the total matter) and it is also the least understood.

- Dark energy $\Omega_\Lambda = 68.3\%$ gives the most important contribution to matter-energy density of Universe [10]. DE is also more mysterious than dark matter: it is homogeneous through the universe and with low density. DE should explain the accelerated expansion of Universe and the balancing of universe density $\Omega = 1$ making Universe flat [9].

Alternative theories exist which do not include dark matter to explain observations. They involve modifications to Einstein's theory of gravity but they do not satisfy the observed phenomena at all scales.

Between various hypothetical explanations of dark matter, one of the favorite is that dark matter is made of weakly interacting massive particles (WIMPs). These massive particles are big enough to not have relativistic motion during the decoupling in the initial expansion of Universe. Nevertheless, the Standard Model does not contemplate these types of particles. Moreover, they have never been observed in any particle accelerator experiment [14] [15].

Several supersymmetric models beyond the Standard Model admit the WIMPs existence: an observation of the WIMPs will open new physics beyond the Standard Model [16] [17].

Three main families of experiments are studied for DM search.

- The first method is indirect: it searches for traces of DM annihilation products that are suggested by some theoretical models. According to these models DM particles can interact with one another, transforming their residual mass into detectable or ordinary particles. Between these there are antiprotons, positrons, neutrinos and γ rays that are searched by observing different astrophysical objects that are thought to harbor gravitationally confined populations of dark matter particles. For example, DM annihilation is suggested as a possible cause to explain PAMELA satellite data that show a positron excess in the cosmic rays [18]. Again, the DM annihilation could explain the γ emission in the Galactic center that are not fully in agreement with the background models. These measurements are made by Fermi Large Telescope that is sensitive at gamma-rays from 20 MeV to 300 GeV [19]. The PINGU project is the extension of ICECUBE and it would detect low-mass DM annihilations (down to 5 GeV/c^2) in the Sun and in the Galactic center [20].
- The second type is the searched through particle accelerators, where the accessible range of DM particle masses depends on the total energy in the center mass. At the LHC (Large Hadron Collider) with its 13 TeV , ATLAS and CMS experiments have among their main aims the research of dark matter WIMPs in proton-proton collisions. During Run II, the sensitivity to research the WIMP masses decreased to around a few GeV/c^2 [21] [22]. With the next improvement High-Luminosity LHC it is expected a 10 time bigger data collection [23]. Moreover, it is expected that sensitivity will remain competitive with direct DM experiments for low WIMP masses ($< 10GeV/c^2$) and the results will put strong constraints for different kinds of dark matter interactions for high WIMP masses [24].
- A wide variety of direct DM searches exists, using different technologies: cryogenic bolometers with ionization or scintillation detection (SuperCDMS [25], CRESST [26]), sodium/cesium iodide scintillation detectors (DALMA/LIBRA [27], KIMS [28]), bubble chambers (PICASSO [29], PICO [30]), point contact germanium detectors (CoGeNT [31], MALBEK [32]), detectors using liquid xenon (XENON-100 [33], LUX [34], PandaX-II [35], XENON1T [36]), detectors using liquid argon (WArP [37], DarkSide-50 [38]).

All these experiments have the two same objectives: the first one is to obtain a low enough energy threshold to detect the collision between WIMPs and target nuclei, the second is to obtain a low enough background to identify these extremely rare collision events. In Fig. 3 are shown the main results (update to 2016) of direct detectors.

The direct search of WIMPs is well justified in particular for the high masses region (of the order of few hundred GeV/c^2), that will be out of the LHC reach,

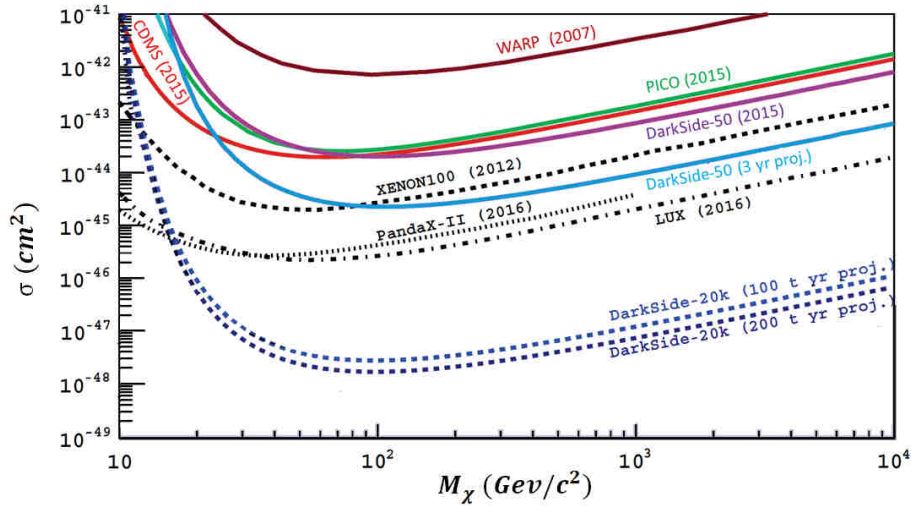


FIGURE 3: The mean exclusion sensitivities of different experiments updated until 2016 from references cited elsewhere in this section. They are compared with the full exposure of DarkSide-50 and of DarkSide-20k. Original figure taken from [24]. Actually the best result is achieved by XENON1T (2018) in [36] with a minimum of $4.1 \cdot 10^{-47} \text{ cm}^2$ at $4.1 \cdot 30 \text{ GeV}/c^2$ and a 90 % confidence level.

and for low cross-section region (between 10^{-45} cm^2 and 10^{-47} cm^2). The direct and indirect researches of WIMPs are complementary and it is important to improve their sensitivity of a few orders of magnitude. Moving in this direction, the new direct detectors are developed to operate in a background-free mode.

In 2015 DarkSide Collaboration submitted a long term program of DM searches at Gran Sasso National Laboratory (LNGS) that comprises the DarkSide-20k project [24].

0.2 The DarkSide-20k experiment

This section mainly refers from [24].

DarkSide-20k experiment is the natural successor of DarkSide-50 in terms of cross-section sensitivity and mass region researched as it is shown in the Fig. 3. With a total exposure to $200 \text{ t} \cdot \text{yr}$ to be accumulated in a run of $5+5 \text{ yr}$, it would improve WIMPs mass range directly detected between few tens GeV/c^2 up to $1 \text{ TeV}/c^2$ ($10 \text{ TeV}/c^2$) with a cross section sensitivity between $7.4 \cdot 10^{-48} \text{ cm}^2$ and $1.2 \cdot 10^{-47} \text{ cm}^2$ ($1.1 \cdot 10^{-46} \text{ cm}^2$) respectively.

DarkSide collaboration wants to achieve these objectives with a liquid argon Time Projection Chamber (LAr TPC) with a total Underground argon (UAr) mass of 50 t .

Usually, noble liquid TPCs detect both the scintillation light (signal S1 generated by recoiling nuclei) and the ionization electrons (signal S2). These give some

advantages for direct DM searches. In particular for liquid argon (LAr), the time development of primary signal of scintillation S1 is an efficient indicator for the rejection of the background, this is called pulse-shape discriminator (PSD), see Fig. 4. Moreover the TPC provides a precise 3D event position. At the same time a high chemical and cryogenic purification of the argon has been demonstrated [39].

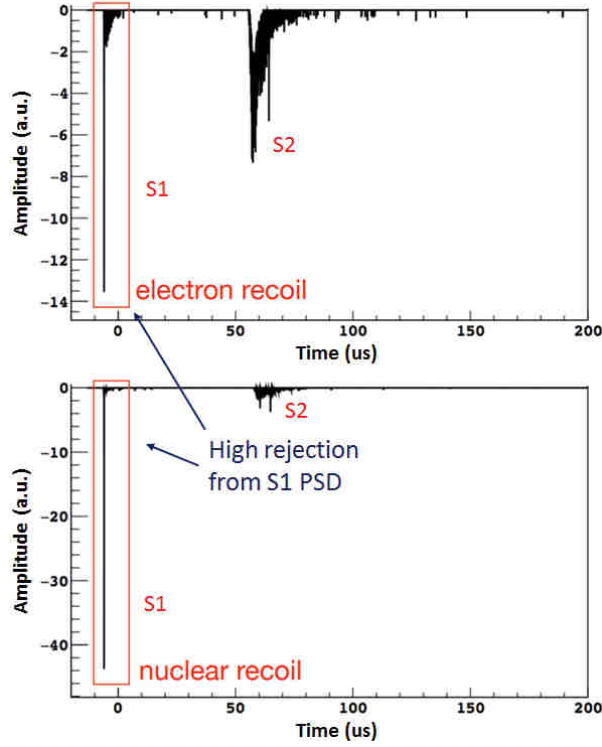


FIGURE 4: Comparison of S1 and S2 signals in case of an electron recoil and a nuclear recoil. Original figures taken from [40]

The search of DM particles with high mass allows to focus on the nuclear recoil energies range from 30 keV_{nr} up to 200 keV_{nr} . In this specific range, argon detectors have an excellent β/γ ¹ background rejection [41] [38]. The electric field to drift the electron on the top toward the second argon phase is set at 200 V/cm . The electric field reduces light yield of nuclear recoils (S1) as it has been studied in [42] so 200 V/cm is chosen as a compromise between minimizing the loss of light yield and improving the ionization signal (S2). The event energy reconstructions are made to consider both S1 and S2 signals.

0.2.1 Background event rate

Since DarkSide-20k goal is to discover extremely rare events, it is of paramount importance to contain the number of background interactions during all exposure: a

¹Lorentz factor $\gamma = 1/\sqrt{1-\beta^2}$, $\beta = c/v$, c = speed of light and v = particle speed

low but non-zero background could prevent the discovery of the DM. For example positive detection of DM to 5σ ², 4-5 WIMP events are necessary if the expected number of background events level is ~ 0.1 . While if the expected number of background events level is 1, the WIMP events necessary for the 5σ go from 10 up to 15 events depending on the background model error [43].

Consequently, if 1 background event is expected, the experiment will need up to 3 times more WIMP interactions compared to a background free experiment.

The background can be generated by different physical processes due to several sources:

- Neutrino-induced coherent nuclear scattering: only the atmosphere neutrinos and those from diffuse supernova neutrinos have enough energy to produce nuclear recoils in the interest region of WIMPs. They are indistinguishable from nuclear recoils induced by WIMPs and in full exposure time (10 yr) only 1.6 events of this type are estimated to happen.
- Neutron scattering: the elastic neutron-nuclear scattering events are indistinguishable to a WIMP-nuclear elastic scatter. Consequently, all neutron sources (radiogenic and cosmogenic) must be reduced well below the < 0.1 events level. To keep under control these phenomena it was studied a neutron veto system to be applied in DarkSide-20k.
- Electron recoil: the suppression strategies of this background source include stringent materials screening and selection, analysis cuts and pulse shape discriminator analysis to identify residual electron recoil. The main sources are due to solar neutrino-induced electron scatter, ^{238}U and ^{232}Th decay chains due to impurities. Argon isotope ^{39}Ar and ^{85}Kr that come from leaks during the collection and purification of argon and from deep underground natural fission processes respectively.
- surface nuclear-nuclear recoil: if a radioisotope decays on the internal surface of the detector and if during the decay an α particle is ejected toward the detector wall, the radioisotope will recoil into the active argon volume producing a nuclear recoil signal. Surface events are rejected using fiducial cuts, drift time cuts and S2 trigger cuts due to the low charge collection efficiency along the sides.

More details can be found in [24].

²events at 5σ mean that has a probability of $3 \cdot 10^{-7} \%$ of being an artefact of statistical fluctuations in the background, $3\sigma \rightarrow 10^{-3} \%$ and $1\sigma \rightarrow 0.16 \%$

0.2.2 The time projection chamber (TPC)

To achieve prefixed goals, the TPC must respond to a large variety of requirements. Here only some of the main requirements are mentioned, an exhaustive description can be found in [24].

Fig. 5 shows the octagonal TPC (3.6 m diameter, 2.6 m height) for LAr target that provides 50 t [44] of mass of ultra pure argon (^{40}Ar). By the experience matured in DarkSide-50, argon is extracted underground (Urania project [39]) and purified (Aria project [45]) to significantly increase the chemical and isotopic purity.

Also the TPC is realized with low radioactive material like oxygen-free-copper (OFHC) and teflon (PTFE). A precise, stable and uniform electric field is realized with a cathode voltage at -52 kV to maintain the drift electric field to 200 V/cm . Moreover, a wire grid just below the LAr surface generates an extraction electric field of 2.8 kV/cm for 3 mm of LAr and a luminescence electric field at 4.2 kV/cm for 7 mm in the uniform pocket of gaseous argon. This generates an electroluminescence region for high resolution signals of S2. The expected space resolution of an event position is of 10 mm in $x - y$ and 1 mm in z (this last measured by drift time).

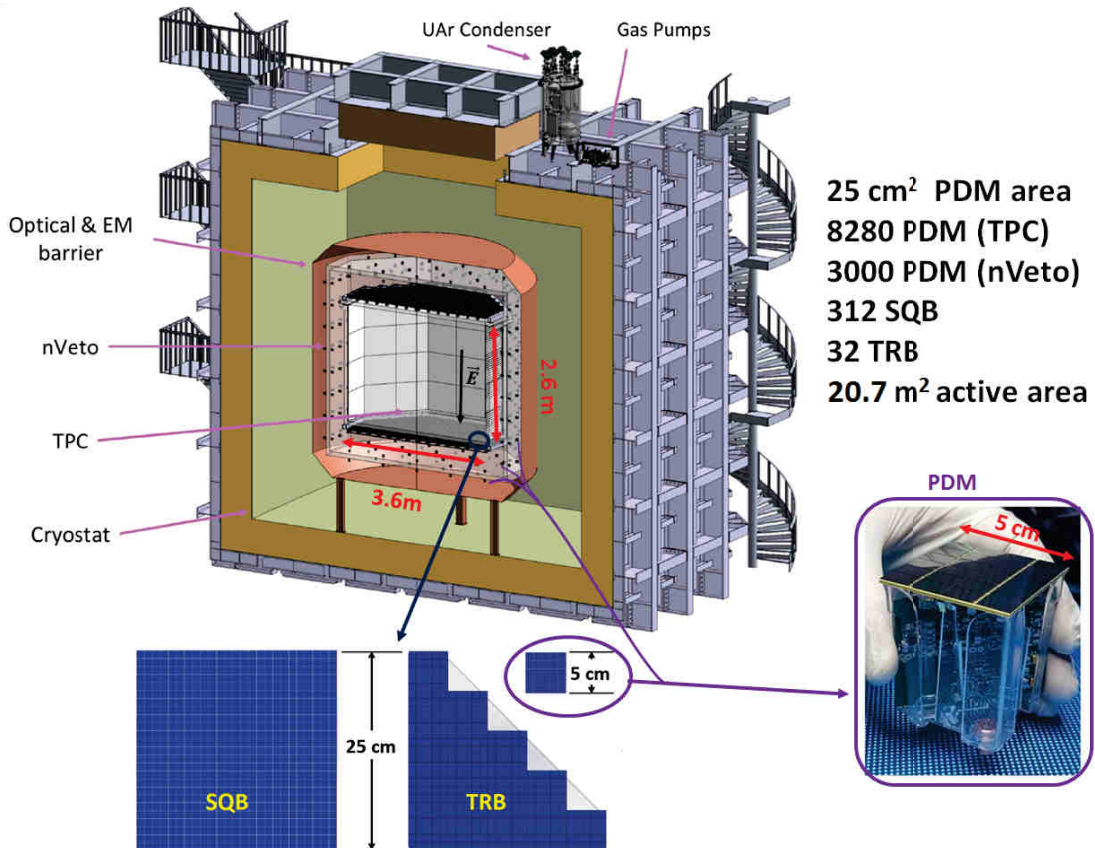


FIGURE 5: On the top left, a section of the TPC inside acrylic vessel immersed in LAr cryostat projected for DarkSide-20k, at the bottom the mechanical board and a picture of a complete PDM. Original figures taken from [44]

The argon scintillation and the electroluminescence signals have their wavelength in the far ultra-violet region around 128 nm . To optimize the light detection, the inner surface in contact to the active volume is coated with tetraphenylbutadiene (TPB). TPB is a highly efficient wavelength shifter from the region at 128 nm to the region at 420 nm .

Two arrays of photosensors cover the inner top and bottom part of the TPC (20.7 m^2 active area), where S1 signal is read roughly equally over both arrays, while S2 signal emitted in the gas region is concentrated in top array and involves few close photosensors.

0.2.3 Photo-Electronics and constraints

Compared to DarkSide-20k predecessor (DarkSide-50 [38]) that uses photo tube multipliers (PMTs) [46] [47] as the main photosensor, DarkSide collaboration has chosen to use silicon photon multipliers (SiPMs) for light detection. SiPM is one of the key technologies for large-scale LAr-based DM experiments.

SiPM has different advantages over the traditional PMT:

- insensitivity to magnetic fields;
- high photon detection efficiency in the interest wavelength region;
- high single-photon resolution;
- low bias voltage (some tens of volts);
- linearity up to high light intensity;
- easily scalable, compact with a high fill factor and with high electronic integration;
- high radio purity.

Thanks to these properties, SiPMs are efficiently integrated into tiles; for the project the basic unit will be a photodetector module (PDM) (sees Fig. 5). A single PDM is a tile of SiPMs covering an area of $50 \times 50\text{ mm}^2$ operating on single channel. Each PDM integrates a cryogenic amplifier and a system of signal transmission via on optic fiber. It features a mechanical structure to assemble all components and to efficiently dissipate heat to minimize gas bubbles in the LAr target.

PDM disadvantage compared to PMT is its high output capacitance ($\sim 50\text{ pF/mm}^2$) that imposes a constraints for the read-out electronic and connection design to maintain a high enough signal to noise ratio (SNR)³ for the experiment requirements.

³SNR = The signal to noise ratio is defined as the ratio of the mean value of the integrated single photoelectron (SPE) response to the RMS of the integrated baseline.

Consequently, it is necessary an accurate design of readout electronics and SiPM connection scheme on tile.

In particular, PDM is composed by 24 SiPMs with an area of $\sim 8 \times 12 \text{ mm}^2$; apart from the mechanical tolerance and the minimum distance to place the SiPMs, the PDM surface is fully covered. As it is described in work [48], SiPMs are symmetrically subdivided in four quadrants that are independently readout by low noise transimpedance amplifier (TIA) [49]. The PDM partitioning is due to a compromise between a constraint on the total power dissipation of the detector, proportional to the total number of TIAs, and the bandwidth and SNR obtainable for a given detector capacitance. The four TIA outputs are then summed by a second-stage amplifier into a single analog output.

The electrical configuration of single quadrant is composed of a parallel of three series of two SiPMs as shown in Fig. 6.

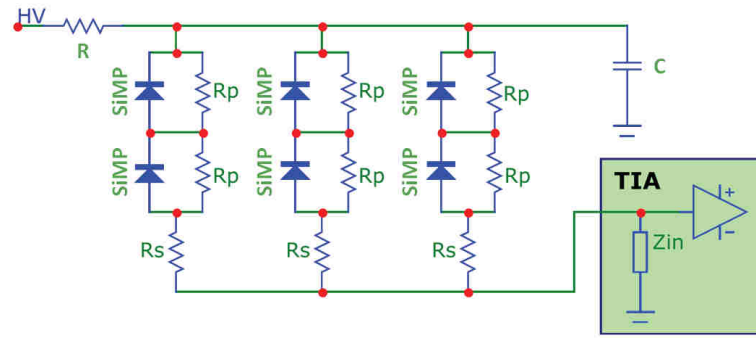


FIGURE 6: Electric circuit of a PDM quadrant composed of six SiPMs and a TIA amplifier. Original figures taken from [48]

The electric circuit is equipped with: a resistor R (tens of $k\Omega$) that limits the total PDM current to avoid potential damage, a capacitor C to compensate fast transient noises and precision resistors R_p ($100 \text{ M}\Omega$) to stabilize the voltage divider of the single SiPM series. The series resistance R_s (some tens of Ω) is particularly important for high frequencies because it limits losses toward the inactive branches of the quadrant. Moreover, R_s resistors contribute to balance the impedance matching between the SiPM quadrant and the TIA input [48].

5210 PDMs are and just as many channels of readout are used in total to completely cover the top and the bottom surfaces of the TPC. PDMs are mounted into a larger square and triangular mechanical board (SQB and TRB) with side of 25 cm , Fig. 6.

The main performances of single PDM are:

- photon detection efficiency (PDE) exceeding 40 % at 420 nm with a gap between SiPMs lower of $100 \text{ }\mu\text{m}$ and a PDM fill factor of 92 %;

- a total power dissipation of lower than $100 \mu W / mm^2$ equivalent to $250 mW$ per PDM. This reduces the thermal load that the cryogenic system must support;
- pre-amplifier dynamic range exceeding $50 pe$ detected simultaneously, necessary to have a good reconstruction of S2 without affecting the SNR;
- time resolution of single PDM must be less than $10 ns$, for a very efficient discriminator power through the PSD of S1;
- single photon sensitivity with $SNR > 8$;
- overall noise rate below $80 mHz / mm^2$, this includes false pulse of electronic noise, dark count rate (DCR) and correlate noise of SiPMs.

The last requirements set has very stringent limits because it influences the trigger efficiency, the PSD power and the SNR.

PDM is considered as discrete photosensor/electric unit. For this reason, SiPM specifications must guarantee that all PDMs will reach the previous requirements set. A list of minimal SiPM requirements for operating at liquid argon temperature is:

- PDE equal to or greater than 45 % at $420 nm$, set to compensate the inactive gaps in the PDM tile and the inefficiency of the trigger detection;
- Individual SiPM size larger than $5 \times 5 mm^2$ to ease the assembly of SiPMs into tiles. Ideal sizes would be $10 \times 10 mm^2$;
- DCR lower than $80 mHz / mm^2$
- total correlated noise probability, crosstalk (CT) + afterpulsing (AP), lower than 60 %.

The development of SiPM technologies that will be used in DarkSide-20k is carried out by FBK/TIFPA, in particular by IRIS unit (Integrated Radiation and Image Sensors) [50].

During my PhD in FBK | IRIS, IRIS developed different SiPM technologies, from which it realized a technology of SiPM suitable for cryogenic applications.

The aim of this thesis is to characterize and compare the different technologies developed by IRIS in a wide range of temperatures down to cryogenic temperatures. The characterization of SiPMs in a cryogenic environment is a recent challenge for FBK, for this reason another purpose of my thesis is to develop setups and to adapt analysis software to characterize SiPMs in cryogenic conditions.

Chapter 1

Silicon Photomultiplier SiPM

1.1 SiPM introduction

The aim of this chapter is to give a general description of the SiPM, explaining its working principle, its fabrication structure and its main characteristics. Then, we will discuss the SiPM electric model and introduce its main features, including current-voltage (IV) characteristics and physics models of SiPM noise (primary noise and correlated noise). At the end of the chapter, we discuss the photon detection efficiency.

The SiPM is an efficient photon counter with sensitivity at the single photon level. It is a solid state opto-electronic device realized with standard planar, usually CMOS-compatible process on epitaxial (or epi) silicon grown on a doped monocrystalline silicon wafer. The wafers are sliced from silicon ingots, usually grown using the Czochralski process manufacturing as single crystals and in widely used large-scale integration [51].

The SiPM is composed of microcells, each one sensitive to single photons. In the analog SiPM, which is the most common variant, they are all connected in parallel and biased at the same voltage and operate independently. Microcells are biased above breakdown voltage. They are in a metastable condition, in that, if no carrier is generated in the active volume, the current is zero.

However, when a couple of carriers are generated, either because of thermal generation or when a photon interacts, an avalanche may be triggered, with a probability parametrized as on the Photon Detection Efficiency (described in Section 1.6). A single microcell, or SPAD (Single Photon Avalanche Diode), is an inherently digital device, in that it can trigger one photon or not. If more than one photon hits the SPAD at the same time, the generated signal is, to good approximation, identical to the one generated by a single photon. When all cells are connected in parallel, as in the analog SiPMs, the current of each microcell is summed at the output. Thus, if many photons hit the SiPM surface at the same time, they trigger (with a certain probability distribution) an avalanche in a number of cells proportional to the number of impinging photons. We assume here that the probability of two of these photons hitting the same cell is negligible. The sum current generated by all cells is

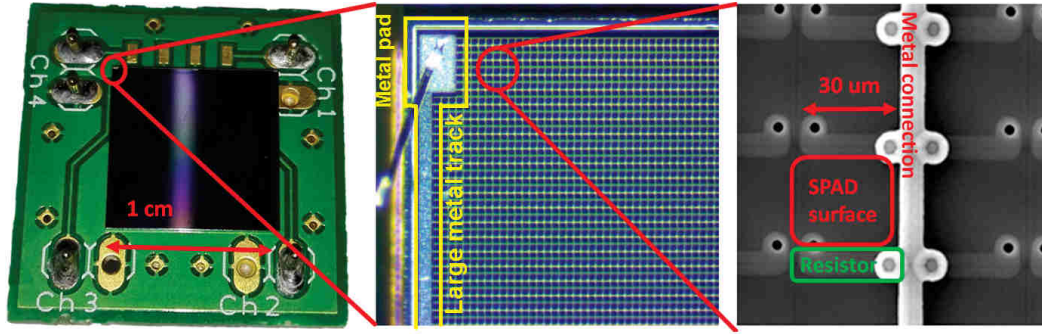


FIGURE 1.1: On the left, there is a SiPM $1 \times 1 \text{ cm}^2$ packaged on PCB, entirely realized in FBK. In the middle, an enlargement of the SiPM corner, where the contact between the metal pad and the gold wire ball bonded is visible. On the right, a picture realized with scanning electron microscope (SEM), where polysilicon resistor and SPAD of some microcells are visible with metal track of common contact

collected at the output pad of the device as a proportional response to the intensity of the incoming light.

Microcell dimensions usually go from $5 \mu\text{m}$ [52] up to $100 \mu\text{m}$ [53]. Microcells are usually square but, in the case of small cells an hexagonal layout is preferred to maximize the detection efficiency. An example of hexagonal microcell layout is the ultra high density (UHD) SiPM realized by FBK [52]. In Fig. 1.2 a schematic cross-section of a SiPM microcell is shown.

Each microcell is composed of two fundamental elements connected in series:

- A single photon avalanche diode SPAD (or Geiger-avalanche photo diode G-APD) [54][55] sensitive to the wavelength of incident light, see section 1.6,
- A polysilicon quenching resistor [56][57], that limits the current grown during the avalanche, turns off the avalanche and restores the bias of the cell preparing it for the detection of a new photon [58]. The advantages of a quenching resistor over other options like digital active quenching [59][60], are an easier circuit, a lower number of production steps, and lower cost.

In a SiPM, microcells are identically and the SPAD signal shape is insensitive to the incident light wavelength. Microcells are electrically connected in parallel through metal tracks (on the right in Fig. 1.1). Tracks have a comb structure with teeth usually every second microcell row to minimize parasitic capacitance.

The metal tracks are connected to one another through a larger metal strip on one SiPM side toward the metal pad. One or more pads are positioned along the SiPM side, the pad number depends on the SiPM dimensions and the application. The main benefit of the microcell parallel configuration is the simple single channel readout of the signal. All signals are summed and the amplitude of the output signal is proportional to the number of detected photons. The disadvantage is loss of

the information of the position of activated microcells on the SiPM. Recently within FBK, the IRIS unit has developed a position-sensitive, linearly graded SiPM (LG-SiPM). LG-SiPM uses a double quenching resistor for every SPAD that splits the signal over two independent lines (vertical and horizontal). The position information is obtained from the relative amplitude of 4 reading pads, two for the X coordinate and two for the Y, as opposed to just one. With this technique, the position of each triggering microcell can be determined within a hundred μm [61][62].

A metalization on the SiPM back side provides a Ohmic contact over the silicon substrate [63]. Thus, the two output terminals of the FBK SiPMs (in its standard configuration with only one signal output per device), are the top lateral metal pad refer to middle fig.1.1 and the metallized surface on the back side.

1.2 The diode

Each SPAD is a semiconductor pn junction diode. It is made of two differently doped silicon regions, n-type (excess of electrons) and p-type (excess of holes) in contact with each other. The formation of the pn junction, or diode, happens at the interface between the two regions as illustrated in Fig. 1.3.

At zero external bias, the electrons from the n-type region diffuse to the p-type region recombining with holes and leaving positive ions in the n-type region. Similarly, holes migrate from the p-region to the n-region leaving negative ions in the

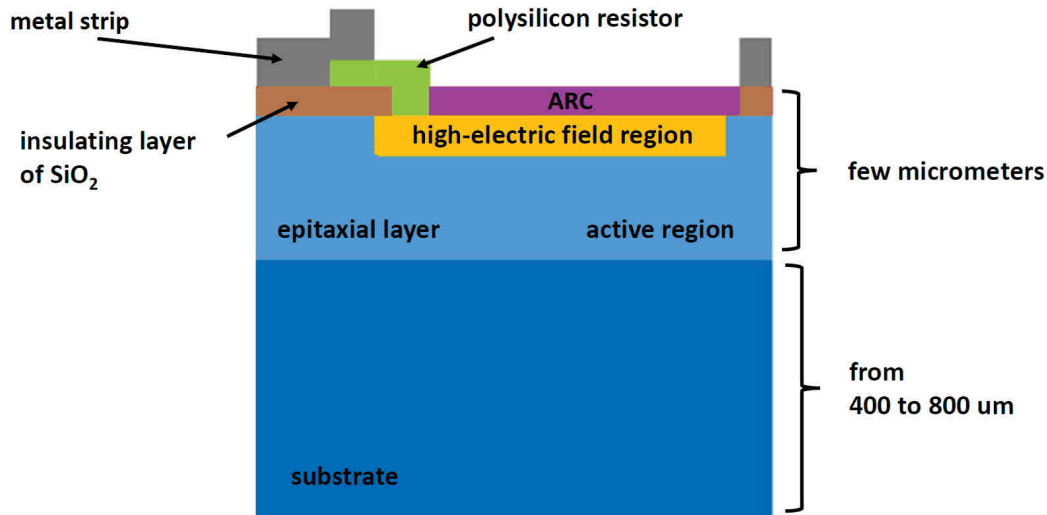


FIGURE 1.2: Cross-section of a microcell where blue layer is a monocrystalline silicon layer which gives robustness to the device. On the substrate, an epitaxial silicon layer is grown and on its surface the photosensor is realized. The high field region is the core of device, as explained in next sections. In the upper left there are the polysilicon resistor, used to quench the avalanche, and the metal strip, that connects the microcell to contact pad

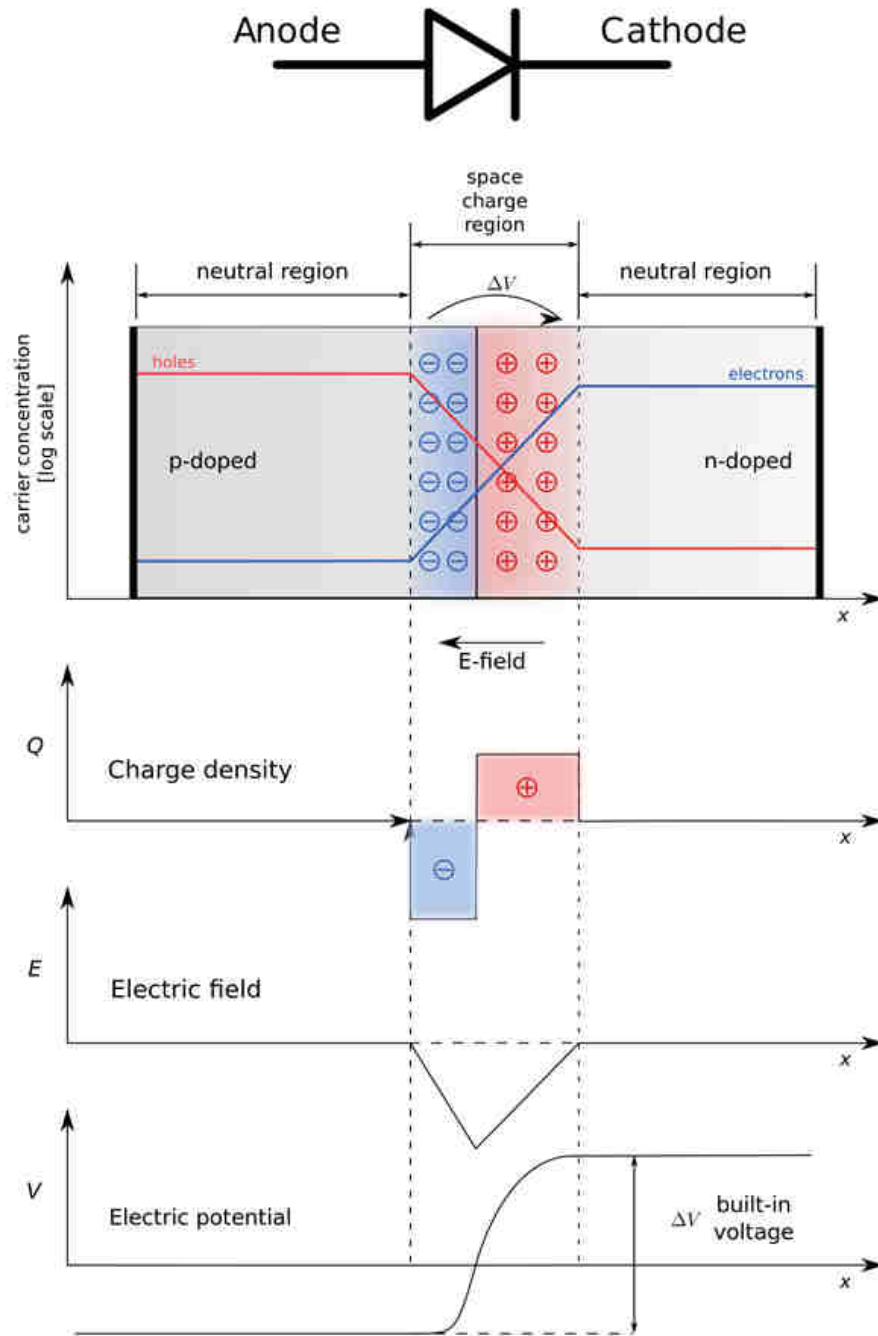


FIGURE 1.3: On the top picture there is the diode symbol in which the cathode corresponds with the n -type and the anode corresponds with the p -type. Further down, the transverse section profile of pn -junction is depicted, in a simplified model that assumes box-like distribution of space charge. The depletion region and the adjacent neutral region are highlighted. In red and blue lines there are the hole and electron densities along the semiconductors. Going down there are charge, electric field and electric potential profile along the pn -junction transverse profile. Picture taken from [64].

p-type region. This diffusion process generates a region called space charge region (SCR), or depletion region. This region is due to the dopant ions in proximity of

junction uncovered by the majority carriers and here, as shown in Fig. 1.3 for a simplified, didactic model of the pn -junction, an electric field different from zero created by the same depletion region is opposed to the diffusion process of two charge species.

If the p-type region is negatively polarized and the n-type region is positively polarized the diode is reverse-biased. In reverse bias, the holes in the p-type (majority carriers) are pulled away from the junction leaving behind charged ions. On the other hand, the electrons in the n-type (majority carriers) are pulled away from the junction leaving behind leaving negative ions, consequently, the width of the SCR to increase. This increases the voltage barrier and the flow of charge carriers is dominated by minority carriers that pass through the pn junction.

1.3 From the G-APD to the SiPM-pixel

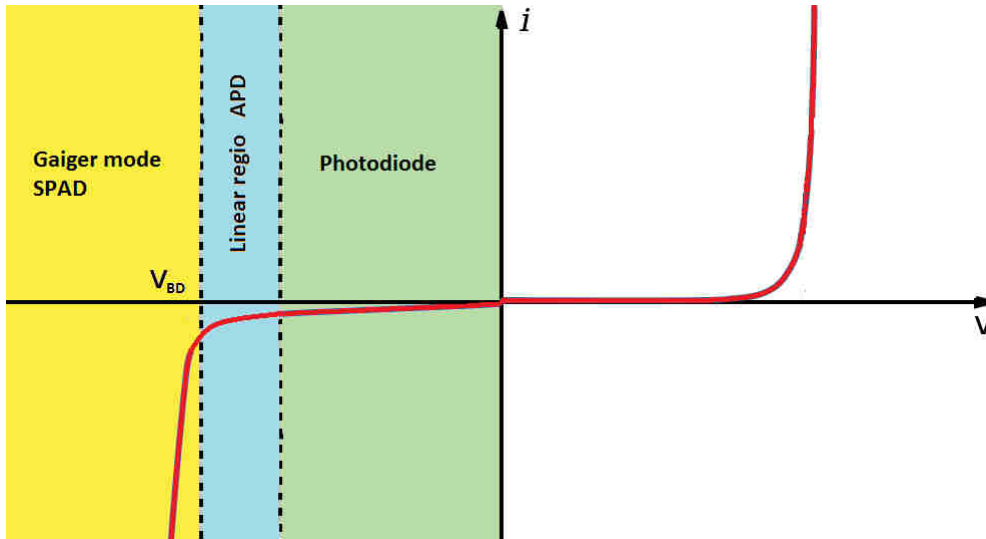


FIGURE 1.4: Characteristic current-voltage plot of a photodiode with work regions highlighted

A photodiode is a pn or p-i-n junction where "i" is an intrinsic semiconductor or a lightly doped semiconductor. In reverse bias and at dark condition, the current that crosses the device is called dark current. The dark current is dominated by minority carriers and the thermal generation is the main process that generates minority carriers at room temperature.

When a photon goes through the semiconductor, it has a certain probability of being absorbed. The probability depends on material properties and on the wavelength of the incident photon, see sec.1.6. If the photon is absorbed in the depletion region, it generates one or more electron-hole pair (it depends on photon energy).

The diode is reverse-biased the electrons drift to n-type region and holes to the p-type region. The device current is the sum of the dark current I_D and of the current associated with photo generated carriers, or photocurrent I_{ph} .

In reverse bias the photodiode can operate in three different modes. The diode structure (i.e. doping levels, geometry and fabrication process) is optimized according to the type of desired detector. Fig. 1.4 shows the operating modes of the photodiode on the diode current voltage plot. There are:

- Photodiode mode [65]: in this regime, the diode works in the linear gain region. This means that the current is linearly proportional to the incident light added to offset due to dark current.
- Avalanche photo diode or APD mode [63][66]: is when carrier multiplication (gain) is present but the device is biased below breakdown. This region is defined as linear region, because the current is still proportional to the incoming light intensity but is amplified by a factor which is highly non-linear with respect to the reverse bias of the device. Carrier multiplication is caused by impact ionization in the high field region defined of p and n dopant profiles, Fig. 1.2. In high field region, there is depletion region where the carriers has enough energy to ionize atoms of the crystal lattice freeing electron-hole pairs which are accelerated by the electric field on pn -junction. In turns, they can generate new electron-hole pairs so that the number of the collected carrier at the diode terminals is larger than the ones generated either by photo-generation or by thermal generation. This process is called avalanche multiplication because electrons and holes drifting in opposite directions, initiate an avalanche. The avalanche grows until some current-limiting effect intervenes, otherwise, the total number of secondary carriers generated by a single, initial couple of carriers would be infinite.

In the linear multiplication region, however, impact ionization is not strong enough to initiate avalanche. The multiplication process is quickly exhausted, all the mobile carriers generated by an initial couple exit the depleted region and no further multiplication can take place. The average number of carriers generated during this process defines the linear gain of the APD.

The probability that each hole or electron generates carriers increases with the reverse bias. Commercial APDs provide gain values between 10^2 and 10^3 . As for the photodiode, zero illumination results in a current which is the dark current multiplied by the gain.

- Geiger-mode photo diode or G-APD [54][67][55]: is a device operated beyond the breakdown voltage. In this case, the multiplication effect due to impact ionization in the high field region is high enough to generate a self-sustaining avalanche for any number of primary carriers, Fig. 1.5. When an avalanche is

triggered in this condition, current flowing through the junction is limited by resistance in series with the diode. Some series resistance is always present due to the resistance of contacts and the bulk resistivity. In most cases, however, an external current limiting resistor is employed. Before the avalanche occurs the voltage drop across the junction is well above the breakdown voltage (V_{BD}). When the avalanche happens, the voltage difference across the junction drops to just above V_{BD} , (within a few mV), according to the current intensity.

In order to use this effect in a functional detector, it is necessary to stop the avalanche and restore the junction bias to the initial conditions. The simplest solution is to use a properly sized quenching resistor (R_q). Indeed, if the avalanche current falls below a certain level, I_{quench} , because of statistical fluctuations of the number of carriers present in the depleted region, the avalanche is self quenched after a time depending on I_{quench} . A value of I_{quench} of $10 \mu A$ is considered sufficient to obtain almost instantaneous quenching of the avalanche (within a few ps), from empirical observations and for most application purposes [58].

The number of carriers passing through the high-field region and, thus, reaching the front-end electronics is determined by the bias applied to the device, by the quenching properties and by geometric parameters of the microcell, as reported in section 4.4. In particular the same signal is generated irrespective of whether the avalanche is triggered by a single or by multiple photons. The G-APD is effectively a digital device.

When operated in these conditions, the G-APD can be also referred to Single Photon Avalanche Diode, or SPAD.

Avalanche triggering probability, on the other hand, is affected by the number of impinging photons in each microcell, and, for obvious statistical reasons, increases as the number of photons simultaneously impinging on the SPAD, because the number of trials to start the avalanche is increased. It is common to avoid operation of SiPMs in this condition, which corresponds to saturation of device response to incoming light [68]. Usually, SPADs have gains between 10^5 and 10^6 times or more.

In FBK technology, a polysilicon resistor is used to quench the Geiger-avalanche of a SPAD [69][70].

In Fig. 1.6 left, you can see the schematic circuit of a reversely biased microcell composed of SPAD with quenching resistor in series. On the right, there is the small-signal, equivalent circuit of the microcell. C_d is the junction capacitance of the SPAD. C_q is the parasitic capacitance of R_q , which depends on fabrication technology and layout. The switch S simulates the avalanche triggering and the voltage generator

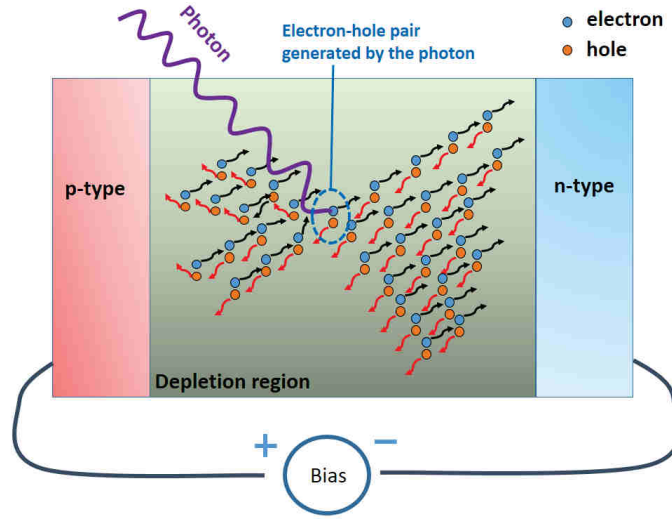


FIGURE 1.5: Representation of an avalanche. If photon is absorbed in depletion region, photo generated carrier pair can triggers an effect of multiplication and generate an avalanche

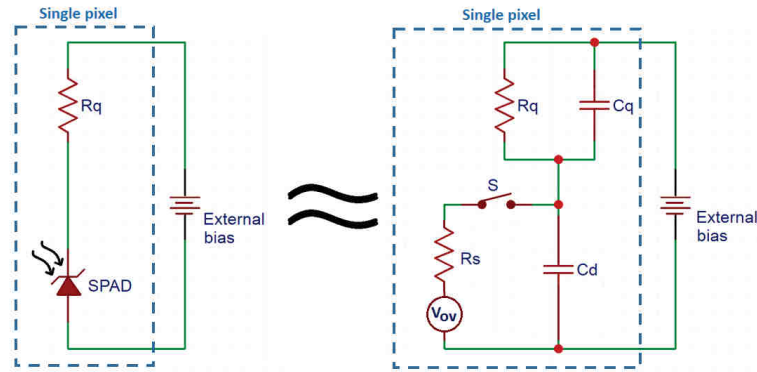


FIGURE 1.6: On the left, the electric circuit of external biased microcell composed of SPAD in series with quenching resistor. On the right, the transient equivalent model of biased microcell

V_{OV} is equivalent to Geiger-avalanche. R_S is the junction resistance or diode resistance. R_S is given by two terms:

- the series of space charge resistance of diode junction;
- the equivalent resistance of avalanche defined as dV/dI of current voltage characteristic of multiplication.

Typical R_S value is few hundreds of Ohms; it depends on structure of SPAD, depletion region width and concentration of dopant. Fig. 1.7 shows different phases corresponding to the triggering of and avalanche, where plot shows the transient current of junction and voltage time plot shows the voltage signal generated on SPAD.

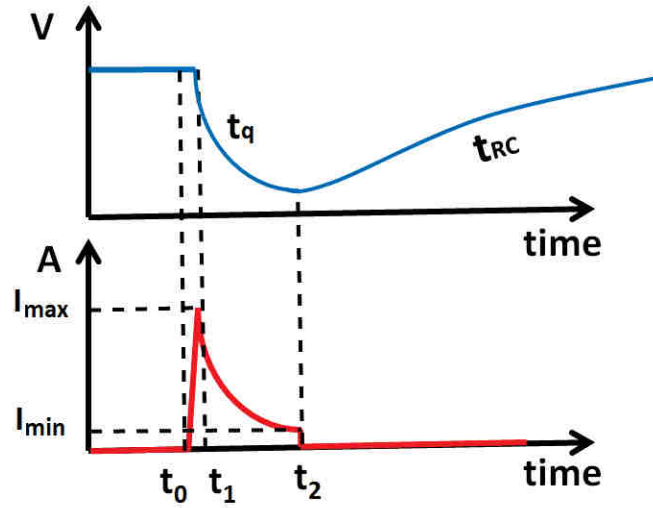


FIGURE 1.7: On the top, pulse waveforms of a SPAD is shown during an avalanche, while lower, there is the avalanche current of diode

We present here a simplified model for the transient signals inside the SPAD when an avalanche is triggered. For the convenience of the reader, we represent all the voltages with an offset equal to V_{BD} , that is in term of the so-called overvoltage, or V_{OV} . Then, the V_{BD} corresponds to $V_{OV} = 0$ V and V_{bias} corresponds to the operating overvoltage.

If t_0 is the time at which the avalanche is triggered, for $t < t_0$ the unmultiplied dark current in R_q is equal to the dark current, which as a first approximation, it is equal to zero and V_{diode} is about V_{OV} . At $t = t_0$ photo generated carrier or thermally generated carrier triggers an avalanche. The current increases rapidly at t_1 , up to I_{max} , whose value is limited by V_{OV}/R_s .

After $t = t_1$, junction capacitance is discharged through R_s down to the breakdown, i.e. at $V_{OV} = 0$ V, with a time constat equal to τ_q (eq.1.1).

$$\tau_q = (C_d + C_q) \left(\frac{R_s R_q}{R_s + R_q} \right) \cong (C_d + C_q) R_s \quad R_s \ll R_q \quad (1.1)$$

V_{OV} is reached at t_2 . At this point, current is limited by the quenching resistor at a value equal to V_{OV}/R_q . With a proper choice of the value of R_q , the quenching condition is reached and $I_{diode} \leq I_{quench} \sim 10 \mu A$. Thus the avalanche is rapidly quenched. After that, no more current flows through the junction and C_d is recharged exponentially to $V_{OV} = V_{start}$ through R_q , with a recharge time constant τ_{RC} equal to eq.1.2.

$$\tau_{RC} = (C_d + C_q) R_q \quad (1.2)$$

We note that current signal exits the SPAD through the readout pad in two phases: between t_1 and t_2 through C_q , which connects the SPAD anode and output pad,

which stays at constant bias, during the recharge of the microcell through R_q .

On the contrary, the current that discharges C_d is local to the microcell and does not exit the device.

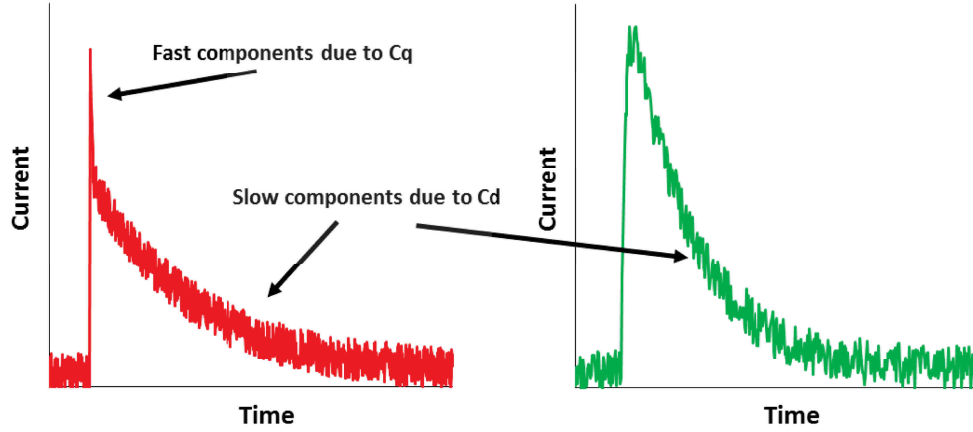


FIGURE 1.8: Two real signals with and without a fast peak due to C_q .

Fig. 1.8 shows two real cases of SPAD signal. On the left, the fast peak due to the C_q contribution is visible, while on the right, the fast peak is fully filtered by the input impedance of the front-end combined with the output capacitance of the SPAD or SiPMs because τ_q is very fast, even a relatively high-frequency readout can significantly filter the fast peak [49]. The fast peak is highlighted in the case of cryogenic temperatures [71] because $\tau_q \sim \text{constant}$ with temperature while τ_{RC} increases with decreasing of temperature.

1.4 Electric model of the SiPM

As mentioned above, the analog SiPM is a two dimensional array of microcells, each microcell composed of SPAD in series with a quenching resistor. All microcells are connected in parallel.

If no cell is triggering an avalanche, the microcell model explained in previously sec.1.3 can be simplified as in Fig. 1.9, where the branch with transient voltage generator V_{OV} is deleted. Instead, C_d is always the capacitance of the SPAD-junction, R_q is the quenching resistor and C_q is the parasitic capacitance of R_Q .

Now it is possible to describe the SiPM as an electric net only composed of passive components. Fig. 1.10 reports an electric model of a SiPM packaged with a print circuit board (PCB) of support.

Inside the dashed square we represent the parallel connection of the n pixels that that compose the SiPM. In a real case there are other parasitic components depending on the SiPM model used. In this model, three other components are considered in common parallel with all n - microcells:

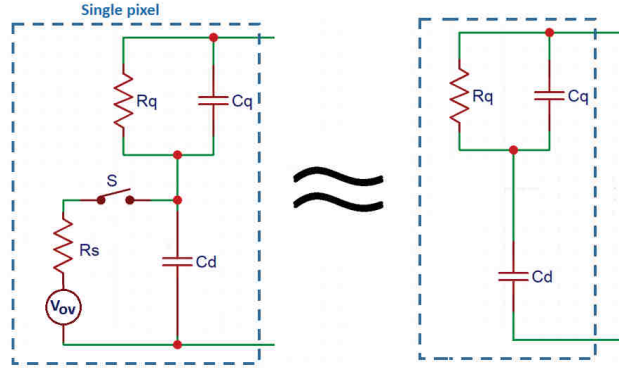


FIGURE 1.9: On the left the complete, small-signal SPAD model. On the right the simplified microcell model which it does not trigger an avalanche

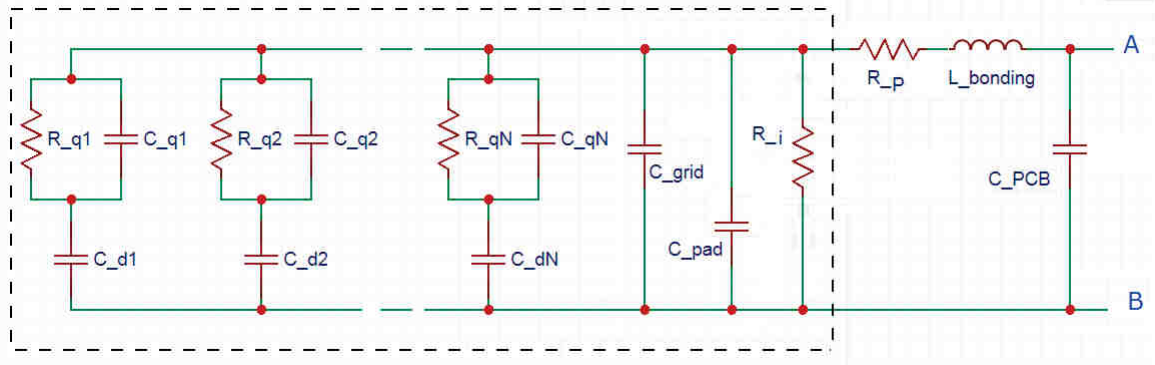


FIGURE 1.10: Full electric model of a SiPM packaged on support PCB(for example see Fig. 1.1)

- The first is the grid capacitance (C_g) [72][73]. It is a parasitic capacitance between the surface metal lines and the bulk.
- The second parasitic capacitance is called pad capacitance C_{pad} . It is between the bonding pad on the SiPM surface (central Fig. 1.1) and the epitaxial layer with the SiO_2 layer between them. It depends on pad number, pad area and SiO_2 layer thickness.
- The last element is the resistor R_i , which accounts for the unmultiplied dark current of the SiPM, mainly composed of surface leakage current [74].
- R_p , L_b and C_{PCB} are external parasitic components due to the PCB and SiPM packaging on the PCB. They limit the bandwidth and, in particular, the SiPM signal rise time. They can be reduced with an optimized PCB layout [73].

From A to B terminals, the SiPM in the frequency domain is seen as an impedance $Z_{AB}(\omega)$. To calculate the $Z_{AB}(\omega)$ some considerations are necessary:

- A precise LCR meter can measure Z_{SiPM} where C_{PCB} is previously compensated in the setup calibration, see section 2.4.
- The dark current resistor R_i can be estimated with reverse Ohm Law (eq.1.3) by the dark current I_{dark} of the reverse I-V plot for bias voltage values $< V_{BD}$.

$$R_i = \frac{V_{Bias}}{I_{Dark}} \quad (1.3)$$

Reverse I-V of a SiPM fabricated in FBK with area of 1 cm^2 is measured at two temperatures 300 K and 77 K. In the table below, the data are reported with the R_i that results always negligible.

T	300K	77K
V_{bias}	34 V	27 V
I_{dark}	$3 \cdot 10^{-10} \text{ A/mm}^2$	$< 1 \cdot 10^{-12} \text{ A/mm}^2$
R_i	$11 \cdot 10^{10} \Omega/\text{mm}^2$	$> 27 \cdot 10^{12} \Omega/\text{mm}^2$

- The single microcell impedance can be written as

$$Z_{SPAD} = \frac{R_q}{1 + j\omega C_q R_q} + \frac{1}{j\omega C_d} = R + jX \quad (1.4)$$

The total impedance due to only microcells term Z_N is given by the parallel of Z_{SPAD_n} .

$$Z_N \equiv \left(\sum_{n=1}^N \frac{1}{Z_{SPAD_n}} \right)^{-1} = \left(\sum_{n=1}^N \frac{1}{R_n + jX_n} \right)^{-1} \quad (1.5)$$

Typically, it is a good approximation to assume that microcell parameters are uniform for microcells of same SiPM, so we can written

$$R_n + jX_n = (R + jX)_n \quad (1.6)$$

with R and X the average values of R_n and X_n . If we replace eq.1.6 in eq.1.5

$$Z_N \approx \frac{\prod_{n=1}^N (R + jX)_n}{\sum_{n=1}^N \left[\prod_{m=1}^{N-1} (R + jX)_m \right]} = \frac{(R + jX)^N}{N (R + jX)^{N-1}} = \frac{(R + jX)}{N} \quad (1.7)$$

After these simplifications, the SiPM electric model with zero fired microcells is reported in fig1.11.

According to the eq.1.4, eq.1.7 becomes

$$Z_N = \frac{1}{N} \left(\frac{R_q}{1 + j\omega C_q R_q} + \frac{1}{j\omega C_d} \right) \quad (1.8)$$

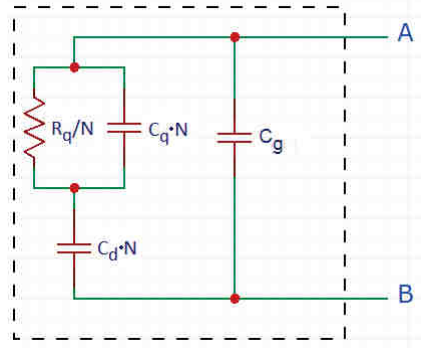


FIGURE 1.11: Electric model of simplified SiPM

As a first approximation parasitic components R_p , L_b and C_{PCB} are negligible, thus, we can write that the total impedance of SiPM is

$$Z_{SiPM}(\omega) \sim \left(\frac{1}{Z_N} + j\omega C_g \right)^{-1} \quad (1.9)$$

At intermediate frequencies the output capacitance is the equivalent parallel capacitance $C_{par} \approx NC_d$. On the contrary at high frequencies $\omega \gg R_q C_q$ and C_{par} is proportional to eq.1.10 [74] [73] where C_g is usually too small to be measured.

$$C_{par} \approx N \frac{C_d C_q}{C_d + C_q} \quad (1.10)$$

Finally, at low frequencies $Z_{SiPM} \approx R_q / N$ [74].

Now, the SiPM model has three parameters R_q , C_q , C_d . We can use an LCR meter to derive these parameters. If we choose the output of the instrument as series R-C model, the impedance $Z_{SiPM}(\omega)$ can be rewritten to separate the real part from the imaginary part, eq.1.11 (fig.1.12).

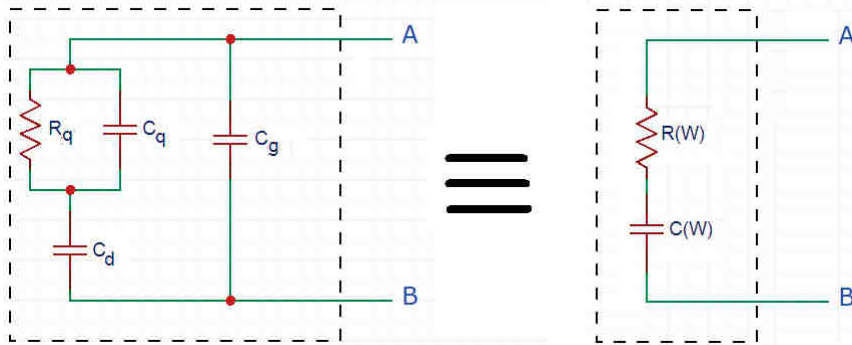


FIGURE 1.12: The SiPM electric model is compared to a series R-C model, which is the format of the data output by the LCR meter

$$Z_{SiPM}(\omega) = R(\omega) + \frac{1}{i\omega C(\omega)} \quad (1.11)$$

If measure setup is not optimized, especially at high frequency, this method can be affected by parasitic capacitances and inductors.

Measurements of $R(\omega)$ and $C(\omega)$ at 300 K and 77 K have been made for different SiPM parameters and they have been presented in the final results chapter.

A second method consists on separately measuring the parameters with different types of measurement.

- R_q can be determined by the forward current voltage (IV_{FW}) plot of the SiPM, Fig. 1.13.

Approximating the junction of diode to a resistance (R_{diode}), it quickly becomes negligible if compared to R_q with increasing of bias voltage. Electrically, SiPM is made by N parallels of N microcells with single microcell composed of a SPAD in series with a R_q , thus, total resistor equivalent is

$$R_{SiPM}(V) = \sum_{n=1}^N \frac{1}{R_n(V) + R_{q_n}} \quad (1.12)$$

If $V_{bias} > 0.6 V$ at 300 K, SiPM behaviour is dominated by quenching resistors and eq.1.12 becomes

$$R_{SiPM}(V) \approx \sum_{n=1}^N \frac{1}{R_{q_n}} = \frac{R_q}{N} = R_{eq} \quad (1.13)$$

R_q is the average quenching resistor searched and $R_{eq} = N \cdot R_q$ is the equivalent resistance measured.

As in Fig. 1.13, R_{eq} is measured through linear interpolation of current in linear region (R_{fit}). The main problem of this measurements is due to parasitic series resistance (R_{series}) given by setup like bad electric contacts and packaging of SiPM, typical values are of few Ohm. The quenching resistor measured $R_q^{measured}$ is equal to

$$R_q^{measured} = N \cdot R_{fit} = N \cdot (R_{eq}^{measured} + R_{series}) \quad (1.14)$$

where $R_q^{measured} > R_q$ of $N \cdot R_{series}$. For example, two SiPMs with area of 1 mm^2 and 1 cm^2 , cell size of $30 \mu\text{m}$ and R_q of $1.5 \text{ M}\Omega$ have a R_{eq} of $1.3 \text{ k}\Omega$ and of 13Ω respectively. Thus, for large SiPM at room temperature R_{series} can increase $R_q^{measured}$ also of 20 – 30 %.

- C_q and C_d are indirectly obtained by single cell gain (G) measurements. Single cell gain means how many charge passes through the high-field region during an avalanche. Techniques to measure G are discussed in sections 2.2. Below, the relation between G and $C_q + C_d$ is reported

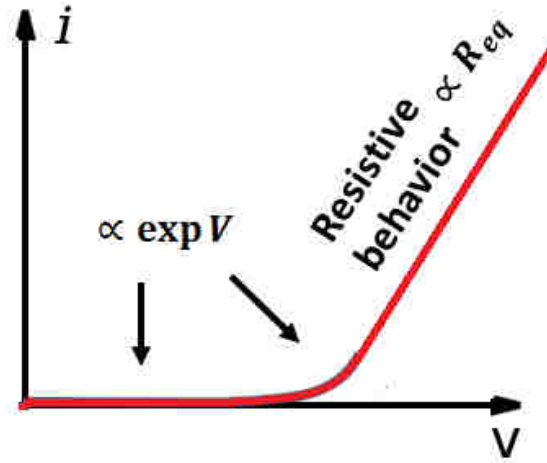


FIGURE 1.13: The forward IV plot of a SiPM

$$G = \frac{(C_q + C_d) (V_{bias} - V_{BD})}{q_0} \quad (1.15)$$

V_{BD} is the breakdown voltage and q_0 is the elementary charge of the electron [73].

Last term is grid capacitance (C_g), in modern FBK SiPM technology, typically is too small to be measured. However, it can be approximately estimated with some basic considerations. Normally, both SiPM and microcell shapes are square and layout of metal tracks is comb. Practically, metal tracks are parallel along the whole SiPM. In addition, at least one orthogonal metal track on one side of the SiPM connects all tracks together. One metal track is placed every second row of cells (fig.1.1). Therefore, the total number of metal tracks N_{strip} can be estimated from the number of microcells from the equation:

$$N_{strip} \sim \frac{\sqrt{N_{cell}}}{2} + 10 \quad (1.16)$$

$\sqrt{N_{cell}} \sim$ is the microcell row number and if it is divided by 2 becomes N_{strip} . The correction "10" considers orthogonal track that is larger and last parallel track on SiPM side that is added to connect last row of microcells. L_{strip} and W_{strip} indicate the length of each metal strip and its width, respectively. Total metal strip area (A_{strip}) is:

$$A_{strip} \sim N_{strip} \cdot L_{strip} \cdot W_{strip} \quad (1.17)$$

From the equation of a parallel plate capacitor, it is possible to estimate total grid capacitance

$$C_{grid} \sim K \epsilon_0 \epsilon_{SiO_2} \frac{(A_{strip} + A_{pad})}{W_{SiO_2}} \quad (1.18)$$

with ϵ_0 = the vacuum permittivity, $\epsilon_{SiO_2} = 3.9$ is relative permittivity of SiO_2 [63] and K is a correction factor (or average relative permittivity) due to a particular cross-section layout of microcells. W_{SiO_2} is average thickness of SiO_2 layer which separates the metal strip to bulk.

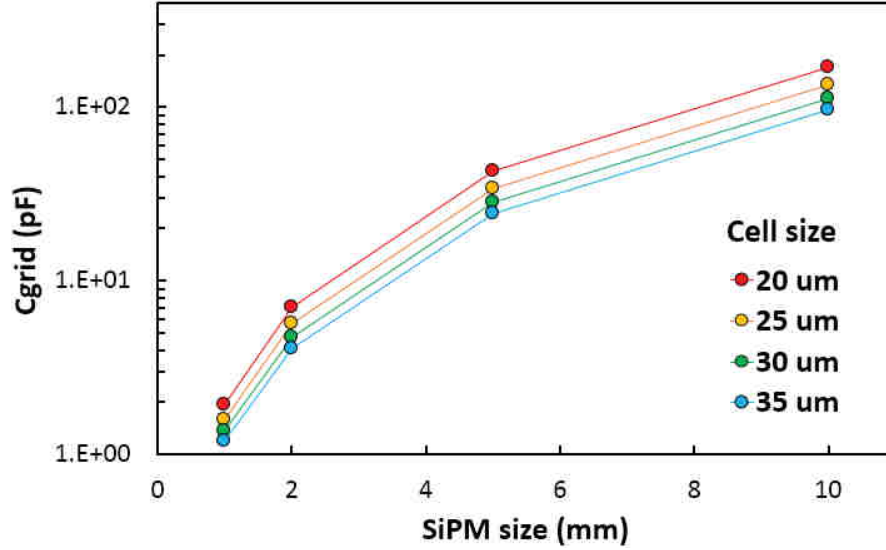


FIGURE 1.14: Trend of the grid capacity C_g depending on the SiPM size for different microcell size. Cell size and SiPM size are typical values used in IRIS[50] group on FBK

Using the approximate model of eq.1.18 and realistic SiPM technology parameters, behaviours of C_g as function of SiPM size and on cell size (CS) are plotted in Fig. 1.14. Used parameters are $W_{SiO_2} = 1.5 \mu m$ and $W_{strip} = 3 \mu m$ with single bonding pad large $100 \times 100 \mu m^2$, while K is unknown and has been placed at one.

C_g is proportional to the second power of the SiPM side because $L_{strip} \sim size_{SiPM}$ and $N_{cell} \sim size_{SiPM}^2 / size_{cell}^2$, substituting these relations in eq.1.17, it is easily verifiable that $C_g \propto A_{SiPM}$, where A_{SiPM} is the area of SiPM.

The used model overestimates C_g because from the geometries shown above in Fig. 1.2, only a part of the metal capacitance involves the C_g (bulk), the rest is C_q (polysilicon resistor).

1.5 SiPM noise sources

SiPM noises can be divided in two types: primary noise and correlated noise. Primary noise is called dark count rate (DCR) and comes from random generation of carriers in the active region. Instead, correlated noise refers to all avalanche that

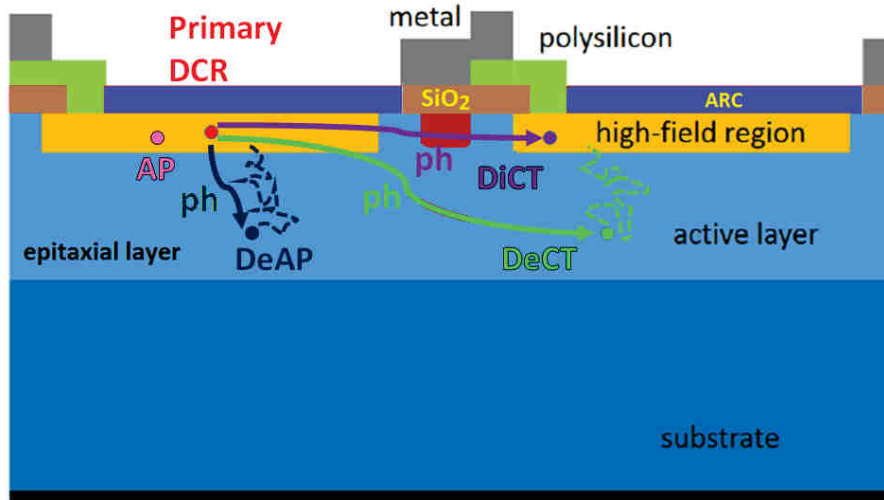


FIGURE 1.15: Conceptual transverse section of two microcell which represents the main source types of SiPM noise.

are generated as a consequence of the detector triggering an avalanche because of another, primary event, such as thermal generation or detection of a photon.

DCR noise is due to carriers generated in the depletion region or to minority carriers diffusing to the depleted region from adjacent neutral regions, where they have a certain probability to trigger an avalanche. DCR follows a Poisson distribution. Carriers generation in the depleted region can be caused by two distinct processes:

- the first one is thermal generation in which a carrier can be promoted to the conduction band by thermal energy present in the system [75]. In SiPM, the process is usually field-enhanced due to the very high electric field necessary to the impact ionization mechanism;
- the second process is the band-to-band tunneling generation [76].

As Fig. 1.16 shows, thermal generation exponentially depends on temperature and dominates at high temperatures. On the contrary, band-to-band tunneling generation weakly depends on temperature and its effect dominates at cryogenic temperatures, where thermal generation is strongly suppressed.

1.5.1 Afterpulsing

Considering correlated noise, afterpulsing (AP) is generated when a cell re-triggers itself, a certain time after it has triggered an avalanche because of a previous event. This process is due to the trapping and release of charge in depletion region. In the active volume of each SPAD, there can be trapping centers that can catch, with a certain cross section, one of the numerous carriers passing through the junction during an avalanche.

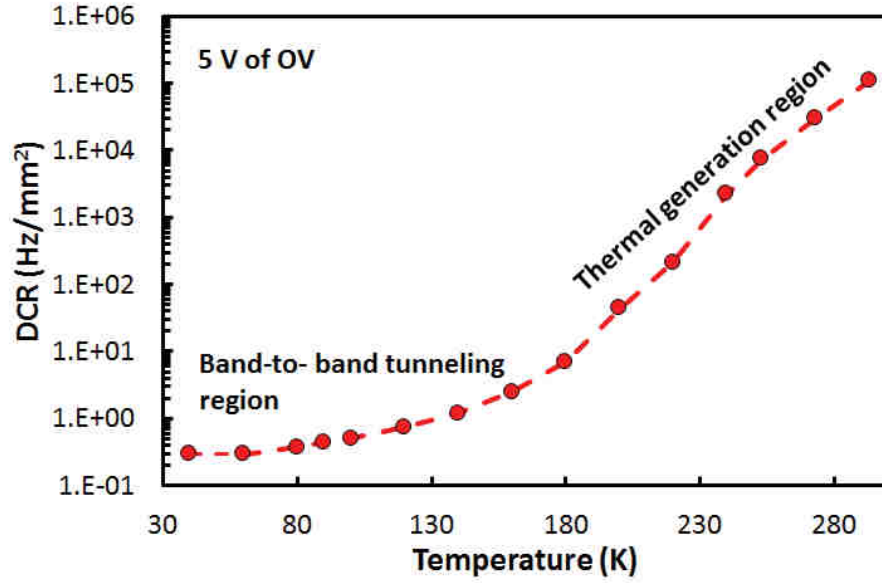


FIGURE 1.16: Primary noise characterization as function of temperature for a SiPM-SF

After a certain time, which depends on trap level and temperature, carriers are released and can re-trigger a new avalanche in same cell, if the cell has already been recharged by the quenching resistor. Thus, a very effective method to reduce AP, is increasing the recharge time of microcells. Trapping centers can be generated by defects in the crystal lattice like dislocations, vacancies and impurities. AP probability depends on trapping centers concentration, on temperature, on cell gain and on recharge time constant of cell (characterization in chapter 4).

A second type of AP noise is indirect (or diffused or delayed) afterpulsing (DeAP). During the avalanche, carriers generate so-called secondary photons through different mechanisms (fig.1.15) [77]. From experiments, it is estimated that, on average, the efficiency of this process is approximately $3 \cdot 10^{-5}$ secondary photons emitted per carrier passing through the high-field region during the avalanche [78]. These photons can be absorbed in the neutral regions adjacent (below) the depleted region and generate a carriers pair. The minority carrier of the pair can then diffuse to the depleted region before recombining and trigger a new avalanche.

1.5.2 Optical Crosstalk

Optical Crosstalk (CT) is generated when the secondary photons generate an avalanche in another cell, different from the one triggering the initial avalanche. If the secondary photon is absorbed in the depleted region of the second cell and trigger an avalanche, it happens almost at the same time as the first one. This phenomenon is called direct optical crosstalk (DiCT). DiCT mainly depends on cell gain, cell size and layout among near cells (characterization in chapter 4).

A second type of CT is indirect (or delayed) crosstalk (DeCT), in which, similarly to DeAP (Fig. 1.15), secondary photons generate carriers in the neutral region below another cell. In this case, the DeCT event happens with a certain delay after the primary event. The probability of triggering a DeCT event is not affected by the recharge time constant of the first microcell [79].

During the characterization, two families of external noise source can be classified:

- External electronic noise; output signal of SiPM can be degraded by amplification chain, whose design is particularly sensitive to the very large output capacitance of the SiPM, compared to more traditional detector technologies [49] [53]. As seen in sec.1.4, output impedance of SiPM depends on its parameters, that in turn, can depend on temperature as will be seen in chapter 4. Other external sources are all radio frequency phenomena that can generate impulsive signals, because they can generate false events that are traded for SiPM signals and so they influence results of characterizations (see section 2.2.1).
- Second noise family is due to environmental light, thus it is a problem of shield of setup. SiPM is an optoelectronic device, so the external light can change dark count rate (DCR) measurements. Shielding the device from external light is of uttermost importance at cryogenic temperatures, because DCR decreases up to seven order of magnitude, Fig. 1.16, and then even few photons can influence measurements.

1.5.3 Shape and amplitude of the signals

Signals generated by a DCR event are identical in shape and in amplitude to ones generated upon detection of a photon. Therefore, single event of DCR can not be distinguished from single event of a photon.

Signal generated by an AP event features the same shape of DCR event, but it can have a lower amplitude if the event is triggered when the microcell bias is only partially restored to the nominal value through the quenching resistor, as outlined in Fig. 1.17. If the signal amplitude of a DCR event is averagely equal to "1", AP signal amplitude can range from 1 up to 0 depending on when trapped carrier is released after the initial avalanche.

Because DiCT signals happen almost simultaneously with the initial event, they cannot be distinguished in the SiPM waveform, given the relatively limited bandwidth of the front-end electronics and the relatively long recharge time constant of the microcells, which is usually in the order of tens of nanoseconds. DiCT events are simultaneously seen by oscilloscope because a photon takes about 0.1 ps to cross $100\text{ }\mu\text{m}$ of silicon.

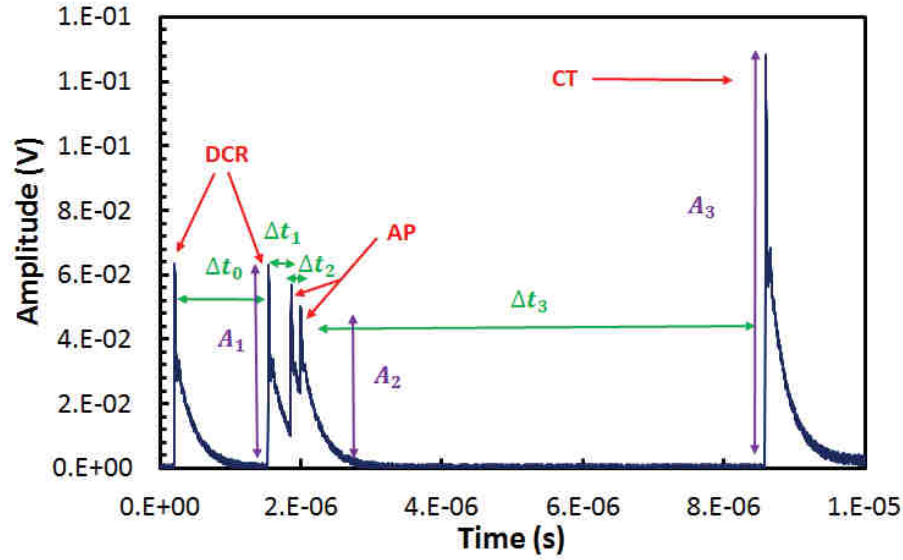


FIGURE 1.17: Typical voltage signal of a SiPM amplified with trans-impedance amplifier. Different information of signal are highlighted

Furthermore, more than one DiCT event can happen at the same time, either caused by the same primary cell or by a chain of crosstalk events. Thus, DiCT signals can have discrete values of amplitude n , where " n " is number of simultaneous firing cells, as shown in Fig. 1.18. Single simultaneous signals of n cells are not recognized on the basis of the source type that generates it. Then, simultaneous events like the double-DCR, the double-photon, the DCR + photon and the single-DiCT, give the same signal.

Finally, the DeCT can be seen as single firing cell, because the average diffusion time of the photo generated carrier to arrive in depletion region is in the order of a few nanosecond. Total process time is along enough to distinguish DeCT event from previous event that generates it.

1.6 Photon Detection Efficiency (PDE)

PDE is the probability that the SiPM detects a single photon impinging on its surface. It is the product of three terms, as described in 1.19

$$PDE(V, \lambda) = FF(V) \cdot QE(\lambda) \cdot T_P(V, \lambda) \quad (1.19)$$

$FF(V)$ is the fill factor of single cell, $QE(\lambda)$ is SiPM quantum efficiency and $T_P(V, \lambda)$ is avalanche triggering probability.

- Fill factor is the ratio between the active area and the total area of the cell. Active area is the part of the cell with high electric field, where an avalanche can be started. Thus, it is the only part of the cell sensitive to light. It is smaller

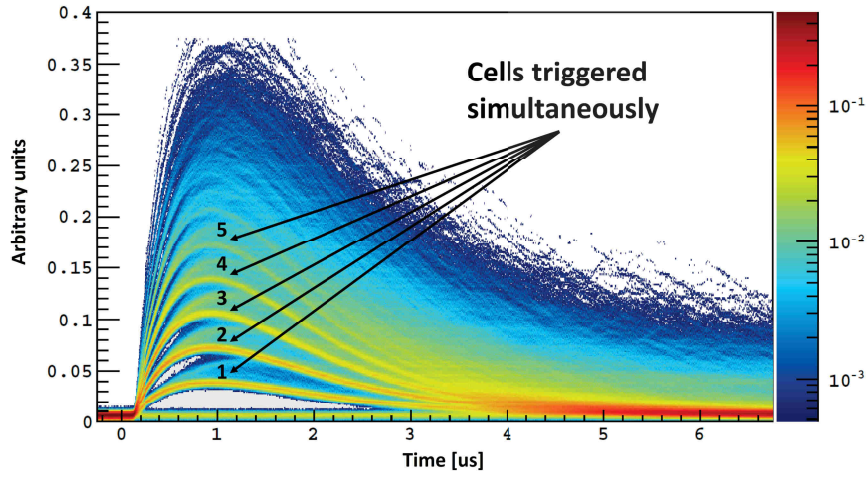


FIGURE 1.18: A persistence plot of SiPM signal, filtered at 20 MHz. The used SiPM (1 cm^2) is similar to one in Fig. 1.1. The acquisition was made at 77 K with $\sim 12 \text{ M}\Omega$ of quenching resistor

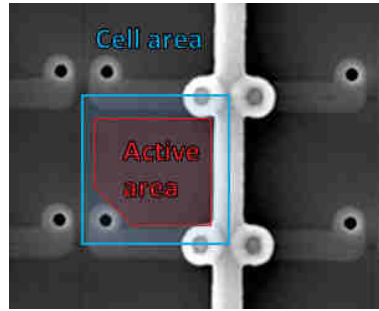


FIGURE 1.19: SEM microscopy picture of cell. Total cell area and active area are highlighted

than the cell area because of the need of lateral guard structures, as described in section 4. It is normally defined by the size of the high-energy deep implant. FF can be rewritten as:

$$FF(V) = FF_A \cdot FF_B(V) \quad (1.20)$$

with $FF_A \leq 1$ that is layout fill factor, calculated from the size of the deep implant, while, $FF_B(V)$ is a corrective factor taking into account that there is always a loss of detection efficiency at the edges of the active area, as described in [80]. It is due to non uniformity of the electric field and charge collection efficiency at the border of the active area and to lower. FF_B depends on the bias applied to the device, as the losses at the edge of the active area are reduced at high overvoltage. For a large cell the influence of these losses, which are in the order of few micrometers, is negligible and $FF_B = 1$ [80].

- The $QE(\lambda)$ is given by the product of two terms:

First term is transmission probability of photons from the outside medium to the silicon, where the SiPM microcells are built. It depends on wavelength (λ), thickness of surface layers and their refraction index. As shown in Fig. 1.15, on top of the microcell, an anti-reflective coating (ARC) is used. ARC can be optimized to improve specific parameters, like the detection efficiency of specific wavelength region. Moreover, different optimizations are required to maximize transmission probability between different materials (air, liquids and crystals) and silicon [81].

Second term is absorption probability of a photon in silicon, which depends on the exponential of the inverse of the absorption coefficient. In Fig. 1.20, absorption coefficient and absorption length are shown as function of photon energy. From 700 nm up to 400 nm, absorption length changes from $\sim 5 \mu m$ up to $\sim 150 nm$. For very short wavelength, absorption happens, at least partially, in the undepleted, superficial doped layer, which constitutes on side of the junction. To maximize detection of blue light, the thickness of this layer is kept as small as possible with suitable microfabrication techniques. On the other hand, considering that the high-field region is close to the surface for FBK technologies (RGB-HD, NIR-HD, section 3), the majority of carriers is photo-generated by NIR photons below the junction. In this case, to maximize efficiency, the most common approach is that of increasing the thickness of the epitaxial layer, as described in [82]. Indeed, the full thickness of epitaxial layer is depleted during normal operation of the device and can contribute to charge collection.

- Electrons (e) have an avalanche probability that depends on their generation position along the pn -junction $P_e(z)$ where z indicates the distance on surface. Similar relation $P_h(z)$ exists for holes (h). They depend on ionization coefficients $\alpha_e(z)$ for electrons and on $\alpha_h(z)$ for holes. Ionization coefficients increase with increasing electric field. In silicon, $\alpha_e(z)$ is bigger than $\alpha_h(z)$ because electrons have higher mobility. Total avalanche triggering probability ($P_T(z)$) can be written as

$$P_T(z) = P_e(z) + P_h(z) - P_e(z) P_h(z) \quad (1.21)$$

By the multiplying the absorption distribution (fig.1.20) versus depth for a given lambda and $P_T(z)$, resulting function can be integrated over all depletion region to obtain $T_P(\lambda)$ for a given overvoltage. $P_e(z)$ and $P_h(z)$ are maximized if the position of the photo-generated carriers, either they are electrons or holes, is at the edges of the high-field region [83] [84] [85].

In particular, we can define z_1 as the z coordinate of the edge of the high-field region towards the p-side of the junctions. Under the effect of the electric field,

electrons enter the high-field region from z_1 . Similarly, we can define z_2 as the z coordinate of the edge of the high-field region towards the n-side of the junctions.

We observe that, because ionization coefficient for electrons is higher than the one for holes at any given value of the over-voltage, $P_e(z_1) > P_h(z_2)$. Electrons are more efficient in initiating the avalanche and this should be taken into account when designing SiPMs for different applications.

For example, for NUV light detection, FBK has developed a p-on-n junction. As mentioned above, in this case most of the charge is generated near the surface and, because superficial implant is p -type, electrons will trigger the avalanche, thus maximizing detection efficiency for light. Another advantage of this configuration is that the triggering probability of optical crosstalk, which we assume generates carriers almost uniformly across the depleted region, is minimized.

On the other hand, to detect NIR light, an $n-on-p$ junction is preferred. In this case, charge is generated almost uniformly across the depleted region. However, most of it is generated below the junction, so that, electrons for the most part, initiate the avalanche. On the other hand, triggering probability for incident light increases almost proportionally with triggering probability for optical crosstalk (secondary) photons and, indeed, optical crosstalk is one of the most important noise sources in NIR-sensitive SiPMs.

1.7 IV curves, breakdown voltage and second divergence

In Fig. 1.21, reverse IV of SiPM is shown and two different regimes are clearly visible. Below V_{BD} , dark current is expected to be almost constant, and is usually attributed to surface leakage current, which is not multiplied. The quasi linear dependence on the bias that is observed can be attributed to parasitic leakage between the SiPM cathode and anode contacts on the package. A parasitic resistance of $\sim 1\text{ G}\Omega$ can simply explain the slope observed in the Fig. 1.21.

Above V_{BD} , photo generated carriers and thermally generated carriers can initiate an avalanche, multiplying the observed current by a factor of $10^6 - 10^7$, so that the observed current increases very rapidly above the unmultiplied, surface current. As a first approximation for V_{bias} just above V_{BD} , current is proportional to second power of V_{bias} , because both gain and detection efficiency for the dark count increase linearly with V_{OV} . The two different regions can be separately fitted with polynomial curves and V_{BD} can be determined by intersection of interpolations.

At a given temperature, V_{BD} depends on the profile of dopants forming the pn -junction. Fig. 1.22 shows the reverse IV of two SiPMs with different dopant profiles.

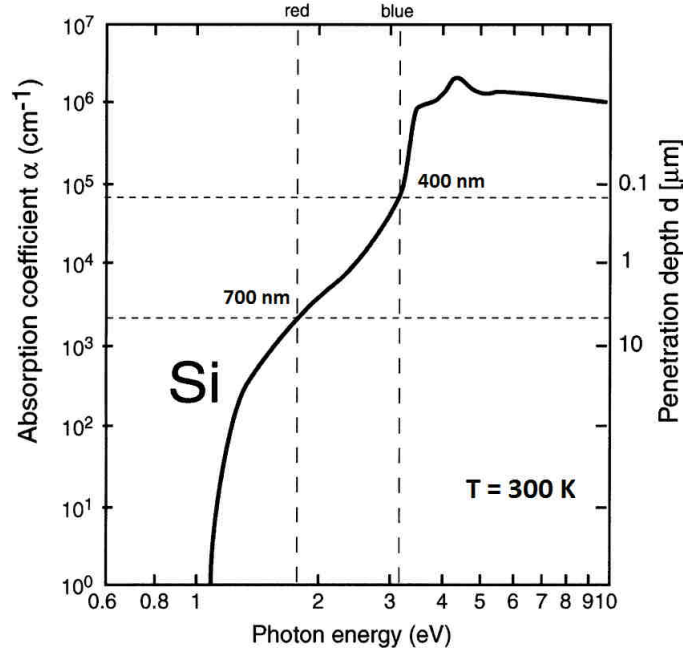


FIGURE 1.20: Absorption coefficient as function of photon energy for silicon at room temperature. The visible range from 700 nm to 400 nm is highlighted. Picture taken from [86]

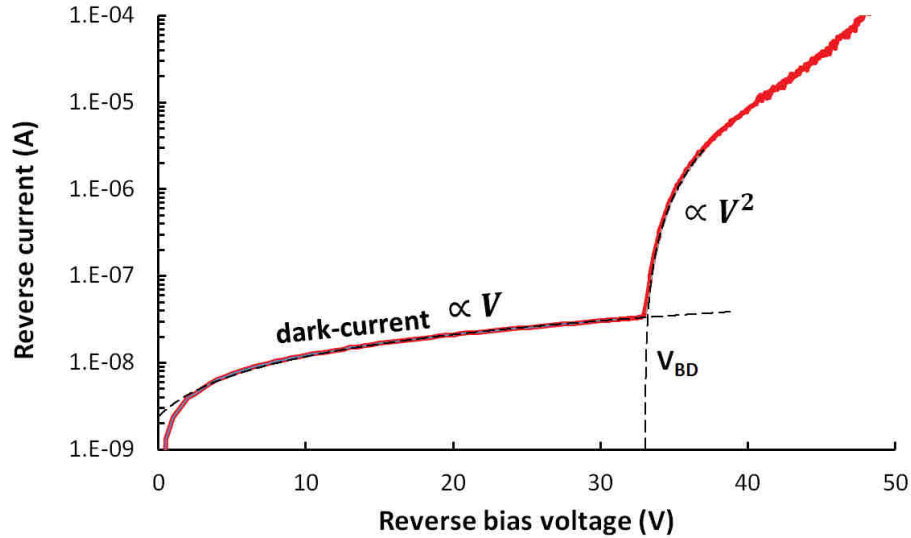


FIGURE 1.21: Reverse IV of SiPM-LF of 1 cm² area in dark condition at room temperature

In this particular case, dopant profiles were modified to reduce the peak amplitude of the electric field in the high-field region, where multiplication of carriers takes place. With deeper dopant, the electric field at breakdown voltage has a lower peak value while, at the same time, a higher V_{bias} to reach breakdown condition. SiPM technology with deeper dopant has been developed by FBK for cryogenic application and is called low field (LF) technology. Other SiPMs with normal dopant profile

are called standard field (SF) [87].

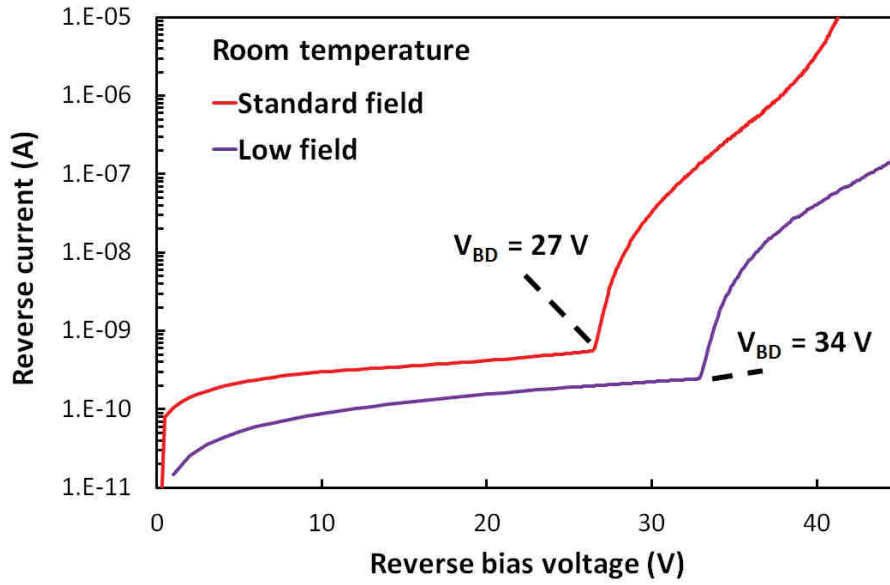


FIGURE 1.22: Reverse IV of two SiPMs (1 mm^2 area) are compared in dark condition at room temperature. SiPMs have different dopant profiles

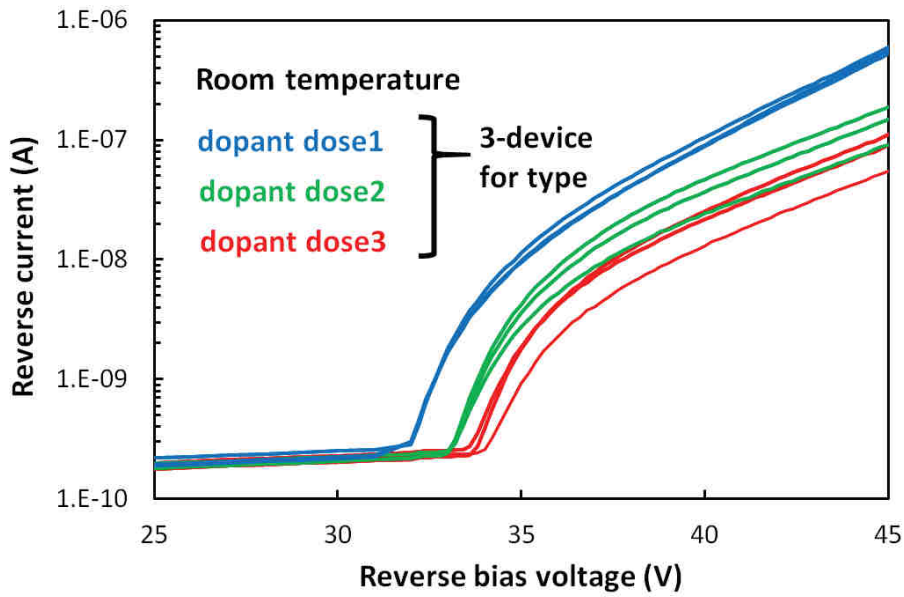


FIGURE 1.23: Reverse IVs are plotted in dark condition at room temperature for nine SiPMs-LF. Colours correspond to different dopant concentrations

Fig. 1.23 shows near breakdown region of reverse IV curves measured on different technology splits. Different colors correspond to different deeper dopant concentrations, while in Fig. 1.24, average breakdown voltage of Fig. 1.23 is plotted

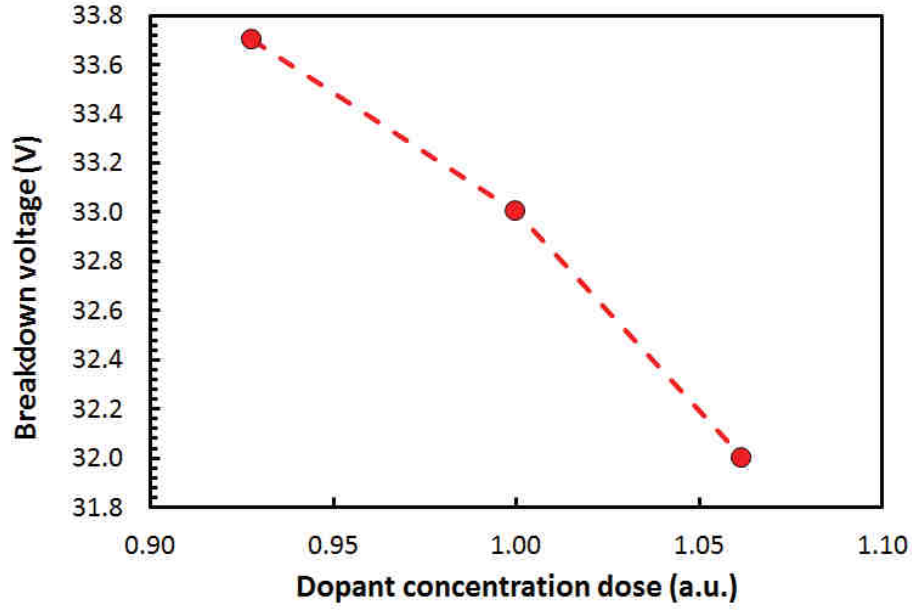


FIGURE 1.24: Breakdown voltage at room temperature depends on dopant concentration.

as function of dopant dose. At the same dopant depth, higher dopant dose reduces depletion region width, thus decreasing V_{BD} [65].

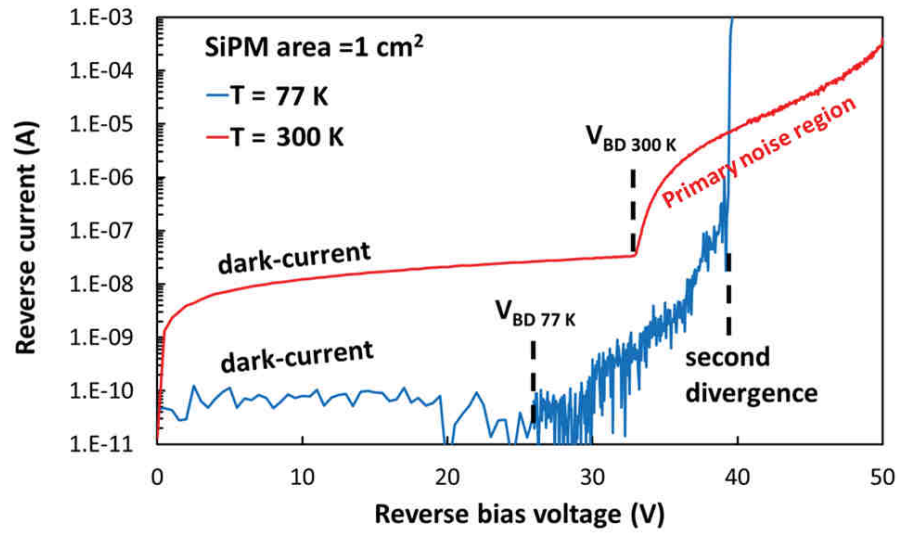


FIGURE 1.25: Reverse IV s of a SiPM-LF with area of 1 cm^2 are made in dark condition at room temperature and at LN temperature

In Fig. 1.25, reverse IV are shown at 300 K and at 77 K of the same SiPM with LF technology. Obvious differences exist between two temperatures:

- If $V_{bias} < V_{BD}$, the dark current is lower than the measurable minimum current of instrument at 77 K

- If $V_{bias} > V_{BD}$, the current grows slower at low temperature, because thermal generation is strongly suppressed with cooling.
- $V_{BD}(77\text{ K}) < V_{BD}(300\text{ K})$, this happens because the collective excitations of lattice atoms (phonons) decrease at lower temperatures, so carrier mean free path among collisions is increased. Consequently, carriers accumulate, on average, a larger energy among collisions under the effect of the electric field and, thus, have increased ionization probability per collision, that in turn, increases the efficiency of impact ionization [63].
- At lower temperatures with $V_{bias} \sim 40\text{ V}$, current has a second steep increase at high values of the bias, which we can define as "second divergence".

In this region, correlated noise dominates and quenching resistor can not longer quench avalanche. Different physical phenomena can create the second divergence:

- correlated noise probability approaching one. In this case, even a single initial avalanche can trigger a diverging number of avalanches which then explains the current divergence.
- the current limit defined by V_{OV}/R_q (see sec.1.3) is no longer low enough to effectively quench the avalanche. In this case, when a cell fires, the avalanche current never stops and SiPM current increases rapidly. Total current grows proportionally with $N_{cell} \cdot V_{OV}/R_q$, because, eventually, all cells are in avalanche condition, each one drawing a current limited only by the quenching resistor.

What it is the actual phenomenon responsible for the second divergence depends on which one of the two happened at lower V_{bias} . The V_{bias} of second divergence determines the maximum operating voltage ($V_{bias_{Max}}$) of the SiPM.

In Fig. 1.26, reverse IVs of SiPM-SF ($4 \times 4\text{ mm}^2$) are shown for different temperatures from 283 K up to 77 K.

IVs are plotted as function of overvoltage V_{OV} , which $V_{OV} = 0\text{ V}$ corresponds $V_{bias} = V_{BD}$.

If we consider a fixed bias voltage (V_{ref}) lower than $V_{BD}(77\text{ K})$, we can plot I_{dark} at different temperatures, as in Fig. 1.27. For $T < 220\text{ K}$, I_{dark} is too low to be measured, while it exponentially depends on the temperature for $T > 220\text{ K}$.

Maximum operating overvoltage range ($V_{OV_{max}}$) is given by equation:

$$V_{OV_{max}} = V_{bias_{Max}} - V_{BD} \quad (1.22)$$

$V_{OV_{max}}$ is particular importance at low temperature as demonstrated in Fig. 1.28. Indeed, for the standard field technology, it decreases from 13.3 V up to 3.3 V with

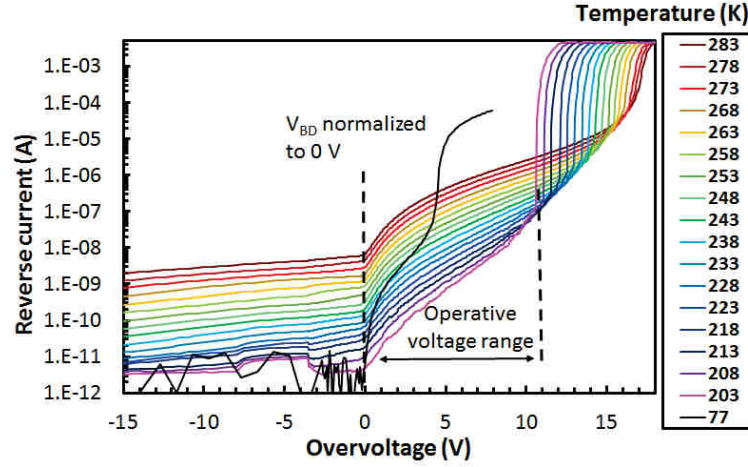


FIGURE 1.26: Reverse IV of a SiPM-SF with area of 16 mm^2 in dark condition, measured at different temperatures

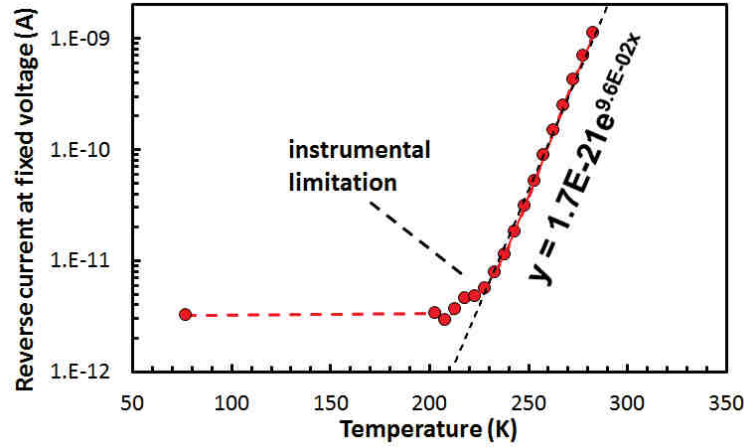


FIGURE 1.27: Dark current depending on temperature for a fixed bias voltage

decreasing of temperature from 280 K up to 77 K . This strongly limits the use of SiPM-SF at cryogenic condition.

To complete the overview of IV s, in Fig. 1.29 and in Fig. 1.30, forward IV s of the same SiPM-SF are reported at different temperatures from 310 K to 77 K . In Fig. 1.29, exponential current due to diode of cells is highlighted in log scale, while in Fig. 1.30, linear current due to quenching resistors is highlighted in linear scale.

The values of the microcell quenching resistor, calculated as explained in section 1.4, are shown in Fig. 1.31. The strong dependence on temperature of the value of the resistor is motivated by the fact that it is made of polycrystalline silicon, in which carrier transport across grain boundaries is heavily dependent on temperature. [88].

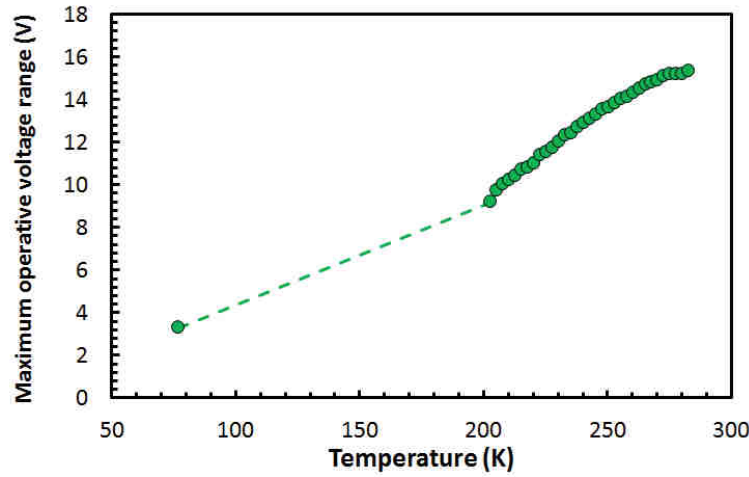


FIGURE 1.28: Maximum operating overvoltage as function of temperature of a SiPM-SF. Beyond this voltage value, current diverges and SiPM is completely useless

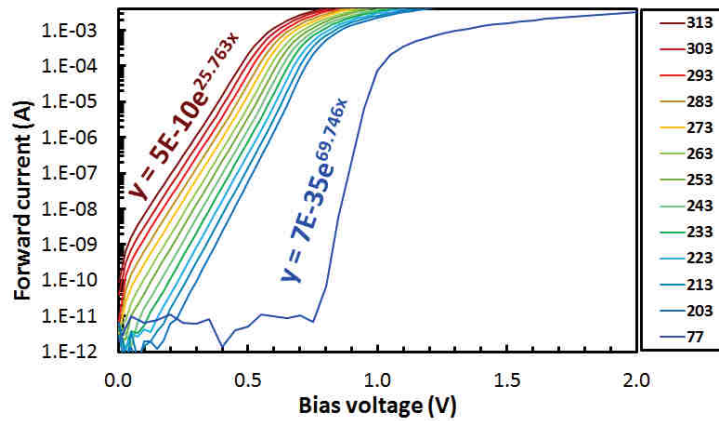


FIGURE 1.29: Forward IVs of a SiPM-SF depending on temperature, where exponential current is highlighted by log scale

1.8 Packaging

Usually, to use a SiPM it is necessary to package it on dedicated printed circuit board (PCB) as in Fig. 1.1 on the left. According to how the SiPM is built, there are different techniques to connect the two elements. The SiPM back side is commonly glued on the pad of the PCB using electrically conductive glue, such as silver-loaded epoxy. It is preferable to have the conductive pad area of the not larger SiPM dimension because this gives two benefit effects:

- to minimize the antenna effect for the electromagnetic interference EMI (or radio frequency interference RFI) generated by external source;
- to maximise the electric contact so it is able to reduce the parasitic series resistor.

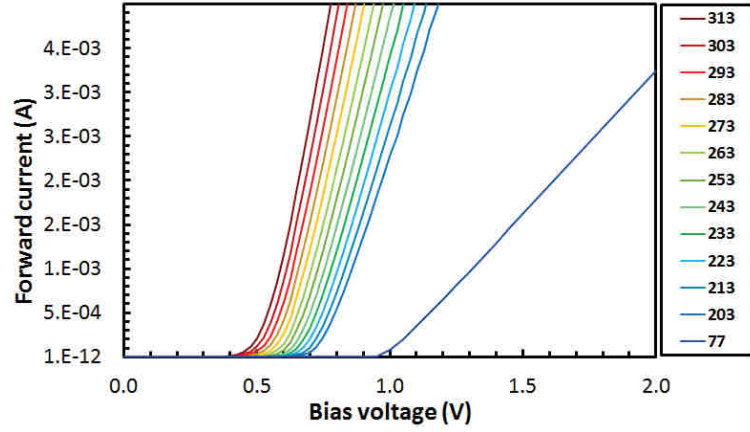


FIGURE 1.30: Same forward IVs of Fig. 1.29, where linear current is highlighted by the linear scale

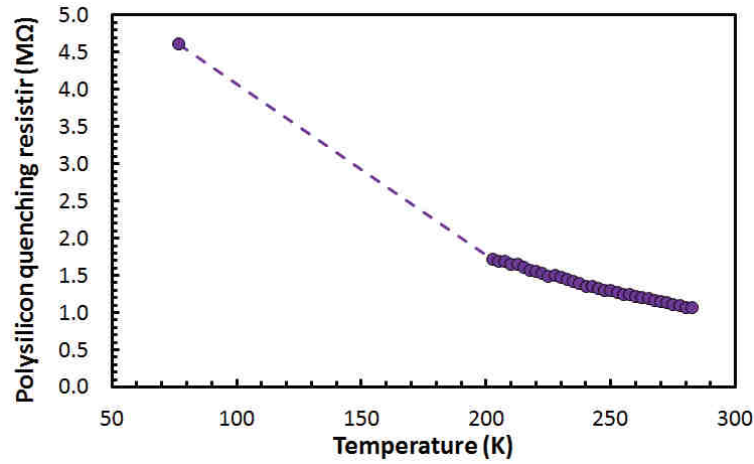


FIGURE 1.31: Average value of quenching resistor as function of temperature

Another important issue is the type of glue used to fix and connect the SiPM with the PCB. The main features of the glue are the electric conductivity and the strength of adhesion; in cryogenic application, however, the thermal conductivity coefficient, the minimum temperature of adhesion (if existing) and the thermal expansion coefficient are equally important. These glues are often bi-components epoxy loaded with silver nanoparticles that must be mixed in accurate proportions and cured at temperature up to 150 °C [89][90].

On the SiPM top side, where the connection between SiPM and PCB is typically made using two types of techniques very common in the microelectronic industry:

- The ball bonding technique [91][92]. It is a wire bonding technique widely used to connect semiconductor devices with fine pitch down to tens microns. Usually, the wire is made of gold with a diameter of 12.5 μm or more [93]. The

ball bonding uses the thermocompression (T/C) and the thermosonic (T/S) joining methods. Fig. 1.32 illustrates phases of this process; starting from the upper left, at the beginning an electric spark melts the wire head on the isolated capillarity tip of bonding machine to create a gold ball. In the upper right, the device pad that has to be bonded is heated up to about $100 - 150^{\circ}\text{C}$. Then the machine tip touches the device pad surface and generates pressure and ultrasonic vibrations through the capillarity tip for an amount of time; this process deforms the ball. The first inter metallic bond between the wire and the device pad has thus been created. In the lower right, the bonding machine positions the tip on the second device pad and combines again heat, pressure and ultrasound to generate a wedge bonding connection [94]. This second bonding is different from the first ball bonding because the wire is pressed into a flat elongated shape like a wedge Fig. 1.32.

- The wedge (or wedge-wedge) bonding technique [95][96] is very similar to the ball bonding considering its range of fine pitch applications. Using this method, the first bonding is also a wedge type. There are other difference: for example, as in the ball bonding technique the first step is to create a starting spark in order to generate a initial ball, with the wedge bonding it is not necessary to repeat this step every times. Furthermore, the wedge bonding can be operated at room temperature or at ball bonding temperature. Usually, the aluminium (sometimes the gold) is used for the wire. In the end, the wedge bonding allows more sophisticate bonding compared to the ball bonding, but in the industrial application it proves slower [97].

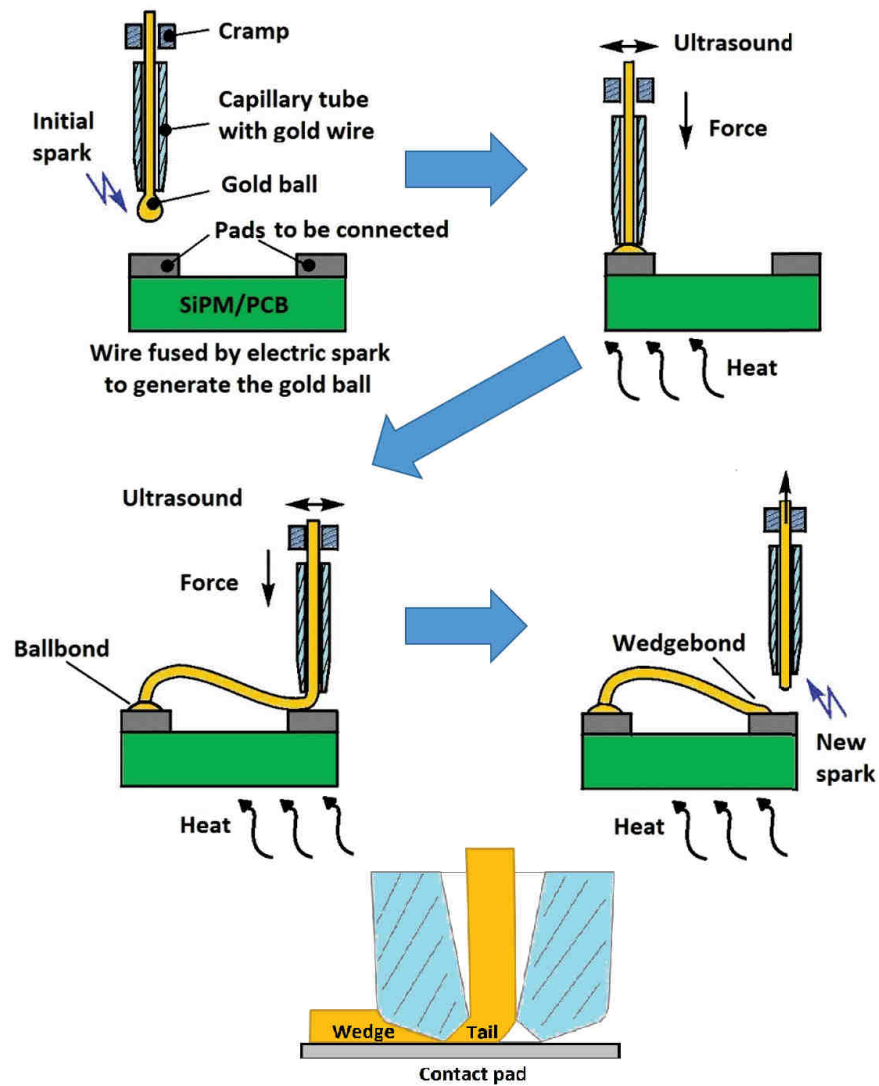


FIGURE 1.32: On the top, the four fundamental steps to realize a ball bonding contact. Picture taken from [98]. Lower, detail of the wedge bonding step of Fig. 1.32

Chapter 2

Experimental setup

Every time that a new lot of SiPMs is fabricated, all main features of the SiPM must be characterized. This procedure is necessary to guarantee the performance and the uniformity of the devices by the manufacturer. It is also the only way to test new technologies and to compare with the models and the simulations. In this chapter we will describe the main experimental setups used to characterize the single SiPM, in particular, those used in the IRIS (Integrated Radiation and Image Sensors) group. IRIS is a team of physicists and electronic engineers. Working on the development of custom solutions for solid-state detectors like SiPMs and silicon drift detectors [50].

First, I will describe the experimental setup for the dynamic characterisation in the dark, where signal analysis of waveform is used to measure noise parameters of SiPMs. In particular, I will focus on the solutions implemented to be made on the hardware and on the analysis software to work cryogenic conditions.

The second part will be dedicated to the PDE (Photon Detection Efficiency) setup. I will also briefly discuss the new custom cryo-setup in which it will be possible to carry out the first cryogenic characterisation of PDE at FBK.

At the end of the chapter, I will describe the setup for capacitance-frequency characterisation.

2.1 Dynamic characterisation in the dark

The first step for characterizing a SiPM is to package it on a PCB adapter (see section 1.1). Afterwards, a complete IV is done to check its basic behaviour.

Fig. 2.1 shows the setup used to characterize SiPMs in the dark. The SiPM is placed inside a thermostatic chamber which, in addition to being dark, maintains stable environmental conditions like temperature and humidity. The chamber that was used has an temperature operating range from -70°C to $+90^{\circ}\text{C}$. Normally, humidity is set to 40 % relative humidity.

The SiPM is electrically connected to a two-stage amplifier placed inside the chamber so that the connection between SiPM and input stage of the front-end is the shortest possible to reduce external interferences and to optimize performance. The amplifier is composed of two stages. The first stage is a trans-impedance amplifier

(TIA) or current to voltage converter. The second stage is an inverting-amplifier. The operational amplifiers are the *AD8099* (voltage feedback, high speed and ultra low noise [100]) for the first stage and the *AD8000* (current feedback, high speed and low noise [101]) for the second stage. They have an operating temperature range from -40°C to $+125^{\circ}\text{C}$. Their total gain is between 1 kV/A and 5 kV/A depending on the SiPM size and the cell size.

The amplifier is biased by an external power supply. The SiPM is biased by a precision power supply controlled by a computer. The signal output of the amplifier is read by an Infiniium 9000 Series oscilloscope. The oscilloscope has a bandwidth of 1 GHz with maximum sampling rate of 20 GSa/s and temporary memory of 100 M points on a single waveform. The re-arm time of $4.5\text{ }\mu\text{s}$ (minimum time between trigger events) is important at cryogenic temperatures [102], as shown later.

The oscilloscope samples the data and transfers them to the computer. The connection takes place through an ethernet cable. Thanks to the real-time analysis software developed by FBK, it is possible to measure parameters like the DCR, AP, DiCT, DeCT, cell gain, recharge time constant, signal amplitude and excess charge factor (ECF). The procedures and the methodologies of this software are described in [99].

To perform measurements below -70°C a dewar provided by Laboratorio Nazionale del Gran Sasso (LNGS) has been used. It substitutes the thermostatic chamber in Fig. 2.1.

2.1.1 Cryogenic stage-amplifier

Experimentally, the *AD8000* operational amplifier operate at -70°C while no longer operate at the liquid nitrogen temperature, the effective turning off temperature is within temperatures range does not achievable by setup. In particular, *AD8000* does not absorb current. Without knowing its exact the internal circuit topology, we can only suppose that some internal MOSFETs (metal-oxide-semiconductor field-effect transistor) of the internal bias do not turn on [103].

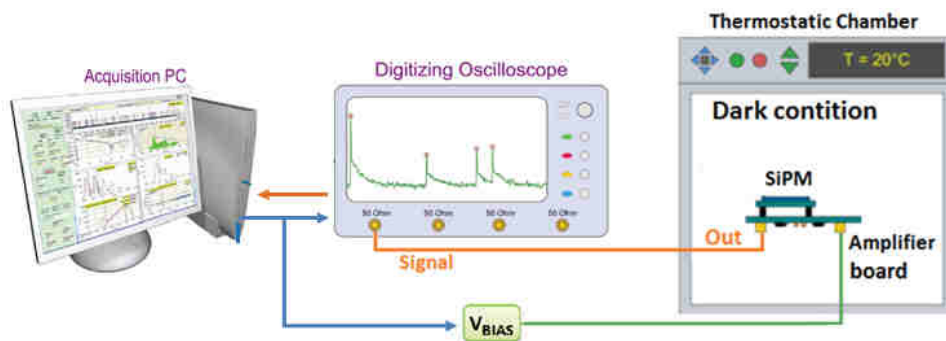


FIGURE 2.1: Setup used to characterize SiPMs in dark conditions and at constant temperature. Original figure taken from [99]

I have compared different operational amplifiers (OPA), choosing the *LMH6629* manufactured by *Texas Instruments* [104]. The *LMH6629* is realized with *SiGe* processes to build with the bipolar complementary metal oxide semiconductor (BiCMOS). The *SiGe*-BiCMOS devices are used in space and in cryogenic applications thanks to their low susceptibility to low temperatures [105]. The *LMH6629* is a high-speed, ultra-low noise amplifier with -3 dB bandwidth of 900 MHz and $1600\text{ V}/\mu\text{s}$ of slew rate. It has a low-input noise $0.69\text{ nV}/\sqrt{\text{Hz}}$ and $2.6\text{ pA}/\sqrt{\text{Hz}}$ [104].

Passive as well as active components change their characteristics with the temperature. Commercial passive components like capacitors and resistors can be realized with different technologies. Depending on the application, a building technology is preferred over to another according to the dependence on temperature (T) and on frequency (f) of the resistance and the capacitance, the operating range in T and in f , the insulating properties of the packaging and, especially for capacitors, the maximum working voltage and the equivalent series resistor (ESR). Generally, the operating temperature range of a devices is given from -40°C to 100°C (-55°C to 125°C for military applications). For this reason, in order to work at cryogenic temperatures it is often necessary to research for different solutions. A study for commercial resistors is presented in [106].

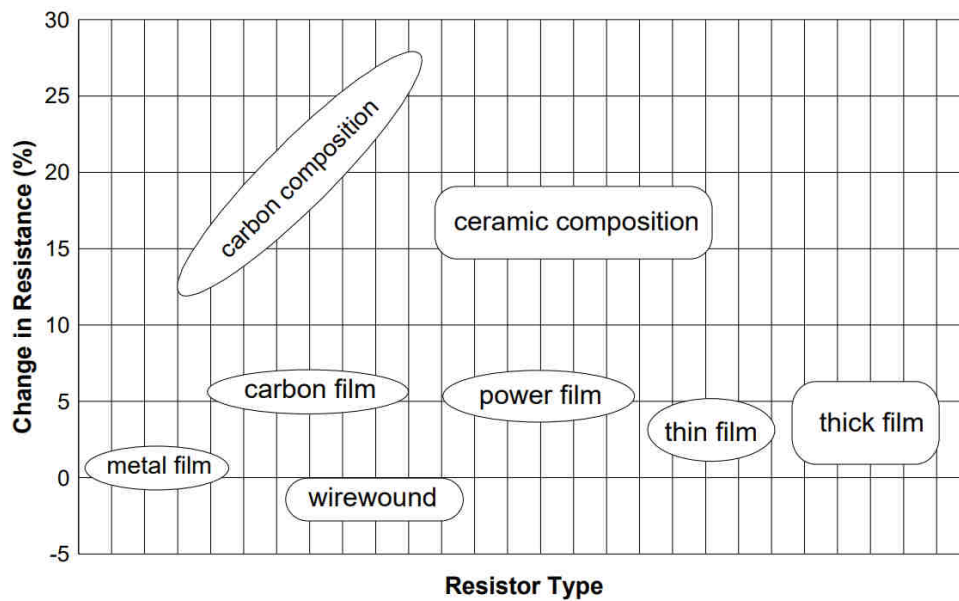


FIGURE 2.2: Percent variation of the resistor value between the value measured at room temperature and the value measured at -190°C . The variation of the values are shown for the main commercial resistor types. Original figure taken from [106].

Fig. 2.2 shows the percent variation of the values measured at room temperature

and at -190°C . The main commercial resistor types are shown. The best performance is given by the metal film followed by the thin and thick film and the wire-wound types. The thin and thick film types are chosen for their small dimension and for the SMD packaging (Surface-mount technology) compatible with fast electronic applications.

Capacitor type	Measured capacitance (100 nF at 300 K)		f \ T	Measured ESR		
	77 K	4 K		300 K	77 K	4 K
X7R ceramic	21.3 nF	3.4 nF	1 kHz	76 Ω	574 Ω	5.6 M Ω
			10 kHz	1.5 Ω	64 Ω	400 k Ω
			100 kHz	0.3 Ω	7.6 Ω	62 k Ω
Y5V ceramic	1.8 nF	0.9 nF	1 kHz	93 Ω	3940 Ω	3910 Ω
			10 kHz	1.8 Ω	410 Ω	360 Ω
			100 kHz	0.6 Ω	50 Ω	40 Ω
NPO ceramic (NPO/COG/COH)	100.2 nF	99.7 nF	1 kHz	2.1 Ω	2 Ω	3 Ω
			10 kHz	0.3 Ω	0.4 Ω	0.1 Ω
			100 kHz	0.2 Ω	0.02 Ω	0.05 Ω
Polyester	71.8 nF	15.3 nF	1 kHz	42 Ω	37 Ω	340 Ω
			10 kHz	1.8 Ω	40 Ω	36 Ω
			100 kHz	0.8 Ω	19 Ω	18 Ω
PPS	92 nF	83.2 nF	1 kHz	21 Ω	4.4 Ω	3.1 Ω
			10 kHz	1.1 Ω	0.2 Ω	0.25 Ω
			100 kHz	0.2 Ω	0.02 Ω	0.3 Ω

TABLE 2.1: Synthesis of the capacitances and the ESRs measurements at 300 K, 77 K and 4 K. Original figure taken from [107]

A real capacitor always shows the presence of parasitic components. Depending on the working frequency and the technology, the electric net of parasitic components can be more or less complex. Usually, the capacitor is represented by capacitance in series with an ESR.

In [107] the capacitances and the ESRs of the main commercial types of SMD capacitors have been measured. Between 3 – 14 capacitors per type have been used, with different nominal values. Values were then normalised to a 100 nF reference at 300 K. Measurements have been taken at 1 kHz, 10 kHz and 100 kHz of frequency and at 300 K, 77 K and 4 K of temperature. In table 2.1 the average values are reported. The best performances are given by the capacitors with ceramic dielectric of COG or NPO type. At 77 K the capacitance changes only by 0.2 % between 300 K and 77 K, while at 77 K the ESR decreases by a factor 10 at high frequency. Moreover, the COG or the NPO types are the commercial capacitors with the lowest tolerance (typically 5 %). Consequently, these types of capacitors are the first choice for our cryogenic amplifier. The inconvenience is due to the commercially available capacitance values, usually lower than 1 μF . Capacitances greater than 1 μF are typically used to filter the bias supply, for which high capacitance stability and low ESR are not required. Therefore, capacitors with X7R dielectric have been used as filtering capacitances. The X7R type capacitors experience a capacitance reduction of about

a factor of 5 at 77 K, but are commercially available with capacitance values of up to 220 μF .

In Fig. 2.3, the schematics full version of the cryogenic stage-amplifier realized in the IRIS research unit is reported. It is a single-stage trans-impedance (TIA) amplifier.

The resistor $R1$ takes back the operational amplifier (OPA) output to the input of the OPA. Thus creating the voltage feedback necessary for the OPA to operate.

The LMH6629-OPA has been chosen in the WSON – 8 package because it gives the possibility to choose the type of compensation. It has either internal auto-compensation or external. It can be switched by the low or high level of the COMP pin. The circuit can be switched in both cases through resistors $R9$ and $R10$ with value 0ω . If the level is high the internal compensation is turned off. This mode increases the bandwidth but also increases the instability of the OPA. For this reason it is necessary to increase the minimum gain [104].

The OPA is used in external compensation mode. Therefore, it is necessary to introduce C_1 in series with R_7 at the inputs of OPA as suggested by the manufacturer. Unfortunately, the formula provided for compensating the OPA is not valid at cryogenic temperatures. Moreover, the *PSpice* simulations are not reliable in cryogenic conditions. An alternative solution is a systematic experimental tuning of C_1 and R_7 .

Fig. 2.4 shows an example of this procedure done at 77 K. It shows the output noise spectrum, measured in closed loop configuration at the output of the circuit. The measurement has been done with a SiPM biased just under the V_{BD} and with 0.5 cm^2 of area, to match the capacitance as closely as possible to the working case, but without SiPM signals during fast-Fourier transform (FFT) measurements. Fixing the other parameters the Fig. 2.4 shows the baseline response depending on the C_1 value. Neglecting the tight peak due to the external disturbances in the radio frequency, it is possible to draw some conclusions. The spectrum has a resonance that changes with the value of C_1 . In particular, it changes the amplitude, the width and the resonant frequency. The resonance depends on the overlap in the Bode diagram between the reverse feedback β function and the open-loop gain of the OPA. Decreasing the C_1 value from 29 pF to 1.5 pF, the resonance shifts toward high frequency, reducing the amplitude and increasing the width. Ideally we want a flattening of resonance at the highest frequency possible. In the case of Fig. 2.4, the best condition is achieved with a C_1 of 1.5 pF. For values smaller than 1.5 pF the resonance moved to low frequencies where the flat baseline grows.

Resistors $R2$ and $R6$ have a stabilization function. Experimentally, we have seen that adding $R6$, it is possible to reduce instability oscillations of OPAs used with voltage feedback.

The $R2$ has an important role because beyond a specific frequency f_{IN} (eq.2.1 in the simple case in which $R6$ is infinite) the circuit behaves like a standard, inverting

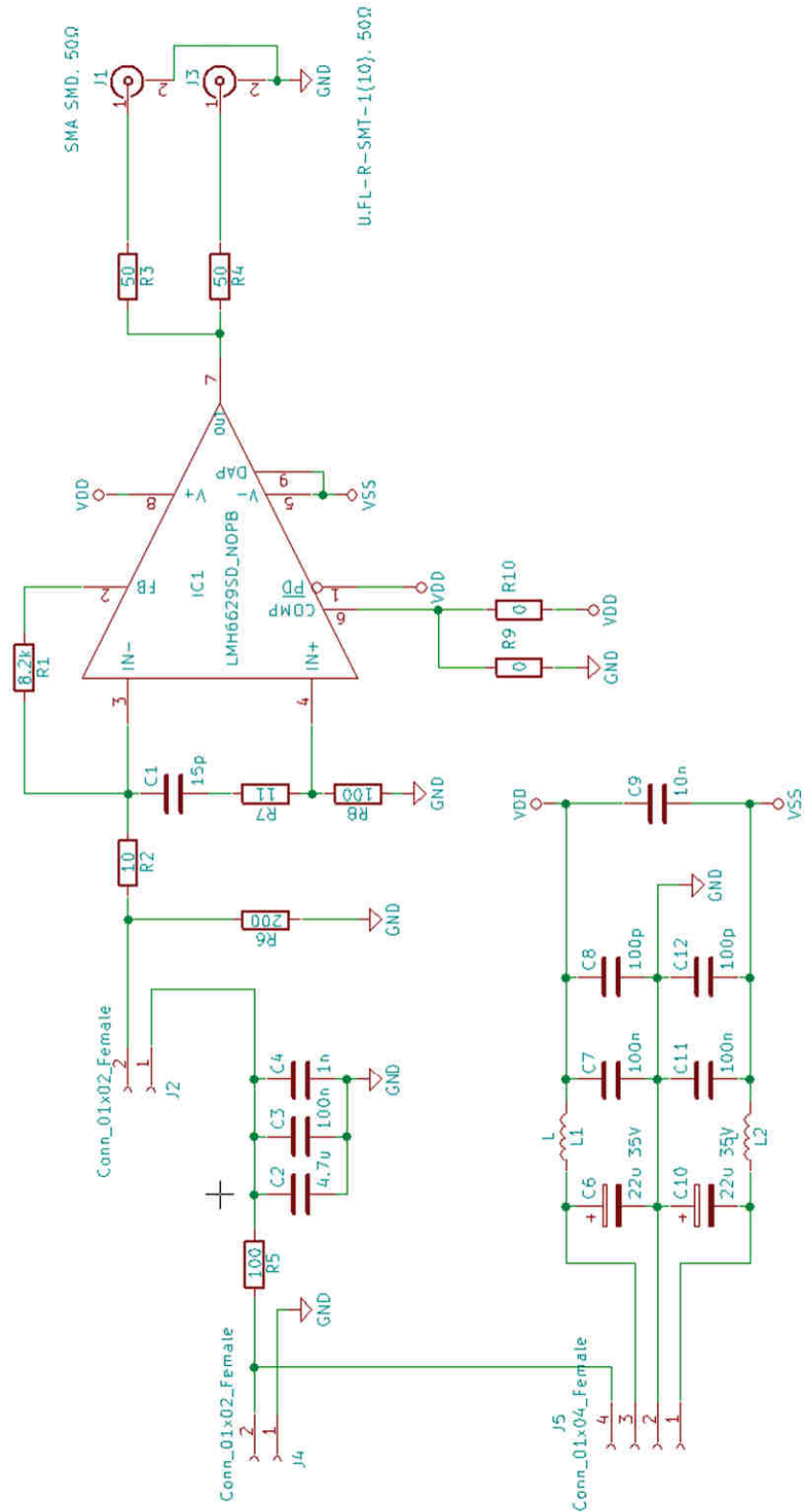


FIGURE 2.3: Full electric circuit of the single-stage trans-impedance amplifier. It is realized during my PhD to work at cryogenic temperatures. The component values are only indicative.

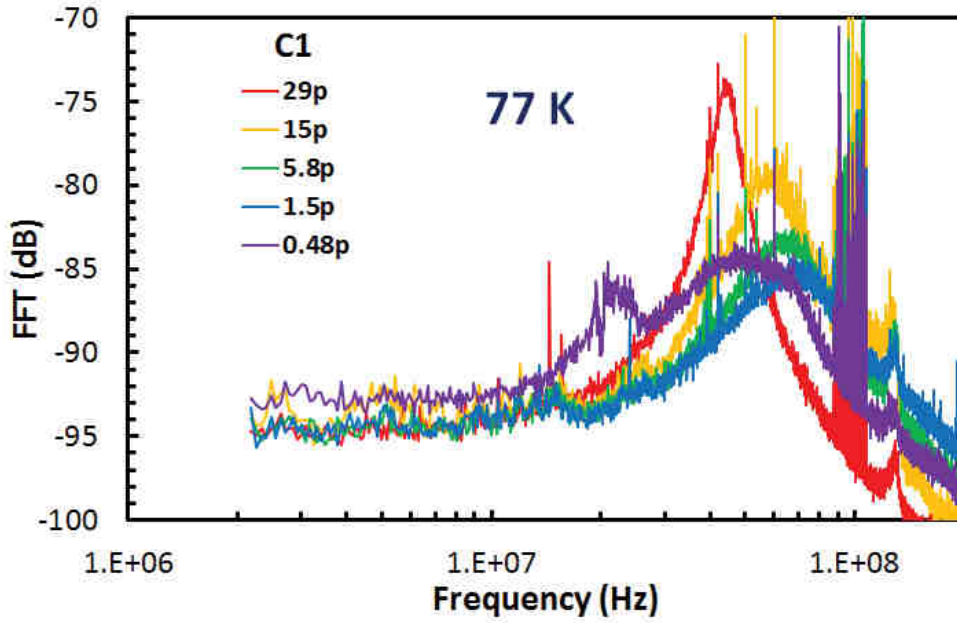


FIGURE 2.4: Example of external compensation through the C_1 tuning of Fig. 2.3 at 77 K. The plot shows the *FFT* of the baseline output of the stage-amplifier for different C_1 values

configuration [49]. This is greatly advantageous because the bandwidth scales linearly with the gain bandwidth product (GBP), while for an ideal TIA the bandwidth scales as $\sqrt{GBP}$ [49]:

$$f_{IN} = \frac{1}{2\pi C_D(R_{eq} + R_2)} \quad (2.1)$$

The benefits of R_2 and R_6 are paid with a major noise on input of the *OPA*.

The resistor R_8 has the function of direct-current (DC) offset compensation. Usually the R_8 value is given by the value input of the $IN -$ pin. That it is dominated by the parallel $R_2 || R_6$.

The *OPA* bias has the capacitors C_6, C_7, C_8 and the inductor L_1 that form a low-pass π -filter between the positive bias and the ground. An equal filter is made by C_{10}, C_{11}, C_{12} and L_2 between the negative bias and the ground. While the resistive parts on the two sides of the two filters are given by the impedance of the power supply and of the *OPA* respectively.

The resistor R_5 with C_2, C_3 and C_4 forms a low-pass filter for the SiPM bias.

There are two types of commercial output connectors for RF application, the UFL-SMT and the SMA-SMD. The connectors are chosen through the resistor R_3 or R_4 .

In Fig. 2.5, we show the 3-dimensional model, the footprint layer and the metal tracks layer of the cryo-amplifier. It has been drawn with the components only on a single side to maximize the thermal contact area for the cryostat-setup. A complete

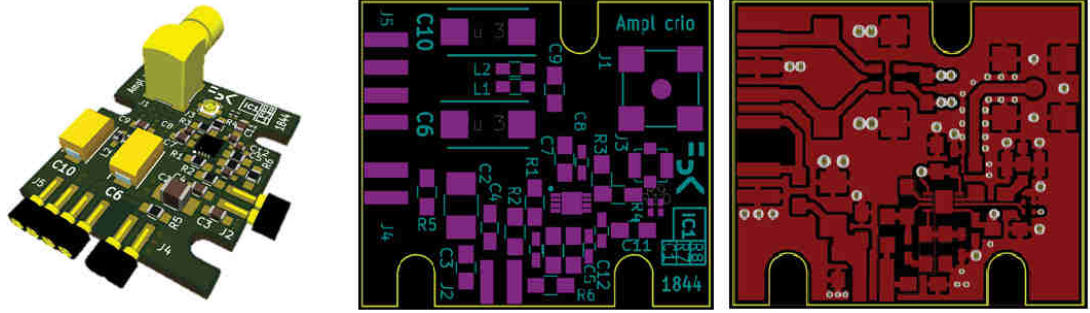


FIGURE 2.5: On left the 3 – D layout of the stage-amplifier on the components side. In the center the component footprints layer and on the right the metal tracks and mass layer

characterization of amplifier is still missing depending on temperature and different SiPM sizes, that it should be made in the near future.

2.2 Analysis software

Thanks to the experience in the SiPM field, the IRIS group has developed a noise analysis software able to characterize the productions of the SiPMs. The software is written in *LabVIEW* (Laboratory Virtual Instrument Engineering Workbench). *LabVIEW* is a development environment for a visual programming language (it is called graphic-language or G-language) from National Instruments.

Usually it is used in the industrial automation for data acquisition, analysis and process control.

The analysis software has been written in *LabVIEW* for its compatible of the FBK laboratory instruments. The software algorithm is described in [99]. In this section we illustrate the working principle of the analysis software and the changes carried out during this thesis work to make it able to operate at cryogenic temperatures.

After the preparation of the setup illustrated in section 2.1, we obtain a typical voltage signal as shown in Fig. 1.17.

In total darkness condition, the first two signals supposedly are DCR events because they have the same amplitude. Moreover, two AP events can be distinguished by their lower amplitudes and by their proximity to the previous event. At the end of the acquisition window a DiCT event is visible, as outlined in the figure.

The average signal generated by a SiPM cell when an avalanche is triggered, also defined as Single Cell response (SCR) depends on different parameters: It depends on SiPM properties like cell gain and recharge time constant τ_{RC} , and on external conditions, such as bias voltage, temperature and amplifier features. In Fig. 2.6, it is shown an example of SiPM signals for different cell sizes, measured at same temperature, overvoltage V_{OV} and R_q . Parameters that change between signals are

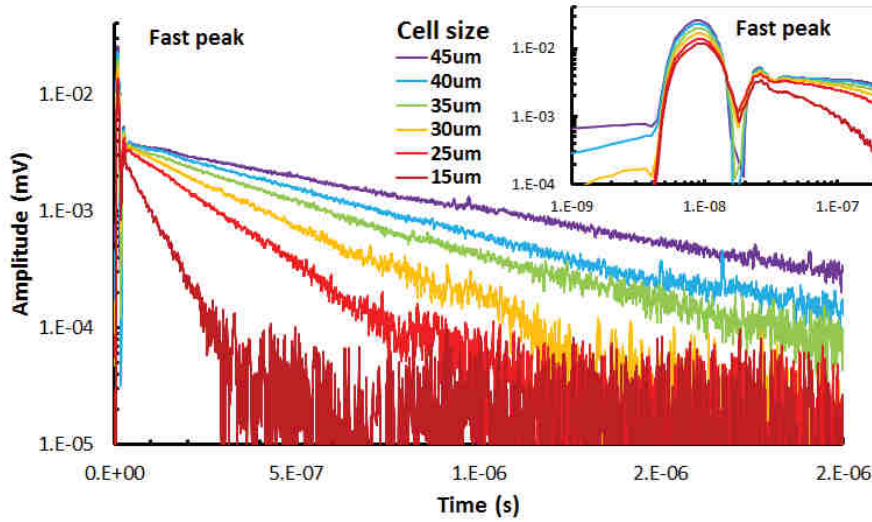


FIGURE 2.6: The characterization of the firing cell signals for different cell sizes at 77 K with the same R_q ($6.5 \text{ M}\Omega$) and the same V_{OV} (5 V). In the inset the fast peaks are highlighted in double log scale

recharge tau τ_{RC} (because cell capacitance changes), fast peak amplitude (increases for larger cell size because capacitance of R_q increases due to layout) and hole depth between the fast peak and the cell recharge phase.

Therefore to analyse a signal as the one in the Fig. 1.17, the software should be able to separate the single events in different conditions, in particular, when two events are triggered at a very short time distance. To this purpose, we employ a type of analog filtering, called DLED (Differential Leading Edge Discriminator) algorithm, that it is described in [108].

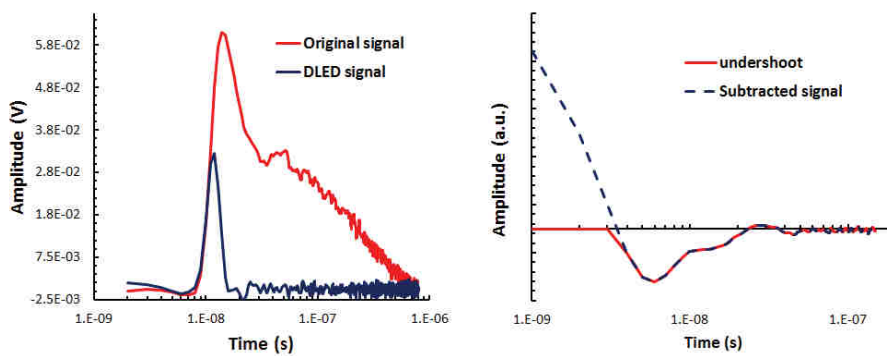


FIGURE 2.7: On the left the original signal of a firing cell signal is compared with its DLED filter signal. On the right the undershoot signal that is used to compensate for the subtraction of the signals

The DLED uses the fast rise time of the initial part of the signal belonging to each firing cell (see the inset of Fig. 2.6). The DLED essentially works as an efficient high pass filter.

We can write the acquired signal as $S(t) + s_{BS}(t)$, where $S(t)$ is the firing cell signal and $s_{BS}(t)$ is the baseline with approximately constant average value.

If the signal is shifted by time t_{DLED} lower than the signal rise time, the subtracted signal $S_{SUB}(t)$ can be obtained by eq.2.2.

$$S_{SUB}(t) = [S(t) + s_{BS}(t)] - [S(t - t_{DLED}) + s_{BS}(t - t_{DLED})] \sim S(t) - S(t - t_{DLED}) \quad (2.2)$$

Typically, the subtracted signal is composed of a fast peak plus a negative part, $U(t)$, that depends on the SiPM properties and the amplification chain. The slower recharge tail of the signal is almost completely cancelled by DLED filter. Initially for each new acquisition, analysis software measures and averages the undershoot ($\overline{U(t)}$) of n -signals, while during acquisition, $\overline{U(t)}$ is subtracted for each event identified by DLED.

As an example of DLED application, on the left of the Fig. 2.7 the raw signal of a firing cell with its equivalent DLED signal with subtraction of average undershoot is shown, while on the right of the Fig. 2.7 the typical undershoot is shown.

If DLED is applied to all signals, we obtain a waveform only composed of symmetric, fast peaks, where the peak amplitudes are proportional to those of original signals.

In this condition, for a peak finder algorithm it is easier to search for the peaks and to calculate the time distance between two consecutive events in different situations because if the SiPM type or the external conditions change, the peak shape of the DLED signal does not change; only the amplitude and the width of the peak change.

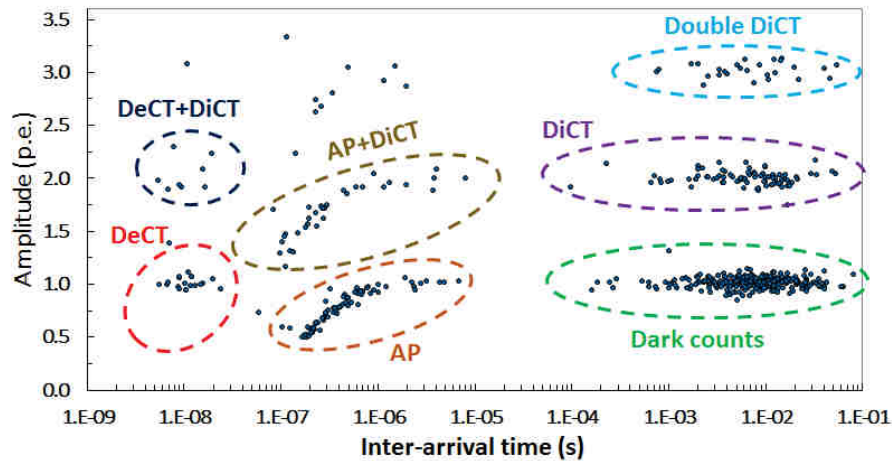


FIGURE 2.8: Scatter plot of a SiPM with an area of 1 mm^2 at -70°C . The different sources of SiPM noise are highlighted.

With the analysis of hundreds of signal windows like that of the Fig. 1.17, we obtain the scatter plot of the signals, like the one shown in Fig. 2.8.

Each event is represented by a point and its amplitude is normalised to that of the SCR (or the equivalent single photo-electron event *p.e.*). The events are plotted depending on their time distance from their previous event.

The main noise sources (DCR, AP, DiCT, DeCT and combinations of these) are clearly visible in the scatter plot. The DCR events have an average amplitude of 1 *p.e.* and their time distribution follows the Poisson distribution. The AP amplitudes go from 1 *p.e.* down to 0.5 *p.e.* only because signals below 0.5 *p.e.* are cut to limit triggering on the electric noise. The AP time distribution depends on the quenching resistor and on the presence of trapping centers for carriers in active volume of SPAD. The DiCT events retain the same, Poisson distribution of the primary event. Indeed, DiCT due to DCR events follow a Poisson distribution with double pulse amplitude. Similarly, DiCT events from AP events follow the AP time distribution with amplitudes from 2 *p.e.* down to 1 *p.e.* The DeCTs have amplitude of about 1 *p.e.* and a time distribution between a few *ns* a few tens of *ns*, depending on the lifetime of minority carriers in the neutral region around the depletion region of SPADs. The DeCTs are not always visible because depending on condition of measure they can be interpreted as DiCT events. To read large SiPM and operate at cryogenic temperatures can limit amplifier bandwidth, consequently, DLED has difficulty to separate very short time distances as DeCT events.

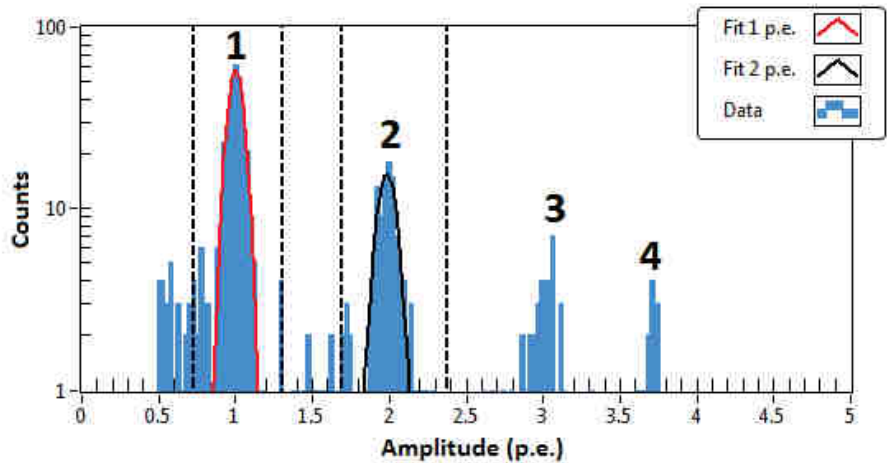


FIGURE 2.9: Amplitude histogram of the data in Fig. 2.8. The highest peak is due to the single firing cell signal. From second to fourth peak, we have single, double and triple events of DiCT respectively

Qualitative observation of the scatter plot can immediately give indications on possible anomalies.

To get quantitative information about the SiPM noise types, the scatter plot is projected along one of its axis. If it is projected along the amplitude axis (Y-axis) we obtain the histogram of the normalized amplitudes as in Fig. 2.9.

The highest peak in Fig. 2.9 corresponds to the sum of all the single cell events(DCR, AP and DeCT). The second peak corresponds to the sum of all the double single cell events that happen simultaneously and so on. The tails on the left of the peaks are the AP events with their amplitudes lower of 1 *p.e.* and 2 *p.e.* respectively.

In darkness and low rate of DCR (away from non linearity of SiPM), DiCT probability $P_{DiCT}(\%)$ can be estimated by the eq.2.3

$$P_{DiCT}(\%) = \frac{A_2}{A_1} \quad (2.3)$$

with A_1 and A_2 that are the areas of the first and the second peak respectively. Except for the tails of the AP, the peak distributions can be considered Gaussian. Therefore, A_1 and A_2 are calculated by the integration of the individual Gaussian fits (eq.2.4). These fits are delimited by the bars in the positions $p_1^{1,2}$ and $p_2^{1,2}$ as in Fig. 2.9.

$$A_n \approx \int_{p_1^n}^{p_2^n} a \exp\left(-\frac{(p-b)^2}{2c^2}\right) dp \quad n = 1, 2 \quad dp = \text{bin size} \quad (2.4)$$

As a first approximation, we can assume that DiCT probability uncertainty (ΔP_{DiCT}) is given by the propagation of area errors. In the end, the area uncertainties are given by the propagation of the Gaussian parameter (a,b and c) errors on the integrals. The uncertainty on the fits includes the contributions due to the position of the bars.

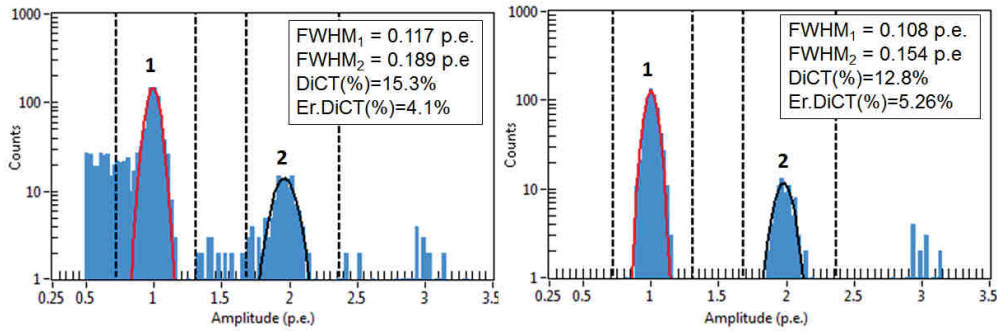


FIGURE 2.10: On the left, the amplitude histogram of a SiPM with high AP and with the main parameters in the square. On the right, the same data set but with a time distance cut-off on the AP events. The measurement has been done at 77 K and on a SiPM with an area of 1 mm²

A problem that I encountered during the characterisation at cryogenic temperatures is that the AP tends to dominate. High AP probability worsens the estimate of DiCT because AP with lower amplitudes creates an asymmetry of peaks in the

amplitude histogram. The asymmetry increases the full width at half maximum (FWHM) from which the areas depend. This fact introduces a systematic error that depends on the AP probability.

The solution that I implemented is a time distance cut-off of the scatter plot on the data that are used to build the amplitude histogram. The cut-off is chosen on the basis of where the AP amplitudes start to decrease in the scatter plot.

In Fig. 2.10 there is an example of the amplitude histograms with the same data set. On the left there is the standard analysis. On the right there is the analysis with the cut-off. With cut-off, the uncertainty on DiCT increases because of decreasing of statistic. On the other hand, with cut-off, the FWHMs are lower and the asymmetry is suppressed systematically. Therefore, the systematic error due to the AP on the DiCT measurement is removed. Cut-of can be used especially at cryogenic temperatures because AP and DCR are well separate.

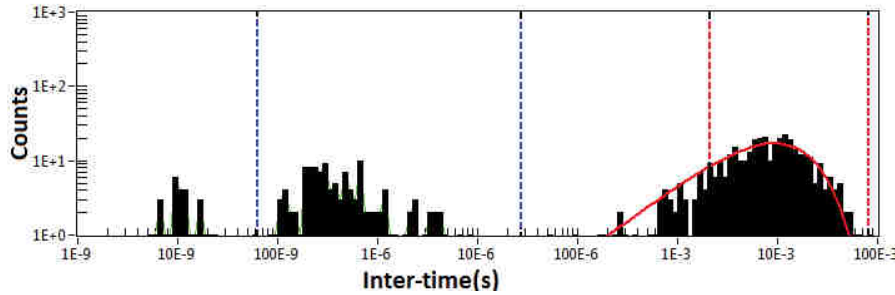


FIGURE 2.11: Time distance histogram of the data in Fig. 2.8. The Gaussian fit and the limit bars are visible

If the scatter plot is projected along the time distance, we obtain the inter-arrival time histogram, as shown in Fig. 2.11. For a better visualization of the histogram data in double log scale, usually the data are plotted with a variable bin size along the inter-arrival time axes.

It is important to note that an event due to the simultaneous firing of n -cells (DiCT) is counted always as a single event. Since DiCT and primary events are poissonian, they do not change the statistic as explained before.

The estimations of the DCR, of the AP and of the DeCT are measured from the inter-arrival time histogram.

- The primary (or DCR) events follow the Poisson distribution. Then the probability density function $P_{DCR}(t)$ to have an event at time distance t from the previous DCR event is exponential. Therefore the rate of the DCR can be estimated by a fit $F_{DCR}(t)$ as in the eq.2.5.

$$F_{DCR}(t) = aP_{DCR}(t) = a(te^{-bt}) \quad (2.5)$$

The " a " is a normalization factor and " b " is the DCR rate. The DCR uncertainty ΔDCR is directly given by the fit parameter errors.

The data used for the fit are delimited by two bars as the two red dashed bars in Fig. 2.11. The ΔDCR depends on the bar time positions, on the acquired statistic and on the possible overlap between the DCR and the AP (typical situation at high temperatures like in Fig. 2.12). If the AP events are included in the data fit, they increase the DCR rate artificially.

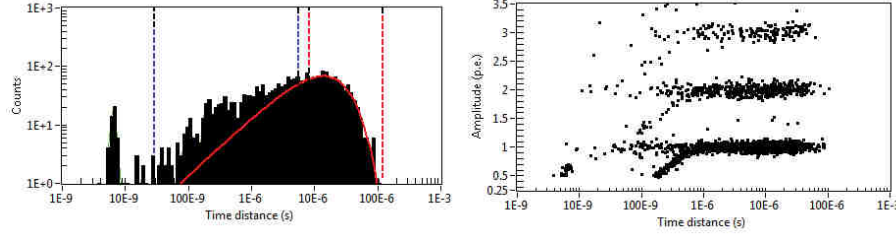


FIGURE 2.12: On the left the inter-arrival time histogram of a case at high temperature with overlap between the AP and the DCR. On the right the scatter plot of the same data set.

The fit is improved if bars are positioned around peak of distribution to reduce the fluctuations. The AP events are obtained as events in excess of the Poissonian fit. On the other hand, the fit depends on the presence of the AP between the red bars. Usually the red bars are manually positioned during the acquisition.

To reduce the uncertainty of the DCR I implemented an algorithm to search the best position of the bars. The algorithm iteratively changes the bars position to minimise the fit parameter error Δb of the DCR.

- The AP and the DeCT are called delayed correlated noise component of the SiPM noise (DCN) and their probability is estimated with similar technique. Usually, the AP and the DeCT distributions are well separated. In the AP case, the AP events are selected between two bars with time position t_1 and t_2 with $t_1 < t_2$ (the blu bars in Fig. 2.11 and in Fig. 2.12). The AP probability $P_{AP}(\%)$ is given by the eq.2.6.

$$P_{AP}(\%) = \frac{1}{C_{Amp}} \left(\frac{N_{t_1 t_2} - \int_{t_1}^{t_2} F_{DCR}(t) dt}{N_{Tot}} \right) \quad C_{Amp} = \frac{\sum_{k=1}^{N_{Tot}} Amp_k}{N_{Tot}} \quad (2.6)$$

$N_{t_1 t_2}$ is the sum of the events between the bars, $F_{DCR}(t)$ is the Gaussian fit of the eq.2.5 and N_{Tot} is the total sum of the events, while the C_{Amp} is the average amplitude value of all the events. C_{Amp} is a correction factor due to

simultaneous n -events that are seen as single event. This happens because the AP probability must be counted for each firing cell case of DiCT events.

In eq.2.7, it is reported the DeCT probability. Where the reference times have changed.

$$P_{DeCT}(\%) = \frac{1}{C_{Amp}} \left(\frac{N_{-\infty t_1} - \int_{-\infty}^{t_1} F_{DCR}(t) dt}{N_{Tot}} \right) \quad (2.7)$$

To calculate the uncertainty on the P_{AP} some assumptions are necessary:

- The AP counts depend on the DeCT counts through the bar positions. If the bars are poorly placed, a correction in the eq.2.6 must be inserted, while the ΔP_{AP} has a correlated error term between the AP and the DeCT. Therefore the good bar positions is a necessary condition to consider the eq.2.6 true.
- A second correlation exists between the AP events and the integral Gaussian that is linked by the Gaussian fit bars. If the bars are well positioned as in the previous point the second correlation is negligible.
- false events due to the external noise and electrical noise are negligible (it is also considered true to calculate the ΔDCR , the $\Delta DiCT$ and the $\Delta DeCT$).

Therefore the AP and the DeCT probability uncertainties can be written as in eq.2.8 respectively.

$$\Delta P_{AP}(\%) \approx \frac{1}{C_{Amp}} \frac{\Delta \int_{t_1}^{t_2}}{N_{Tot}} \quad \Delta P_{DeCT}(\%) \approx \frac{1}{C_{Amp}} \frac{\Delta \int_{-\infty}^{t_1}}{N_{Tot}} \quad (2.8)$$

with $\Delta \int$ the error on the integral that depends on the Gaussian fit parameters and on the bar positions that delimit the AP and the DeCT.

Knowing the time positions of the DLED filtering signals for every acquired window as in the Fig. 1.17, it is possible to calculate the cell gain on the original signal. Given a with a firing cell signal at the time t , the signal area Σ is calculated in charges as shown in the eq.2.9.

$$\Sigma = \frac{\left(\int_{t-t_{pre}}^{t+t_{int}} S(t) dt \right)}{q_e G_{TIA}} \quad (2.9)$$

$S(t)$ is the original signal without DLED of the acquired window that is considered, t_{int} is the integration time, t_{pre} is a corrective pre-trigger time, dt depends on the oscilloscope samples, q_e is the elementary charge and G_{TIA} is the transe-impedance gain.

If all the signal areas are put together, we obtain a gain histogram as is shown in Fig. 2.13.

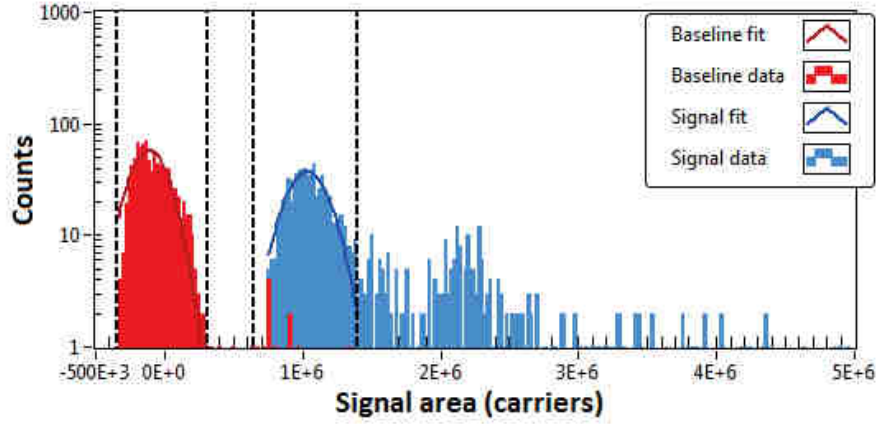


FIGURE 2.13: The gain histogram of the data in Fig. 2.8 with in red the baseline area values around the zero and in blue the firing cell area values.

In Fig. 2.13, the red peak is the cumulative baseline area values calculated for every single cell signal. The baseline areas are integrated for an equivalent time equal to the t_{int} of the signals. The highest blue peak is the cumulative areas of single firing cell signals and so on. The tail on the right of the first blue peak is due to the AP that increases the areas of primary events.

The baseline peak p_B and the single firing cell peak p_C distributions are considered of Gaussian type. With a Gaussian fit similar at the eq.2.4, the Gaussian parameters b'_{p_C} and b'_{p_B} are the corresponding peak centres. In the end, the cell gain is given by the eq.2.10

$$Gain = \frac{b_{p_C} - b_{p_B}}{q_e G_{TIA}} \quad b'_{p_{C,B}} = \frac{b_{p_{C,B}}}{q_e G_{TIA}} \quad (2.10)$$

The subtraction deletes an possible offset while the second relation is true because q_e and G_{TIA} are constants. The gain uncertainty is given by the propagation of two terms:

- the errors of the G_{TIA} that usually it is fixed at 2 % due to the amplifier component tolerances
- the errors on the Gaussian fit parameters b_{p_C} and b_{p_B} .

At cryogenic temperatures, the gain measurement can become difficult or impossible depending on the used SiPM technology. The main causes are explained below:

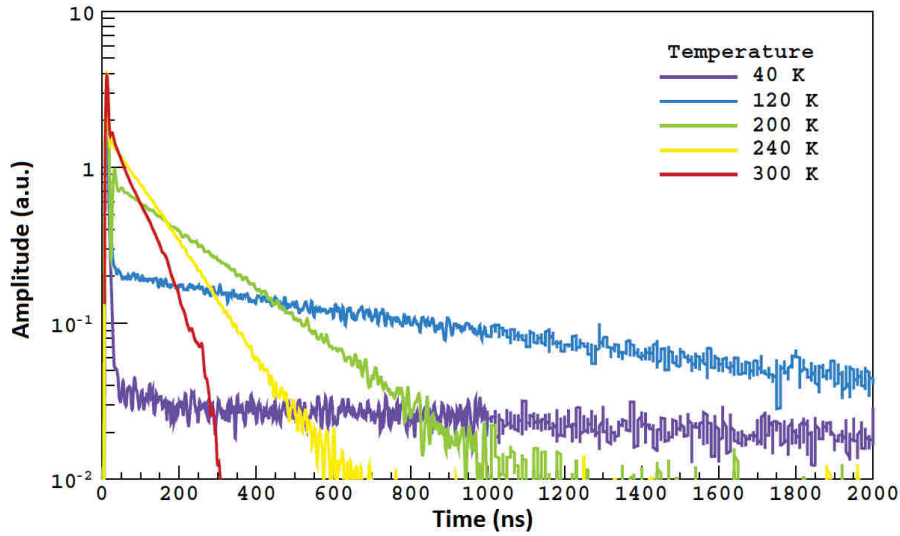


FIGURE 2.14: The single cell signal depending on the temperature with the same cell size and the same overvoltage

- The polysilicon resistor has a resistivity that depends on temperature increasing its value as temperature decreases. The amount of the variation depends on the polysilicon dopant concentration. In Fig. 2.14 an example of a SiPM average signal depending on the temperature is shown. Because cell size and overvoltage are the same, as first approximation the cell gain is not change. However the recharge time constant τ_{RC} substantially changes. Therefore, to measure the cell gain, it is necessary to use a larger integration time t_{int} . Consequently, the amount of white noise integrated increases and so also Gaussian variance, that in turn, increases uncertainty on the gain peak centers.
- Depending on SiPM technology, under to 150 K the AP tends to increase very much. Consequently, the AP tails of the gain histogram tends to increase and to distort the gain peaks.

For these reasons I implemented two algorithms that solve in part both of the two sources of uncertainty. These algorithms extend the operating range of the analysis software to more extreme conditions.

The first algorithm reduces contribution of AP. Thanks to DLED filter and peak-finder algorithms, the time positions of all n -events in an acquired window are known. Therefore, the single event can be selected depending on its time distance to previous $(n - 1)$ and the following $(n + 1)$ event, seen Fig. 2.15. Selection conditions on n^{th} -event are

$$Ok \quad if \quad t_{n+1} - t_n > t_{int} < t_n - t_{n-1} \quad (2.11)$$

The limitation of this approach are:

- It does not work for the APs with amplitude lower than the threshold (usually it is at 50 % of the average single cell amplitude).
- The discarded events depend on the constraint time that I have fixed equal to the integration time t_{int} .
- The AP filter is efficient only at low temperature. Indeed, in this condition, the probability of two consecutive DCR events with time distance lower than the t_{int} is negligible.

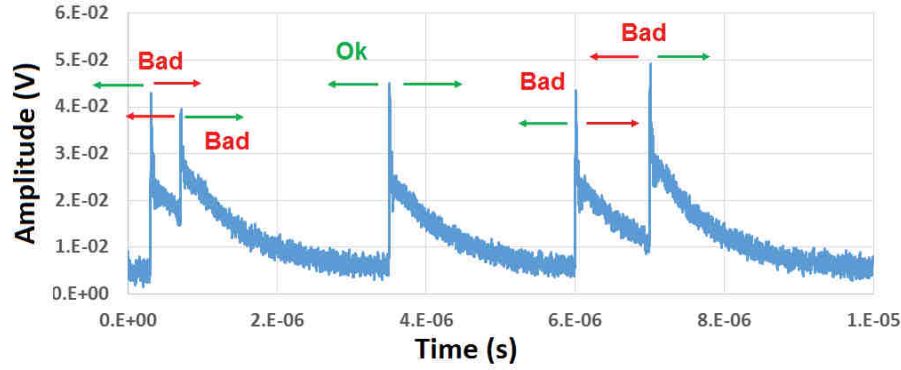


FIGURE 2.15: An acquired window where the AP filter logic has been applied to select the events for the gain histogram

The second algorithm works on long recharge time constant problem at low temperature. The longer the τ_{RC} , the longer is integration of signal, therefore, uncertainty of integration increases. If single cell response is known, it is possible to reduce the t_{int} to the part where the signal-to-noise ratio (SNR) is higher. The cut tails beyond the t_{int} are compensated by a geometric correction that adds an equivalent missing area.

As explained in chapter1, the single cell signal is composed of an initial fast peak, followed by a relatively slow recharge of microcell. The fast peak area is usually from 3 % up to 10 % (depending on layout and on temperature) in comparison to area of recharge time, so as a first approximation is negligible. Therefore the signal function can be written as in eq.2.12.

$$f(t) = c \left[1 - \exp \left(-\frac{t}{\tau_a} \right) \right] \exp \left(-\frac{t}{\tau_b} \right) \quad (2.12)$$

τ_a is the fast rise time, τ_b is the recharge time and c is a proportional constant. Eq.2.9 is used to calculate the single area $\Sigma(t_{int})$ of the geometric correction with the eq.2.12 can be of two types:

$$\Sigma'(t_{int}) = \Sigma(t_{int}) + \int_{t_{int}}^{+\infty} f(t) dt \quad (2.13)$$

$$\Sigma''(t_{int}) = \Sigma(t_{int}) \left(1 + \frac{\int_{t_{int}}^{+\infty} f(t) dt}{\int_0^{t_{int}} f(t) dt} \right) \quad (2.14)$$

I chose eq.2.14 because of the integrals ratio that deletes the proportional constant factor C.

Moreover, as it is visible in the Fig. 2.6 and in the Fig. 2.14, at low temperature it is always true the condition $\tau_a \ll \tau_b$. Therefore a second approximation on the signal shape can be applied as shown in Fig. 2.16.

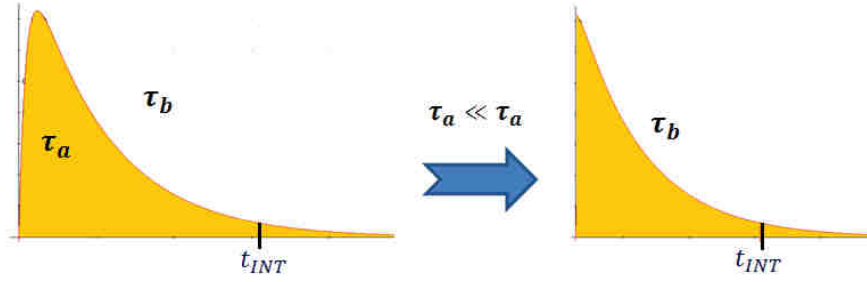


FIGURE 2.16: On the left the simple model of a single firing cell signal without the fast peak. On the right the model approximate if the condition $\tau_a \ll \tau_b$ is true

τ_a becomes really smaller than τ_b and the eq.2.12 becomes the eq.2.15

$$f(t) \approx g(t) = c' \exp \left(-\frac{t}{\tau_a} \right) \quad (2.15)$$

With numerical simulations, the ratio of the geometric correction calculated with $f(t)$ and with $g(t)$ has been checked with the eq.2.16.

$$1 \approx \frac{\left(1 + \frac{\int_{t_{int}}^{+\infty} f(t) dt}{\int_0^{t_{int}} f(t) dt} \right)}{\left(1 + \frac{\int_{t_{int}}^{+\infty} g(t) dt}{\int_0^{t_{int}} g(t) dt} \right)} \quad (2.16)$$

The eq.2.16 can be considered always true if the conditions $10 \tau_a < \tau_b$ and $t_{int} > \tau_b$ are true.

Therefore, in the eq.2.14, $f(t)$ can be substituted with the $g(t)$. In the end, the single cell gain of the eq.2.10 can be rewritten in the eq.2.17.

$$Gain = \frac{b_{pC} - C_{gc} b_{pB}}{e G_{TIA}} \quad C_{gc} = \left(1 + \frac{\int_{t_{int}}^{+\infty} g(t) dt}{\int_0^{t_{int}} g(t) dt} \right) \quad (2.17)$$

The geometric correction can be extracted from Gaussian fit parameters b_{pC} of the single firing cell area peak because if the t_{int} is fixed, the geometric correction is a constant. Now in the propagation of the errors an error term due to the geometric correction exists. This error is the propagation in the integral ratio due to estimation

of the τ_b that corresponds to the recharged time constant of the cell τ_{RC} . The τ_{RC} is estimated on the average single cell signal (Fig. 2.6 and Fig. 2.14) through an exponential fit in the recharge region while the τ_{RC} uncertainty is given by the error on the exponential fit parameter.

In the Fig. 2.17, an example of the geometric correction is compared with the standard method to measure the gain. In particular the gain of a SiPM with an area of 1 cm^2 and a $\tau_{RC} = 580\text{ }\mu\text{s}$ at 77 K and with $V_{OV} = 6\text{ V}$ has been measured. The corrected gain to low ratio of t_{int}/τ_{RC} could be overestimated in part because geometric correction does not count fast peak.

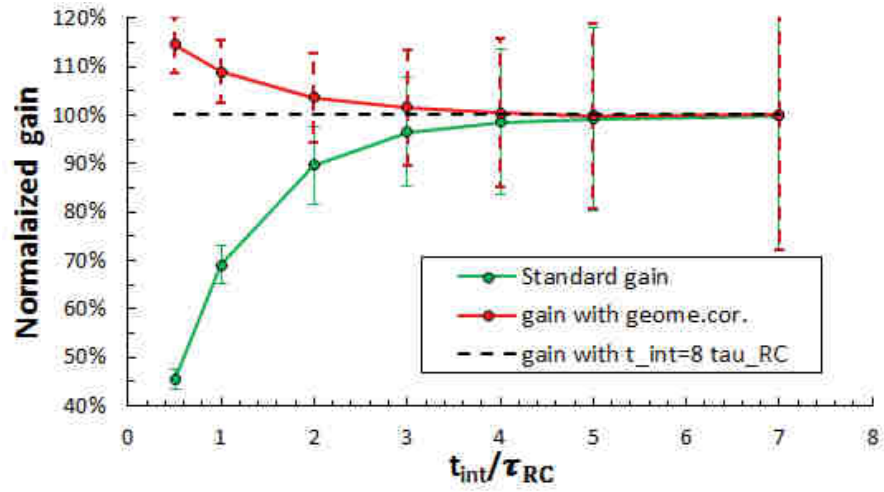


FIGURE 2.17: Plot shows the comparison between the standard method and the geometric correction method to calculate the cell gain. The comparison has been done for different ratio between the integration time and the recharge time of the cell

The measurement has been repeated for both methods with different integration times. Every time only $1.6k$ signals have been analysed to highlight the error bar dependence on the increment of the ratio t_{int}/τ_{RC} . The geometric correction introduces more uncertainty in particular at low rate of t_{int}/τ_{RC} . On the other hand, the measured gain value is much more reliable also at low ratio of t_{int}/τ_{RC} .

Fig. 2.18 shows the improvement of gain histogram is improved thanks to due to the AP filter and the geometric correction. The same measurement has been repeated with the same SiPM with 450 ns of τ_{RC} at 77 K on $10k$ events. On the top left the standard method is shown, with the geometric correction method on the top right. On the bottom left, the AP filter is applied and on the bottom right the two techniques are combined. In the white square the integration time, the measured gain with the error are reported. With the geometric correction I can use only a ratio t_{int}/τ_{RC} of 2 with a gain value that is increased of the 2% while the percent error decreases from the 39.6% down to the 23.5%.

The AP filter does not have a strong effect but it reduces the overestimate gain due to the AP tail and it reduces the error about a certain percentage.

The combination of the methods improves more the estimation of the error. However, the error is always bigger in the gain overestimation due to the geometric correction. In conclusion the method to reduce the integration time at low temperature has been demonstrated to be efficient and permits to extend further the operating range of the analysis software.

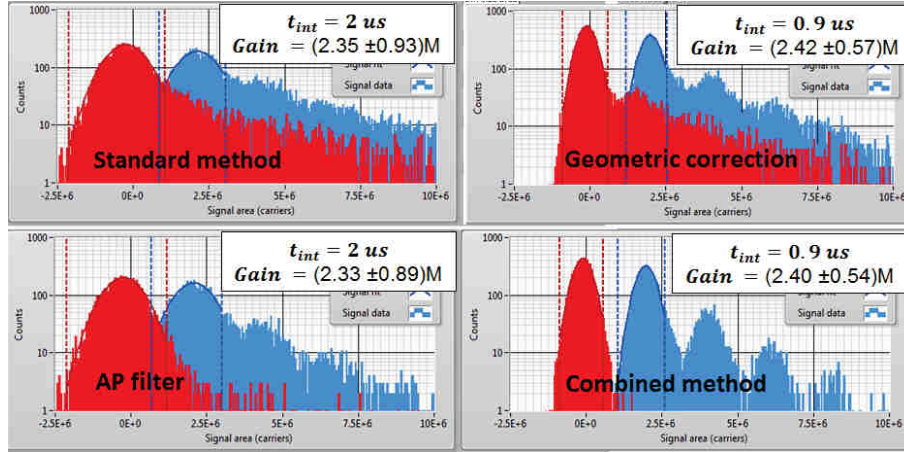


FIGURE 2.18: The four plots show the comparison among the methods to calculate the cell gain with the same conditions. It is possible to see the integration time and the gain measured with the respective error

Finally, the excess noise factor (ECF) [109] is among the measures that are usually done. The ECF quantifies the average charge in excess of the single cell signal due to the correlated noise terms (DiCT, DeCT and AP). The DeCT and the single DiCT give an amount of excess charge equal to a single cell charge while the AP excess charge changes from 0 up to 1 times of the single cell charge linearity. The AP charge depends on when the trapped charge has been released and on recharge time constant of the cell.

The ECF is calculated with the eq.2.18:

$$ECF = \frac{I_{SiPM} - I_{Leak}}{I_{DCR}} = \frac{I_{SiPM} - I_{Leak}}{q_e \cdot Gain \cdot DCR} \quad (2.18)$$

in which the I_{Leak} is the leakage current of the SiPM, obtained by linear fit of the pre-breakdown region of the reverse IV . The I_{SiPM} is the SiPM current that is measured by reverse IV and I_{DCR} is the equivalent current due to only DCR events, while q_e , $Gain$ and DCR have been previously defined.

2.2.1 Segmented mode acquisition

Usually, the technique that we use to acquire SiPM signal is to trigger on electric power distribution, with an acquired window width (T_W) from $100 \mu s$ up to $500 \mu s$. At room temperature, these T_W values guarantee the presence of 30 – 40 events for acquired window at least, depending on the size of the SiPM active area. The chosen T_W depends on temperature, overvoltage, SiPM area and SiPM technology. After that, thanks to the DLED filter and the peak finder algorithm, the parameter characterization of the SiPM can be done.

In Fig. 1.16 you can see the DCR depending on the temperature. From 300 K to liquid nitrogen temperature, the DCR can change of 6 – 7 order of magnitude depending on used SiPM technology, SiPM area and overvoltage.

It is clear that the technique just described can not work. If we consider a SiPM of $1 mm^2$ with DCR of $10 mHz/mm^2$, T_W of $500 \mu s$ and net-line frequency of $50 Hz$, the average probability to have an event in an acquired window is $1/40000$.

The solution of trigger problem is to directly trigger on SiPM signal above the 50 % of single cell signal amplitude.

A second problem is the limited maximum T_W that depends on the oscilloscope samples and the internal temporary storage memory of the oscilloscope. Usually, used samples rate is of $\geq 2 GSa/s$, that is necessary to well rebuild fast signals like rise-time of fast peak used to trigger events. Then, points to track the signal in an acquired window with 30 – 40 events should be about $2 \cdot 10^{12} pts$. Obviously, this approach is impractical. The solution that was adopted by IRIS group is to use the segmented memory acquisition provided by the oscilloscope (segmented mode) to acquire the SiPM signal.

At high temperature, the average time distance between two consecutive events is much smaller, that T_W . Thus the time distances are measured only from the events that are inside the same acquired window. In every acquired window the first signal is always lost. This happens because the first event has not a previous event that gives the time reference. Therefore, it is used only as time reference for the second event. At high temperature this never becomes a problem.

At low temperatures using the same T_W , we have a single event for acquired window, neglecting for now, delayed correlated noise events. In the segmented mode, the starting time T_n of all acquired windows are memorized with a time reference to an internal high-precision clock of the oscilloscope. To determine the j^{th} –relative position in time of all events detected in n –acquired windows, it is necessary to calculate, the time distance between the last event of the window " $n - 1$ " and the first event of the window " n ".

In Fig. 2.19 the segmented mode acquisition concept is illustrated.

For two acquired windows $n - 1$ and n , the time distance between them is:

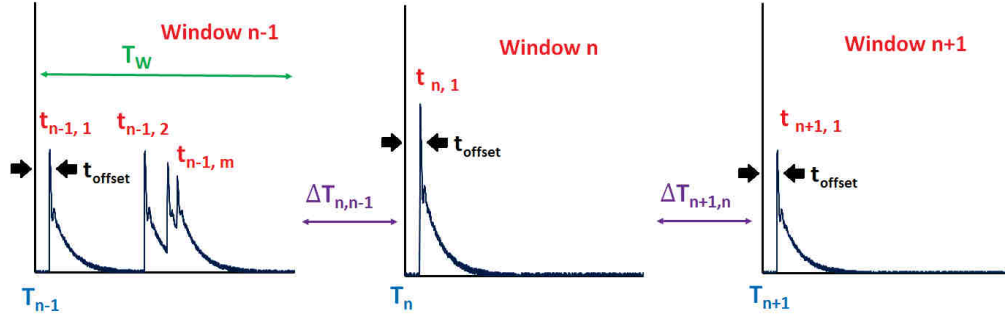


FIGURE 2.19: The main time parameters of the segmented mode acquisition are shown with three sequential acquired windows

$$\Delta T_{n,n-1} = T_n - T_{n-1} + T_W \quad T_{n=0} = 0s, \quad T_n > T_{n-1} \quad \forall n \quad (2.19)$$

The internal time position $t_{n,j}$ of the single j^{th} -events of the acquired window "n" going from 0 to T_W . Therefore the time distance Δt of the first event of the acquired window "n" is given by:

$$\Delta t = (T_n + t_{n,1}) - (T_{n-1} + t_{n-1,4}) \quad (2.20)$$

with $t_{n-1,4}$ the last event of the window "n - 1". The eq.2.20 can be generalized to use the eq.2.19 and to substitute each first event time with the offset time t_{of} that is fixed initially. Therefore the time distance $\Delta t_{n,n-1}$ between the first event of the window "n" and the last event of the window "n - 1" is given by:

$$\Delta t_{n,n-1} = (\Delta T_{n,n-1} + T_W) - (t_{of} + t_{n-1,j_{n-1}}) \quad (2.21)$$

I implemented this logic in the analysis software with internal time distance of the single acquired window. The combination of the two logics extend the DCR frequency operating range of the setup up to some mH , because now it is possible to acquire events $> 1s$ distant, while still keeping the $\geq 2GSa/s$, without overloading the oscilloscope memory. The lower limit to the values of DCR that can be measured is now the duration of measurements, and not the memory depth of the oscilloscope. For example, measurement (statistic of $1k$ events) of $1 \times 1 mm^2$ SiPM with DCR of $1 mH/mm^2$ ideally spends 11.5 days and for a same SiPM of $1 cm^2$ becomes 167 min.

This method is an impressive improvement to characterize the SiPM at cryogenic temperatures.

The combined time distance algorithm shows two peculiarities:

- In the internal time distance method, the first event of every acquired window is lost. On the contrary, with the segmented method only the first event of the first acquired window is lost because of previously explained reasons.

Actually, in segmented mode the oscilloscope memorizes an array of "N" correlated acquired windows every time. It transfers the data on the computer and it restarts a new acquisition of "N" acquired windows when the analysis software requests it. Therefore theoretically only the first event of the first acquired windows of M acquired array are lost.

The analysis software has a detection efficiency $eff_{d.e.}$ of the signals that depends on the equation:

$$eff_{d.e.} = \frac{\sum_{m=1}^M \left[\sum_{n=1}^{N_m} \left(\sum_{j=1}^{J_{nm}} 1_j \right) - 1 \right]}{\sum_{m=1}^M \left[\sum_{n=1}^{N_m} \left(\sum_{j=1}^{J_{nm}} 1_j \right) \right]} \quad (2.22)$$

with "M" that is the acquired array number, " N_m " is the acquired windows number for the single acquired array and " J_{nm} " is the events number of the acquired window number " n_m ".

At high temperature $eff_{d.e.}$ is almost 1 so it is not relevant. At low temperature the average events number for acquired window is $\overline{\sum_{j=1}^{J_{nm}} 1_j} \simeq 1$. Moreover during the acquisition, the acquired window number " N_m " does not change. Therefore the eq.2.22 becomes at low temperature:

$$eff_{d.e.} \sim \frac{\sum_{m=1}^M \left(\sum_{n=1}^{N_m} 1_n - 1 \right)}{\sum_{m=1}^M \left(\sum_{n=1}^{N_m} 1_n \right)} = \frac{\sum_{m=1}^M (N_m - 1)}{\sum_{m=1}^M N_m} = \frac{M}{M} \cdot \frac{N - 1}{N} \quad (2.23)$$

So if we want to acquire 1k DCR events with an average DCR rate of 1 mH, the minimum total time of acquisition will be of 166.7 min for $N \rightarrow +\infty$. In Fig. 2.20, the minimum time of acquisition shown depending on the acquired window number N .

The max number of acquired windows for acquisition N_{Max} is limited by the internal storage memory of the oscilloscope and the internal precise clock of the oscilloscope.

The main solutions to this problem is to use SiPM with large area that actually in FBK it is of 1 cm² to reduce of 100 times the total acquisition time.

A second improvement to reduce the acquisition time is to make independent the data acquisition of the oscilloscope from the data transfer with a dedicated data acquisition system (DAQ). In this case the N_{Max} limitation does not exist and the eq.2.19 simply becomes:

$$eff_{d.e.} = \frac{N_{Tot} - 1}{N_{Tot}} \sim 1 \quad (2.24)$$

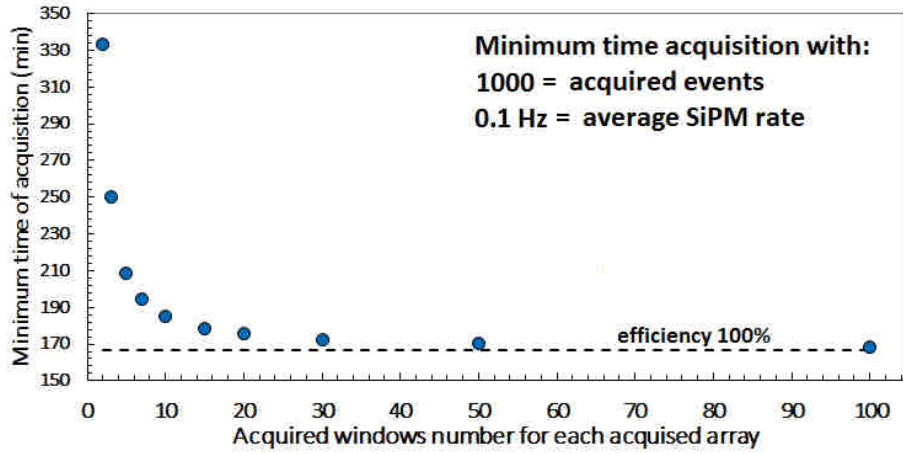


FIGURE 2.20: The acquisition time depends on the acquired window number N for each single acquired array. This dependence is important at cryogenic temperature, while it is always negligible at high temperature

with N_{Tot} that is the total acquired events. The dedicated DAQ deletes the setup limitation of the acquisition time.

- Second peculiarity of segmented mode is the oscilloscope dead time (or re-arm time) T_d . It is the minimum time for oscilloscope to be ready again for recording a new event and a new acquisition window. The direct effect of this re-arm time is shown in Fig. 2.21.

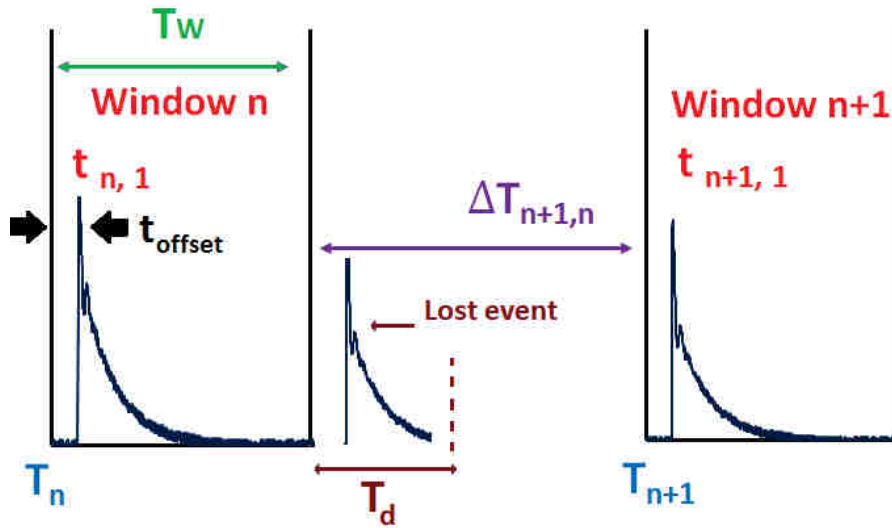


FIGURE 2.21: Lost event due to re-arm time of the oscilloscope between two consecutive acquired windows are shown

As can see on the left of the Fig. 2.21, all the SiPM event signals between $T_n - t_{of} + T_w$ and $T_n - t_{of} + T_w + T_d$ are systematically lost. This means that, regardless of the event source, if the time distance Δt of the event is

$\Delta t \leq T_W + t_{of} + T_d$ it could fall in the dead time, while T_n , t_{of} and T_w have been explained above.

This phenomenon is always maximised for the time distance if $T_W - t_{of} \geq \Delta t$ and $\Delta t \leq T_W - t_{of} + T_d$. On the contrary it does not exist if $\Delta t \geq T_W - t_{of} + T_d$ and it can be negligible for the $\Delta t \leq T_W - t_{of}$ if $T_W \gg t_d$. The condition $T_W \gg t_d$ is not arbitrarily large because it is limited by the internal storage memory of the oscilloscope. Moreover if I use large T_W , I would limit the maximum acquired window number N_{max} for acquisition. This would reduce the efficiency of the analysis software so it would increase the total acquisition time at low temperatures.

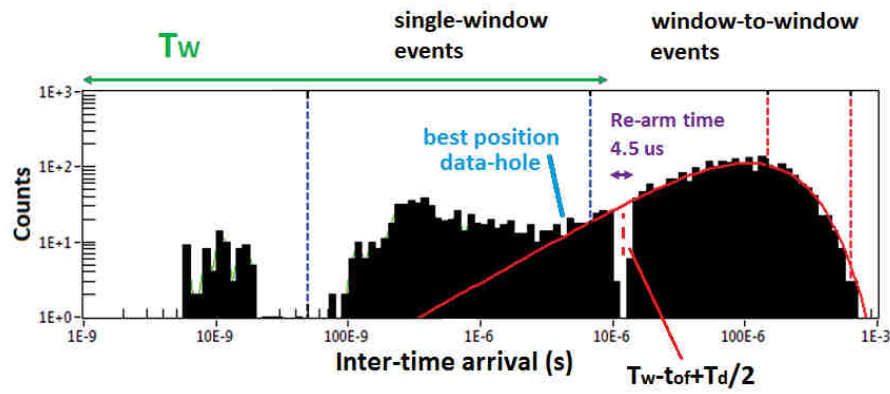


FIGURE 2.22: The data hole in the inter arrival time histogram due to the re-arm time of the oscilloscope is shown

In Fig. 2.22 there is the data hole in the inter-arrival time histogram due to the dead time. In this case the acquired window width is $T_W = 10 \mu s$ and the data hole is between the AP peak and the DCR peak. The data hole center is given by $T_W - t_{of} + T_d/2$ and its time width is T_d (Agilent oscilloscope has $4.5 \mu s$). Considering bigger T_W , the data hole is shifted toward right and if T_W is enough large the data hole is reduced until it disappears completely. This happens because the constant dead time is negligible, if it is compared with the histogram bins that logarithmically change their width.

The data hole phenomena can be considered as high selective band-stop filter. The DiCT value is not influenced by this filter, while for the DCR is enough to move the red bars beyond the right of the data hole.

Observing the eq.2.6 and the eq.2.7, estimation of the AP and the DeCT probabilities are clearly influenced by dead time. Generally the delay correlated noise DCN influence can be written as in eq.2.25.

$$P_{DCN}(\%) = \frac{1}{C_{Amp}} \left(\frac{N_{t_a t_b} - q(T_W, T_d) - \int_{t_a}^{t_b} F_{DCR}(t) dt}{N_{Tot} - p(T_W, T_d)} \right) \quad (2.25)$$

$q(T_W, T_d)$ and $p(T_W, T_d)$ are functions depending on the acquired window width and on the dead time. In the DeCT case $q(T_W, T_d)$ is always equal to zero. On the contrary, the AP case is more complicated by the temperature dependence.

A simple solution is to minimize the effect of the dead time, choosing an acquired window width just beyond the AP time distribution, Fig. 2.22. With this expedient, the AP term $q(T_W, T_d) = 0$, while $p(T_W, T_d)$ works on the total event number N_{Tot} that is low sensitive.

2.2.2 Transient noise at cryogenic temperature

The fast transient external noise is one of the main problem that I met during the cryogenic characterization. The occasional transient noises during the SiPM characterization at high temperature are never a problem. This happens because at high temperature the SiPM used have an area of only few mm^2 to reduce the DCR rate, so, in general, they are less efficient antennas in picking up external noise. Moreover, the DCR rate at near room temperature is always very high compared to the transient noise rate. In the worst case the measure can be repeated in few minutes. Moreover, the small SiPM area usually provides a very high signal to noise rate (SNR).

As discussed in the previous sections, at cryogenic temperatures the DCR rate can be as low as at few mHz/mm^2 . Therefore, large SiPMs are used but anyway the total SiPM rate is about some Hz or less so that the acquisition time can be some hours. In addition, the SNR decreases with the increasing of the SiPM area. Few transient or oscillatory noise events are enough to create hundreds of false events that are able to change the statistic of the SiPM noises. The DLED filter is sensitive to components of the noise signal that has feature similar frequency components as of rise time of cell signal.

The external noise sources can be of extremely different types and can be coupled to the amplifier in three main modes:

- The capacitive coupling is due to the electrostatic noise. Any conductor separated by any insulating material represents a capacitor. The impedance is of reactive type so the parasitic effect increases with the frequency.
- The inductive coupling is a magnetic coupled type of noise. It is due to a variation current flow effect in a conductor or in a plasma. The effect depends on: larger current flow, temporal derivative of the current, proximity to the source, orientation and design of the electric circuit.
- The conducted coupling is due to all the noise phenomena coupled by a direct or galvanic connection such as all devices that share neutrals or grounds. [110].

Typically, the fast transient noises belong to the first two types.

With various hardware expedients more or less expensive in terms of time, space and costs, it is possible to suppress these interferences effectively.

Alternatively, these interferences can be suppressed by software. Observing different scatter plots at cryogenic temperature, I verified that the transient phenomena are most of the time distributed in specific regions. Therefore I implemented a graphic filter on the scatter plot.

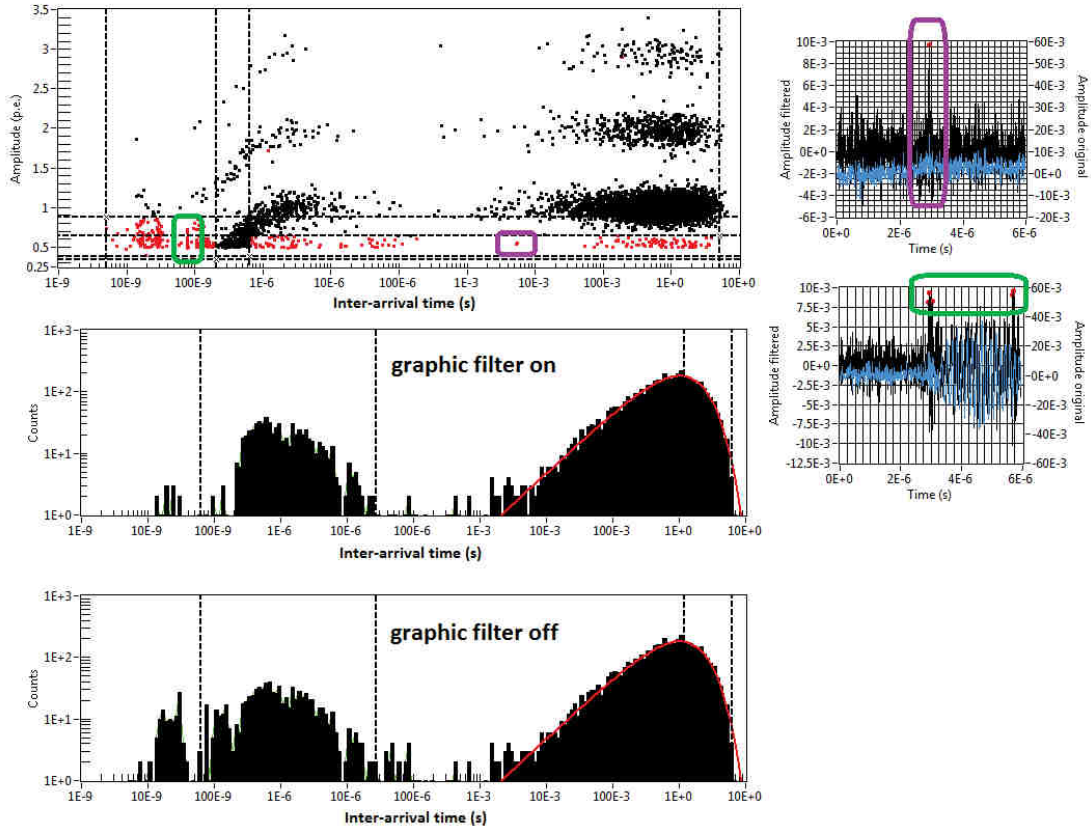


FIGURE 2.23: In the scatter plot, the deleted events that have been selected with the graphic filter are highlighted in red. On the two inter-arrival time histograms the graphic filter effect are highlighted. On the right two example of noise that have been extracted on the scatter plot

I have created windows in the scatter plot that are composed of 2-orthogonally and 2-vertically bars. Through the window I can select the data region that I want to eliminate. The selected data are not considered in all analysis process of the software. Moreover the analysis statistics change in real time changing the data selection.

To distinguish the noise signals I also implemented a plot that shows only the selected signals without the DLED. Extending this concept to multi windows of selection it is often enough to delete the main external noise sources.

In Fig. 2.23 an example of the graphic filter concept is shown. On the scatter-plot on the top of the Fig. 2.23, two selection window are visible. The selected points are

highlighted in red. Two typical sources of noise are shown on the right of the Fig. 2.23, and the corresponding events in the scatter plot are highlighted with a green and a violet frame in Fig. 2.24, respectively. The two inter-arrival time histograms of the Fig. 2.23 shows the same data set with and without the graphic filter.

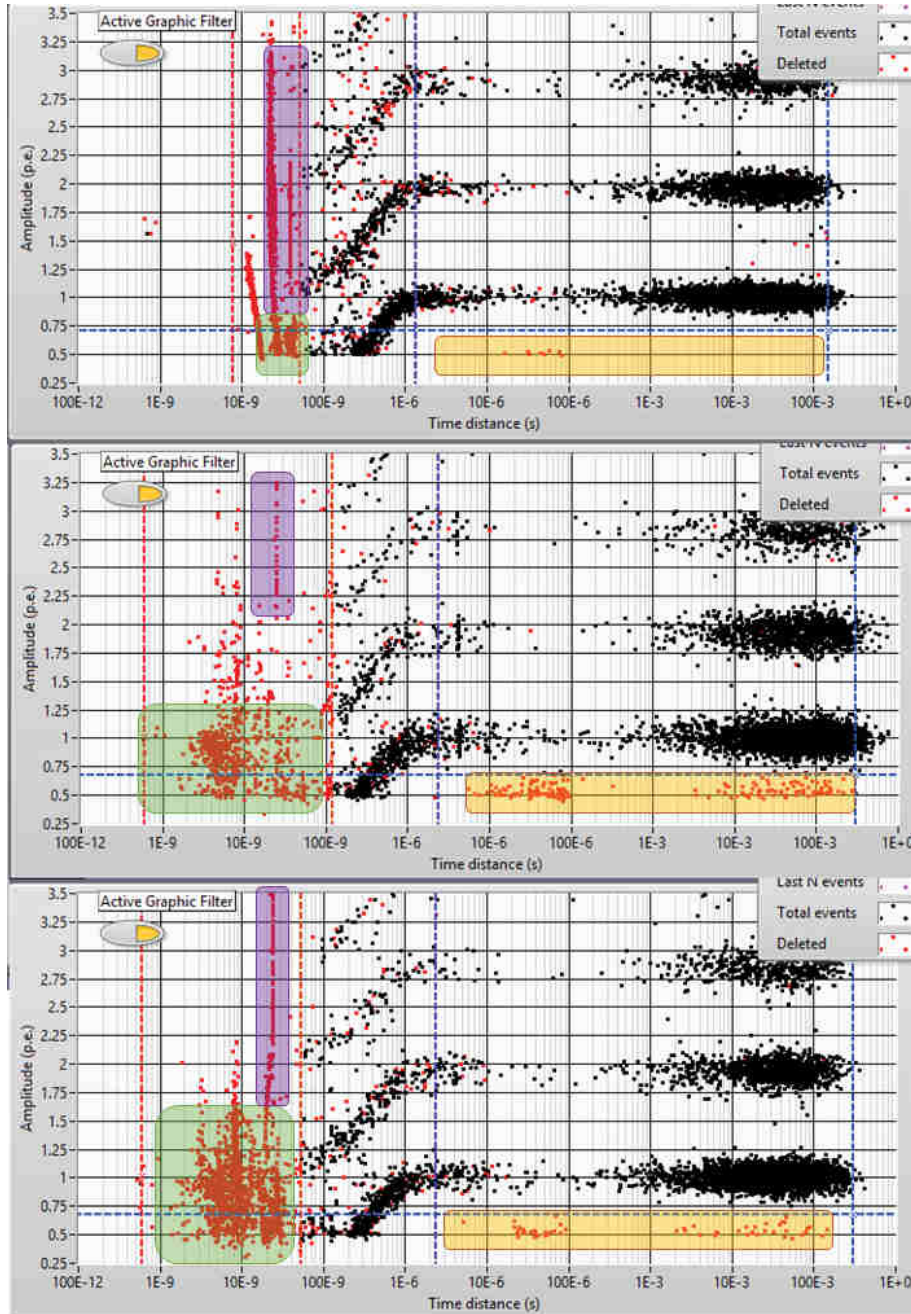


FIGURE 2.24: Three scatter plot of as many different acquisitions at liquid nitrogen temperature. The red points have been deleted with the graphic filter. The coloured squares highlight specific types of noise

In Fig. 2.24 three scatter plot of different acquisition with noise are shown. The acquisition has been done at liquid nitrogen temperature with a standard field SiPM

of 1 cm^2 .

Mostly three families of noise can be identified:

- The yellow noise regions show the typical scatter plot area of the noise due to the random baseline spike noise as shown in the violet frame in the Fig. 2.23. The presence of this noise depends on SNR and so it depends on SiPM size (the larger, the lower the SNR for electric noise) and on overvoltage.
- Usually, the green noise regions are caused by a bad compensation of the undershoot in the DLED filter. The undershoot signal used to compensate the signal in the DLED process is an average of initial signals. If during the acquisition this quantity changes, the compensation of the undershoot can create false events. Sources of this variation can be due to the amplifier instabilities and vertically saturation of oscilloscope due to large signals (in case of high OV and high DiCT).
- The violet noise regions are zone of temporary periodic oscillations with a specific main frequency and fast dampened oscillations generated by external noise (like electric motors, switches, power supplies, transformers).

As you can see in Fig. 2.24 the DeCT and the AP are more sensitive at these types of phenomena not always eliminable with this technique.

A second additional technique to filter the fast transient events was derived with a simple reasoning. Most of the times at cryogenic temperature, the transient noises produce from tens up to hundreds of false event in few consecutive acquired windows. Therefore from the total noise rate can be estimated the average events number $\bar{n}$ for the single acquired window. Then it can be put a limit of maximum events $= c \cdot \bar{n}$ for acquired window. If this value is exceeded then the specific acquired window is deleted.

2.2.3 Signal simulator

We developed a simulator of SiPM signals to check the correct functioning of cryogenic analysis software. It simulates SiPM signals and generates the data in the same format as those generated by the oscilloscope, when operate in segmented mode. The simulator is composed of five main blocks:

- In the first block, with the use of a pseudo random number generator with exponential distribution, all time distances of DCR events are generated.
- In the second block, using segmented mode logic explained in section 2.2.1, the absolute time position of all acquired windows are built depending on DCR time distances.

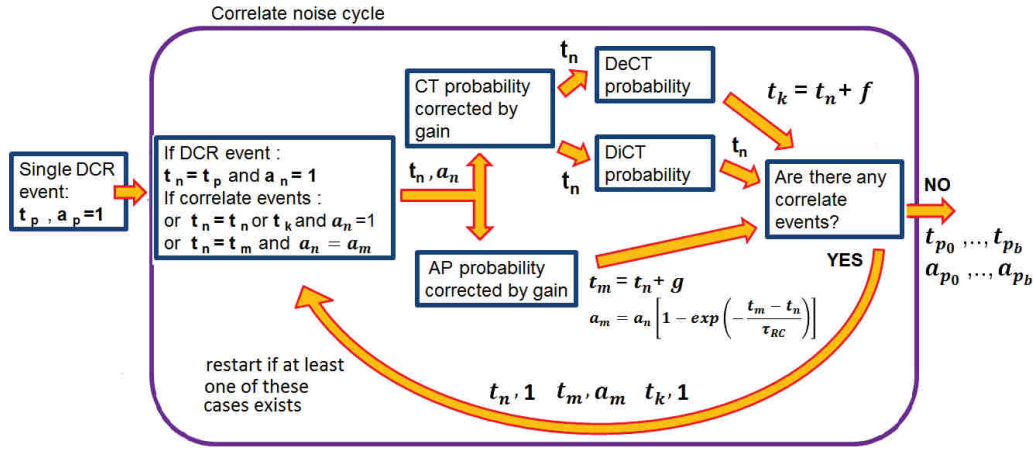


FIGURE 2.25: The main steps of correlated noise generator

- In the third block, for each event of DCR, events probability of AP, DeCT and DiCT are calculated. In Fig. 2.25, the schematic algorithm used to generate correlated noise is shown. Single DCR time positions (t_p) come from the second block of simulator as input data, while the amplitudes (a_p) are normalized to 1. First internal block checks if the event is a DCR event with $t_n = t_p$ and $a_n = 1$, or if it is a correlated event (internally generated). In the second case, the block changes t_n and a_n with three possible new couples of parameters: t_n and 1, t_k and 1, t_m and a_m (they are defined below); they depend on type of correlated events generated. If more than one correlated event are generated (at most one per type), they are analyzed one by one, where $t_n < t_{m,k}$ and a_m is from greater than 0 to 1.

Afterwards, t_n and a_n are sent to the CT and the AP blocks. As will be seen in chapter 4.4, AP and CT are proportional to cell gain, which in first approximation, is proportional to the amplitude of single cell signal. So to properly simulate AP and CT probabilities, they must be corrected for a factor that takes into account whether that generates the correlated noise event was partially recharged or not. Then, AP and CT probabilities are calculated with a pseudo random number generator and are multiplied by a_n .

If CT event has been created, algorithm chooses if CT is a DeCT or a DiCT with a pseudo random number generator. If CT is a DiCT, the time position (t_n) does not change, instead, if CT is a DeCT, the new time position is given by equation 2.26, that is an empirical approximation that approximates well the distributions of measured events

$$t_k = t_n + t_c + \Delta f \quad (2.26)$$

where t_c is a constant of few *ns* and Δf is calculated by pseudo random Gaussian number generator, with condition $|\Delta f| < |t_c|$. In both cases, a_n is always equal to 1 because a new cell is triggered and, assuming low DCR condition, it is completely recharged.

If AP event has been created, new time position $t_m = t_n + g$ is generated, where g is given by pseudo random logarithmic generator of number, while new amplitude (a_m) depends on time distance with respect to the previous event and it is given by the following equation

$$a_m = a_n \left[1 - \exp \left(-\frac{t_m - t_n}{\tau_{RC}} \right) \right] \quad (2.27)$$

with τ_{RC} =recharge time constant of cell.

The last block evaluates if there are generated correlated noise events: in the case of a positive answer, it restarts the cycle with new time positions and new correlated noise event amplitudes. Otherwise, it exists the cycle and sends all events $(t_{p_0}, \dots, t_{p_b}, a_{p_0}, \dots, a_{p_b})$ generated by the starting DCR (t_p, a_p) sequence to the fourth block of simulator.

Algorithm of correlated noise does not simulate all the physics phenomena involved in the generation of correlated noise events in SiPMs, because its purpose, is only reproducing in good approximation a real noise distribution as will be shown below. In [111], the afterpulsing and the optical crosstalk distribution are theoretically studied. The description given in the reference was used as the starting point for the development of third block of the SiPM noise simulator described here, although several approximation were done to simplify the code.

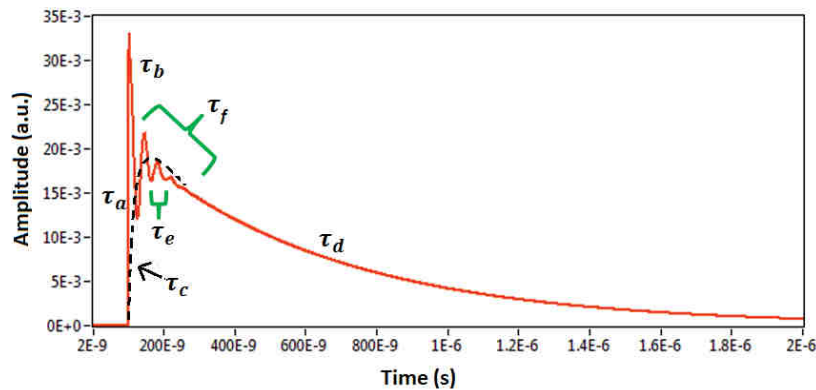


FIGURE 2.26: The complete model of firing signal used is shown with the main time constants

- As input of the fourth block, there are all time positions and amplitudes of DCRs, APs, DeCTs and DiCTs that are renamed t_n and a_n for simplicity. For

each couple of parameters, we use eq.2.28 to generate a simulated single cell signal. The parameters B , C and D balance amplitudes of three contributions, that are: the amplitude of the fast peak (B); the amplitude of the exponential recharge of the cell (C); the amplitude of the signal that simulates a slight undershoot / ringing of the amplifier, caused by a narrow phase margin of the design at cryogenic temperatures (D).

In Fig. 2.26, different time constants linked to the mentioned processes are highlighted: τ_a =rise time constant of fast peak; τ_b =fall time constant of fast peak; τ_c =rise time constant of C term; τ_d =recharge time constant of cell; $1/\tau_e$ =frequency of OPA ringing; τ_f =damping time of OPA ringing.

During generation of signals, all parameters can be independently adjusted at a fixed value or can be variable around their set values, where pre-set dispersion of the value is given by a pseudo random Gaussian distribution.

$$S(t_n, A_n, t) = A_n \left[B \left(1 - e^{-\frac{t-t_n}{\tau_a}} \right) e^{-\frac{t-t_n}{\tau_b}} + C \left(1 - e^{-\frac{t-t_n}{\tau_c}} \right) e^{-\frac{t-t_n}{\tau_d}} + D \sin \left(\frac{t-t_n}{\tau_e} \right) e^{-\frac{t-t_n}{\tau_f}} \right] \quad (2.28)$$

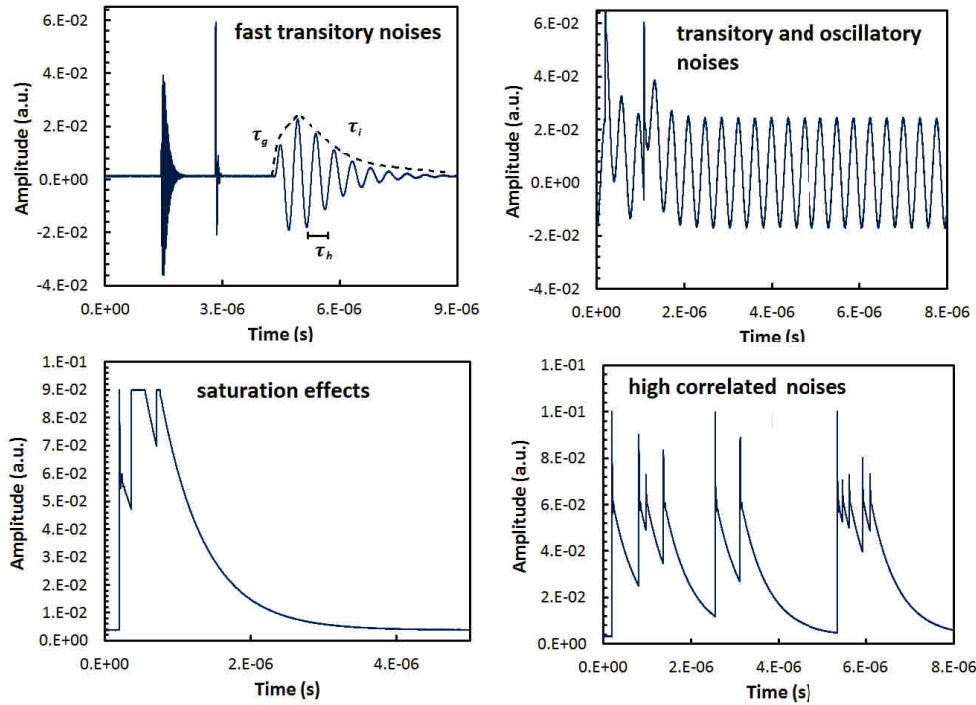


FIGURE 2.27: The main types of simulated noise like SiPM noise, instrumental noise and external interferences

- The fifth block adds the simulated signals and generates segmented waveforms thanks to absolute time stamps generated in the second block. In addition, it independently adds different types of setup noises and non-idealises:

- DC offset, white noise, re-arm time of oscilloscope, saturation of signal, limited sampling rate, limited bandwidth;
- transitory oscillations;
- fast dampen transients, which are created eq.2.29, in which t_m is generated according to pseudo random number generator. Instead, τ_g , τ_h and τ_i are the time constants of the transient (see Fig. 2.27).

$$Tr(t_m, t) = E \left(1 - e^{-\frac{t-t_m}{\tau_g}} \right) \sin \left(\frac{t-t_m}{\tau_h} \right) e^{-\frac{t-t_m}{\tau_i}} \quad (2.29)$$

As in the eq.2.28, the noise parameters and their probabilities of being created can be independently fixed or variable as for parameters of eq.2.28. In Fig. 2.27, some examples of generated noises are shown.

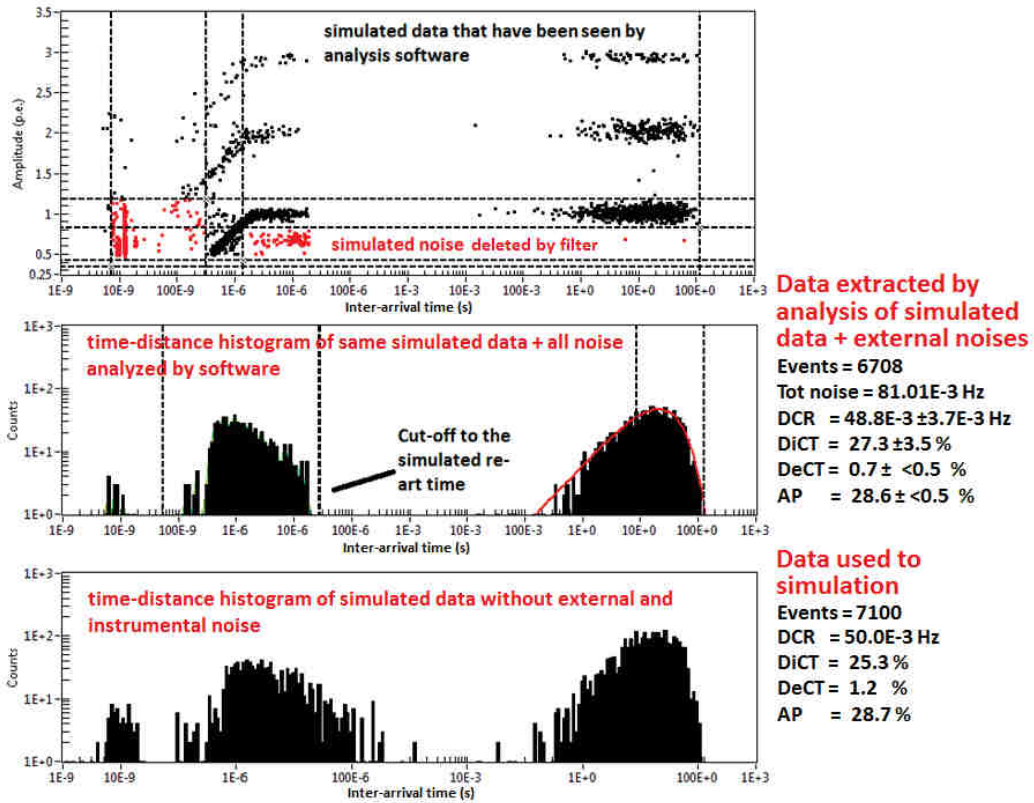


FIGURE 2.28: On the top, the scatter plot of simulated SiPM signals, with all noise events discarded by the analysis software highlighted in red. In the lower part of figure, the comparison between simulated SiPM signals with (middle) and without (bottom) setup noise. In the middle case, the analysis noise software provides filtering of the setup noise, while bottom case is not analyzed on analysis noise software but only generated on simulator. On the right, the SiPM set parameters in the simulator (bottom) and the corresponding SiPM parameters obtained from the analysis are compared (middle)

In Fig. 2.29, a schematic drawing of the setup used to measure the PDE is shown. The main elements are placed inside a black box ($60 \times 40 \times 251, \text{cm}^3$) that was adapted to the scope. The main internal optical components are: an integrating sphere with internal diameter of 5 cm covered in Polytetrafluoroethylene (PTFE), better known as "teflon". Teflon is used as light diffuser for its high reflectivity of light in the wavelength (λ) range between infrared and ultraviolet.

The integrating sphere has three 1 cm circular windows with a angle of 90° between each other, so that the light that enters from one window must undergo at least one reflection before exiting from another window. As shown in Fig. 2.29, one lateral window is used to introduce the light in side the integrating sphere. Depending on wavelength used, light can be direct or indirect. For $\lambda > 340 \text{ nm}$, light comes through an optical fiber from outside of box, while for $\lambda \leq 340 \text{ nm}$, LED is directly mounted on the sphere window, because otherwise, light would be absorbed by fiber optic material. The top window is used for a reference photodiode, which is read with a picoamperometer. The diode does not have an external, certified calibration and it has no internal gain. The other lateral window, illuminates the device under test (DUT), which is positioned at a fixed distance ($\sim 10 \text{ cm}$) from the window. Distance that separates device from sphere provides two advantages:

- incident light has better uniformity;
- amount of light impinging on the DUT is lower compared to amount of light that reference photodiode sees. Thus, reference photodiode can receive a relatively high photon flux that, in turn, generates an easily measurable current signal. If the same amount of light reached the DUT, it could be too high to provide a reliable PDE measurement, as described in the following.

The DUT is connected to an amplifier with amplifier that is fixed onto a rigid holder structure, which maintains the correct distance. The output signal of amplifier is acquired through the oscilloscope in segmented mode, similarly the cryogenic measurement in dark. However, in this case, the trigger signal for the acquisition is provided by the pulse-generator that drives the LEDs, which are operated in pulsed mode. In [109], the calibration of setup is explained in detail.

PDE measurements are made using commercial LED diodes. In table of table 2.2, information like λ emission peak, λ FWHM and LED manufacturing are reported.

Uncertainty of photon rate on device is due to uncertainty of device position, angle of incidence of the light and errors made during the calibration of the reference diode made, for each LED, using an externally calibrated photo-diode, placed in the same position as the DUT [109]. Total uncertainty is typically less than of 2% and also depends on total number of acquired events [109].

λ peak (nm)	λ FWHM (nm)	Manufacturer
295 – 305	15	Roithner LaserTechnik
315 – 325	20	Roithner LaserTechnik
335 – 355	20	Roithner LaserTechnik
363 – 370	20	Roithner LaserTechnik
380	18	Thorlabs
393	18	Roithner LaserTechnik
397	16	Roithner LaserTechnik
407	20	Thorlabs
417	25	Roithner LaserTechnik
428	22	Roithner LaserTechnik
443	27	Roithner LaserTechnik
469	32	Thorlabs
518	34	Thorlabs
533	41	Roithner LaserTechnik
590	19	Thorlabs
639	23	Thorlabs
697	29	Roithner LaserTechnik
780	37	Thorlabs
944	24	Roithner LaserTechnik

TABLE 2.2

Depending on the LED employed, to provide the desired amount of light, the on time of the LED, withing each pulse, ranges between few tens of *ns* and few hundreds of *ns*, while frequency repetition is 20 *kHz* to minimize the effect on measurement of possible afterpulses from avalanches generated by subsequent light pulses.

Number of fired cells in a SiPM can be equivalently calculated from either amplitude or charge histograms. Measurements are made in faint illumination condition (usually for single pulse there are 2-3 *photons/mm²* incident on active area of SiPM), while detected photons are averagely between 0.3 *photons/pulse* and 0.8 *photons/pulse* depending on λ incident, device technology and OV. The value of *photons/pulse* detected is chosen to have a good statistic in the relevant parts of the histogram, that are P_0 and the sum of all other peaks, as will be explained shortly. In any case, under these illumination conditions, the probability of more than one photon hitting the same cell in a single light pulse is minimal, thus PDE measurement is not distorted by this effect. In Fig. 2.30, an example of amplitude peak spectrum histogram is shown, where the first seven peaks are visible. The first peak P_0 is pedestal and corresponds at all the time where SiPM has not detected photons, the second peak P_1 corresponds at all the time where the has detected a single photon, two photons for P_2 and so on.

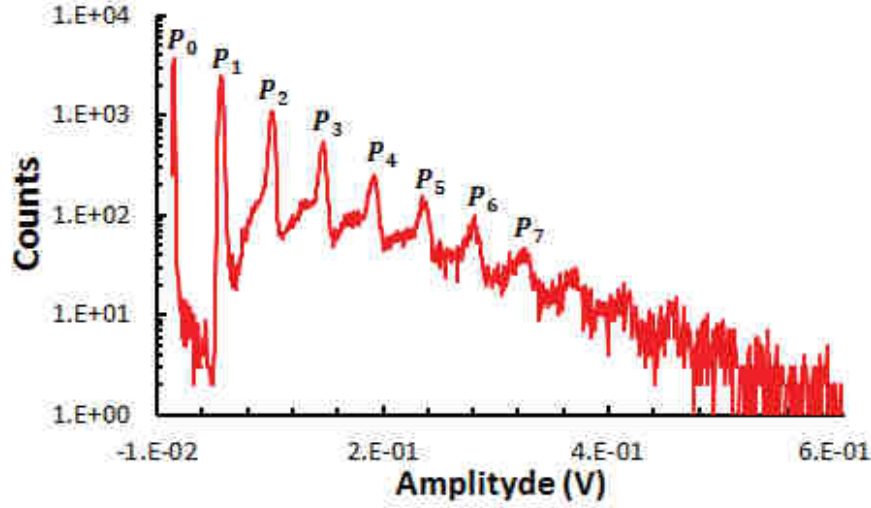


FIGURE 2.30: An example of histogram with amplitude peak spectrum measured of a SiPM-NUV (1x1 mm²) with OV = 7 V at 20 °C

The probability distribution to detect at least a photon is a quasi Poisson statistic, when the firing cell number is ≥ 1 . This is due to presence of correlated noise, while the P_0 peak is not affected because of there are no firing cells. Therefore, the number of event in P_0 follows Poisson statistic and the measurement is not affected by the correlated noise. The P_0 statistic is well known in literature [112] and it is given by:

$$P_0 = e^{-N_p} \frac{N_p^0}{0!} = e^{-N_p} \quad (2.30)$$

where N_p is the average of firing cells.

PDE is probability that an incident photon is detected by device, so the eq.1.19 can be rewritten like:

$$PDE = FF \cdot QE \cdot T_p = \frac{N_p}{N_{ph}} \quad (2.31)$$

where N_{ph} is the total incident photon. Moreover if the same measurement is repeated in dark condition, we can correct any offset in the number of N_p caused by the primary DCR of the detector. Now, we have two histograms with two first peaks $P_{0_{Dark}}$ and $P_{0_{Light}}$, so the corrected average of firing cells is $N_p = \ln P_{0_{Dark}} - \ln P_{0_{Light}}$. In the end, the eq.2.31 becomes:

$$PDE = \frac{\ln \left(\frac{P_{0_{Dark}}}{P_{0_{Light}}} \right)}{N_{ph}} \quad (2.32)$$

2.3.1 Design of the cryostat sample holder

IRIS group is part of a larger center in FBK, called Center for Materials and Microsystems (CMM). Recently, CMM has acquired a DE-204 cryocooler [113]. The

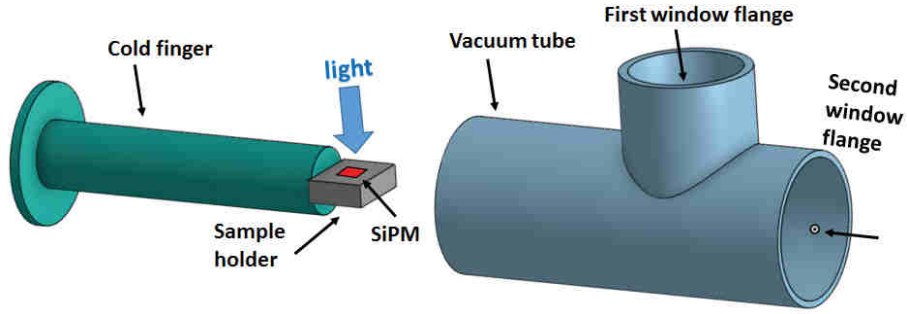


FIGURE 2.31: The main components of the cryostat are visible

cold finger is cooled by a closed-cycle, Helium cryocooler coupled to a secondary water cooling circuit, while an external pump generates a vacuum at $\sim 2 \cdot 10^{-3} \text{ mBar}$. Moreover, heater system with PID controller (proportional–integral–derivative) stabilizes the temperature.

Cold finger can achieve $\sim 4.2 \text{ K}$ on the contact surface with sample holder. The system features a heat extraction power of 14 W at 77 K and of 0.16 W at 4.2 K respectively. Cold finger is placed in a vacuum steel tube that has been modified by adding two window flanges as illustrated in Fig. 2.31. A glass window guarantees high transmittance between infrared and near-ultraviolet.

Cryostat was adapted to characterize SiPMs in dark and in light conditions. To this purpose, we developed a SiPM sample holder through 3D CAD software and then, it was produced using CNC machine available in FBK. Sample holder is composed of three pieces shown in Fig. 2.32.

- Piece *A* is the actual sample holder, in which holes are used for screws that hold together the cryogenic amplifier, described in section 2.1.1 and an custom-design aluminium PCB that functions as the SiPM package. Piece *A* was designed to be placed below the first window, as represented in Fig. 2.31. The shape and the thickness of sample holder were minimized to reduce the material used and space used inside vacuum tube. On the back of piece *A*, a trench is made to place a thermal probe close to SiPM. Piece *A* has two vertical holes used to connect it to piece *C*.
- Piece *B* is connected to the cold finger. In the center, there are a hole and a circular trench to house the screw head that holds sample holder and the cold finger together.
- Piece *C* is placed between piece *A* and piece *B*, it is used to avoid removing piece *B* from the cold finger frequently, in order to prevent damage to the copper screw thread of cold finger. Moreover, piece *C* allows an independent orientation between piece *A* and piece *B*, in fact, the two pieces are independently connected to on piece *C*. Piece *C* is held in place through semi circular

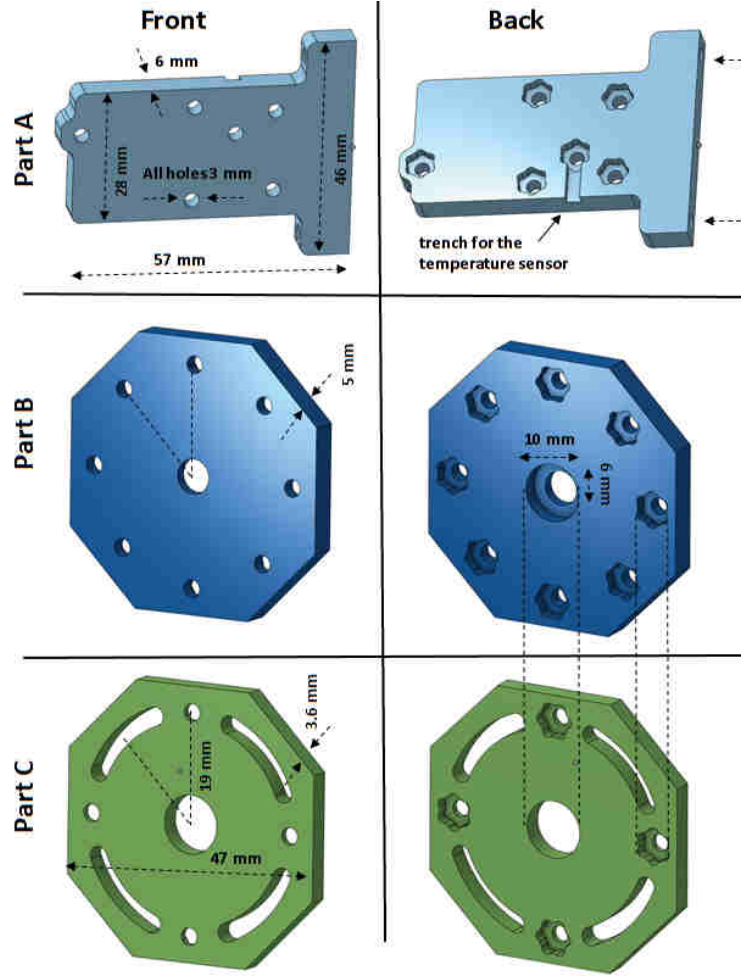


FIGURE 2.32: Schematic pieces that compose the sample holder

holes (Fig. 2.32) on piece *B* and can be rotated by 60° , while piece *B* has eight holes each 45° . This solution placing piece *C* on piece *B* with any orientation. Eventually, piece *C* is connected to piece *A* trough four holes. The holes have trenches with shape equal to the screw head to hide them on piece *B*.

In Fig. 2.33 the 3D model of the sample holder assembled is compared to the real finished holder. The holder was completely realized in copper because it has high thermal conductivity. During the assembly a thin sheet of indium was placed between pieces to improve thermal conductivity. Moreover, the SiPM package and the cryogenic amplifier both have a flat back, in order to maximize contact area with sample holder.

2.4 SiPM output capacitance measurements

The instrument used to measure output capacitance of SiPMs is the *precision LCR Meter 4285A* produced by *Keysight*, featuring a operating frequency between 75 kHz

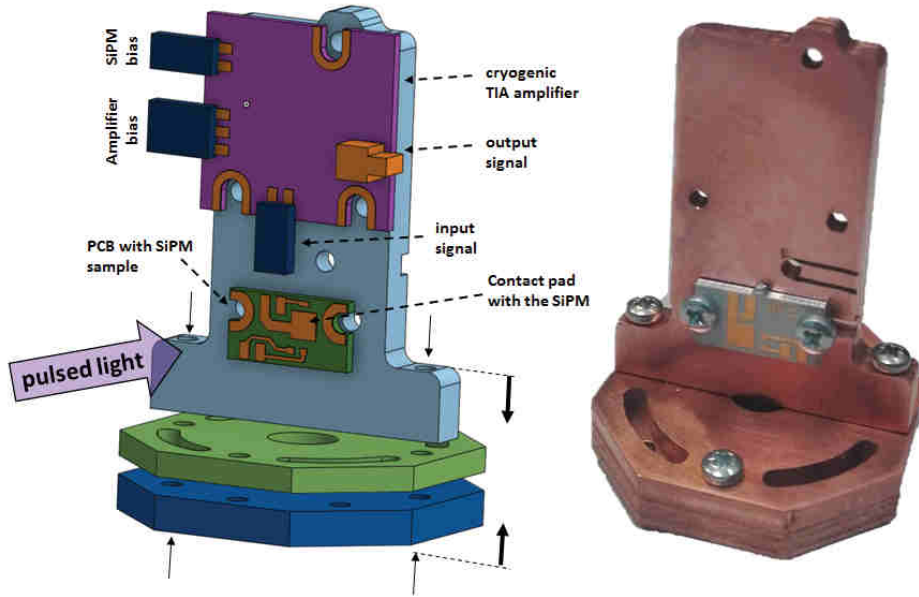


FIGURE 2.33: The 3-d design of sample holder on the left and the finished sample holder in copper on the right

to 30 MHz [114]. The LCR Meter is connected to MFCMU/BNC adapter (Multi Frequency Capacitance Measurement Unit and Bayonet Neill–Concelman). The adapter is a HP - Agilent - Keysight 16494F [115]. Two input BNCs of the adapter are wired to two BNC/SMA cables (SubMiniature version A) with an adapter SMA/SMD pins which, in turn, is connected to PCB of SiPM, as shown in Fig. 2.34.

The adapter chain is necessary to measure SiPM capacitance inside dewar in liquid nitrogen.

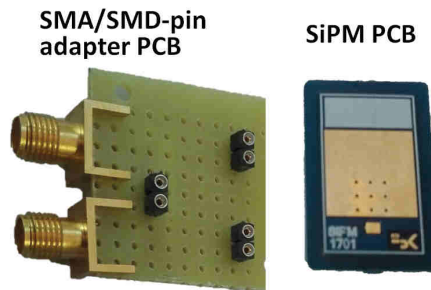


FIGURE 2.34: PCBs that are used to measure SiPM capacitance

LCR meter can execute measurements of capacitance frequency (C-f) at fixed voltage and of capacitance voltage (C-V) at fixed frequency. It can operate assuming different electrical models of the DUT, which are useful to better represent the characteristics of the device being measured. The equivalent electrical model of a SiPM can be seen as a RC series, as explained in section 1.4. According to the eq.1.11, LCR meter measures the equivalent series capacitance C_s and the equivalent series

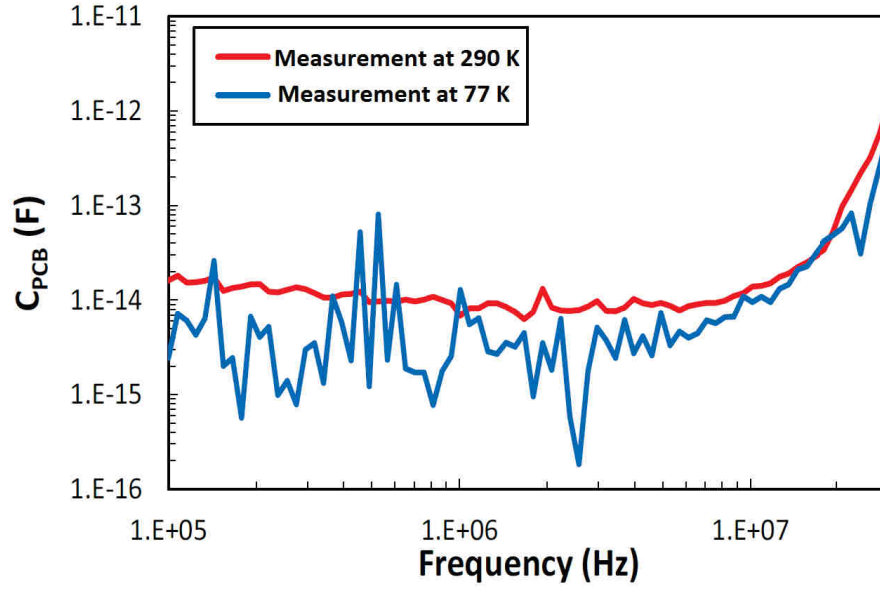


FIGURE 2.35: Parasitic parallel capacitance of all adapter chain from 0.1 MHz up to 30 MHz at 300 K and 77 K

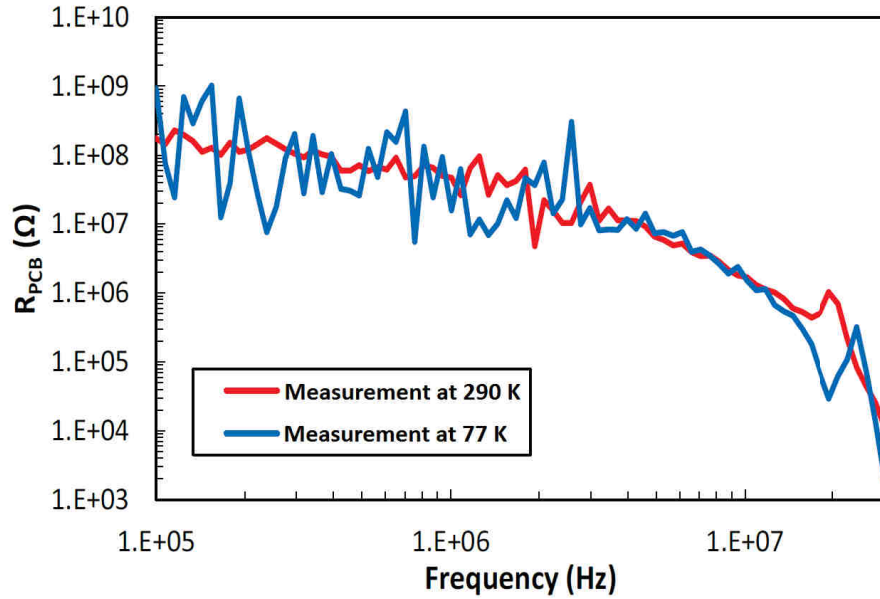


FIGURE 2.36: Parasitic parallel resistance of all adapter chain from 0.1 MHz up to 30 MHz at 300 K and 77 K

resistance R_s of device.

To simplify operations, all measured SiPMs were packaged on same type of PCB (Fig. 2.34). Before SiPM measurements, setup was calibrated.

With all chain of adapters connected up to the PCB but without the DUT, we executed calibration for all frequencies used during the characterization. LCR meter

memorizes the compensations to minimize parasitic component. Operation was executed in two conditions: *Zero short*, where PCB has two contact pads short circuited by wire bonding (eliminates measurement errors due to parasitic stray admittance); *Zero open*, used PCB was without short circuit (eliminates measurement errors due to parasitic residual impedances) [114]. Calibration was done both at room temperature and at liquid nitrogen temperature.

After calibration measurements of C - f and R - f were made with all adapter chain but without SiPM. In this case, RC parallel model was used, because we expect an high parallel resistor (R_{PCB}), caused by insulating material of adapters and a low capacitance (C_{PCB}) due to cables and metal pads. The results are shown in Fig. 2.35 and in Fig. 2.36.

Capacitance was roughly constant (< 20 fF) up to 10 MHz where it similarly increases for both temperatures. Resistance decreased with increasing frequency for both temperatures with a reduction of two orders of magnitude from 100 kHz to 10 MHz.

With SiPM mounted on PCB, C_{PCB} and R_{PCB} are in parallel to the equivalent series R_s - C_s of SiPM. So, LCR meter in input have a total impedance Z_t given by equation

$$Z_t = \left(\frac{1}{R_s + \chi_s} + \frac{1}{R_{PCB}} + \frac{1}{\chi_{PCB}} \right)^{-1} = \frac{R_{PCB} \cdot \chi_{PCB} \cdot (R_s + \chi_s)}{R_{PCB} \cdot \chi_{PCB} + R_s \cdot R_{PCB} + R_{PCB} \cdot \chi_s + \chi_s \cdot \chi_{PCB}} \quad (2.33)$$

with $\chi_s = 1/j\omega C_s$ and $\chi_{PCB} = 1/j\omega C_{PCB}$.

From experience, R_s of SiPM varies from few Ω up to few $k\Omega$ (hundreds of Ω if SiPM is large) depending on SiPM size, quenching resistor and temperature, while C_s of SiPM is around 50 pF/mm². Therefore, using SiPMs with area of 1 cm², we have relations $R_s \ll R_{PCB}$, $C_s \gg C_{PCB}$ and $\chi_s \ll \chi_{PCB}$ that allow to rewrite the eq.2.33 in:

$$Z_t = \frac{R_s + \chi_s}{1 + \frac{R_s \cdot R_{PCB} + R_{PCB} \cdot \chi_s + \chi_s \cdot \chi_{PCB}}{R_{PCB} \cdot \chi_{PCB}}} \simeq R_s + \chi_s \quad (2.34)$$

The denominator is practically almost always equal to 1 and then in good approximation R_{PCB} and χ_{PCB} are negligible.

Chapter 3

SiPM technologies developed in FBK | IRIS

In this chapter, the main SiPM technologies developed at FBK over the last years are briefly described, with particular emphasis on technology steps that lead to the development of SiPM cryogenic technology.

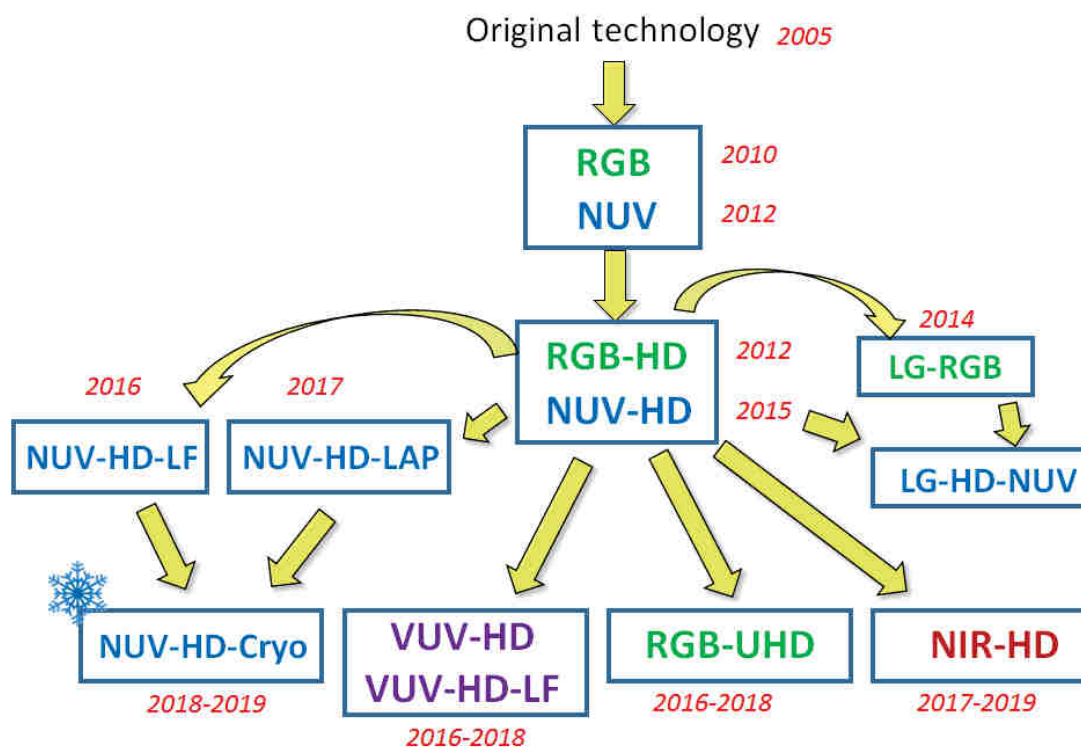


FIGURE 3.1: Evolution of main SiPM technologies developed in FBK over the past 10 years

Fig. 3.1 is diagram of main SiPM innovations realized by FBK | IRIS unit. First SiPMs developed in 2005, within the framework of a collaboration between FBK and INFN focused on development and on application of SiPMs.

Good approach to connect analog microcells is in parallel, on one side, by top metal layer that connect all polysilicon resistors, instead, on the back, by a thin metal

layer on the low-resistivity bulk on which the epitaxial layer is grown. Single cell is a shallow ($\sim 100\text{ nm}$) n^+ -on- p junction with an additional p-type implant, which sets the breakdown voltage of the cell and implements the so-called virtual guard ring structure [116] [117]. The virtual guard function is to shift the edge or lateral breakdown of the junction to voltages significantly higher than the breakdown happening toward the bulk, inside the active area, epitaxial layer to fix the V_{BD} and to prevent premature lateral breakdown. In the initial phases of development, SiPM sizes were not larger than 1 mm^2 with square cells separated by p-stop, superficial implant (see Fig. 3.2A) because of the minimum distance required to prevent early lateral breakdown (thick dead border) between cathode and p-stop is $4\text{--}6\text{ }\mu\text{m}$. This solution was providing a fill factor (FF) of 48 %- 60 % for cell size (CS) of $40\text{ }\mu\text{m}$ [118]. In [118] for a device with FF of 20 %, PDE has a flat peak from 470 nm up to 600 nm because it was used a technology with different dopant profile that increase sensitivity toward red (see section 1.6), while the measurable PDE max is 14 % ($OV = 4\text{ V}$) with DCR of $2\text{--}3\text{ MHz/mm}^2$ ($OV = 3\text{ V}$) at 25°C [118].

Over the years, further developments were carried out [119] [120].

An important advancement was obtained between 2010 and 2012, with a re-design of the electric field in the high electric field region and by differentiating between RGB sensitive (red-green-blue) and NUV sensitive (near-ultra-violet) technologies.

In the NUV technology, compared to RGB technology, the junction is reversed with a p^+ -on- n , see Fig. 3.2D and Fig. 3.2E. The PDE peak of a NUV is around 400 nm , on the contrary, the PDE peak of an RGB is around 550 nm . This is caused by the fact that triggering probability of electrons is higher than that of holes at any given value of the bias applied to the junction. The ratio is approximately three at small bias above the breakdown. In an n -on- p junction, if a couple of carriers is generated superficially, the hole enters the high field region from top and can initiate the avalanche. On the contrary, if charge is photo-generated deep in the epitaxial layer, electrons enter the high field region from bottom and may trigger an avalanche. Thus, detection efficiency tends to be higher for medium wavelengths (550 nm) than for short wavelengths (400 nm). PDE at longer wavelengths, in the other hand, is reduced by the limited thickness of the epitaxial layer. As expected, opposite behavior is observed in a p -on- n junction, featuring peak PDE around 400 nm .

Compared to previous devices, both NUV and RGB have almost a double PDE to $\sim 30\%$ with a CS of $50\text{ }\mu\text{m}$ and a FF of 42 %. Moreover, thanks to electric field engineering, a large improvement was obtained reducing DCR to 200 kHz/mm^2 at 20°C , while the maximum SiPM size has grown up to 16 mm^2 [121] [122].

Another development was done introducing deep trenches to electrically isolate adjacent cells, Fig. 3.2B. Trenches were filled with electrically insulating material and allowed a significant reduction of the dead border around the active area of each cell,

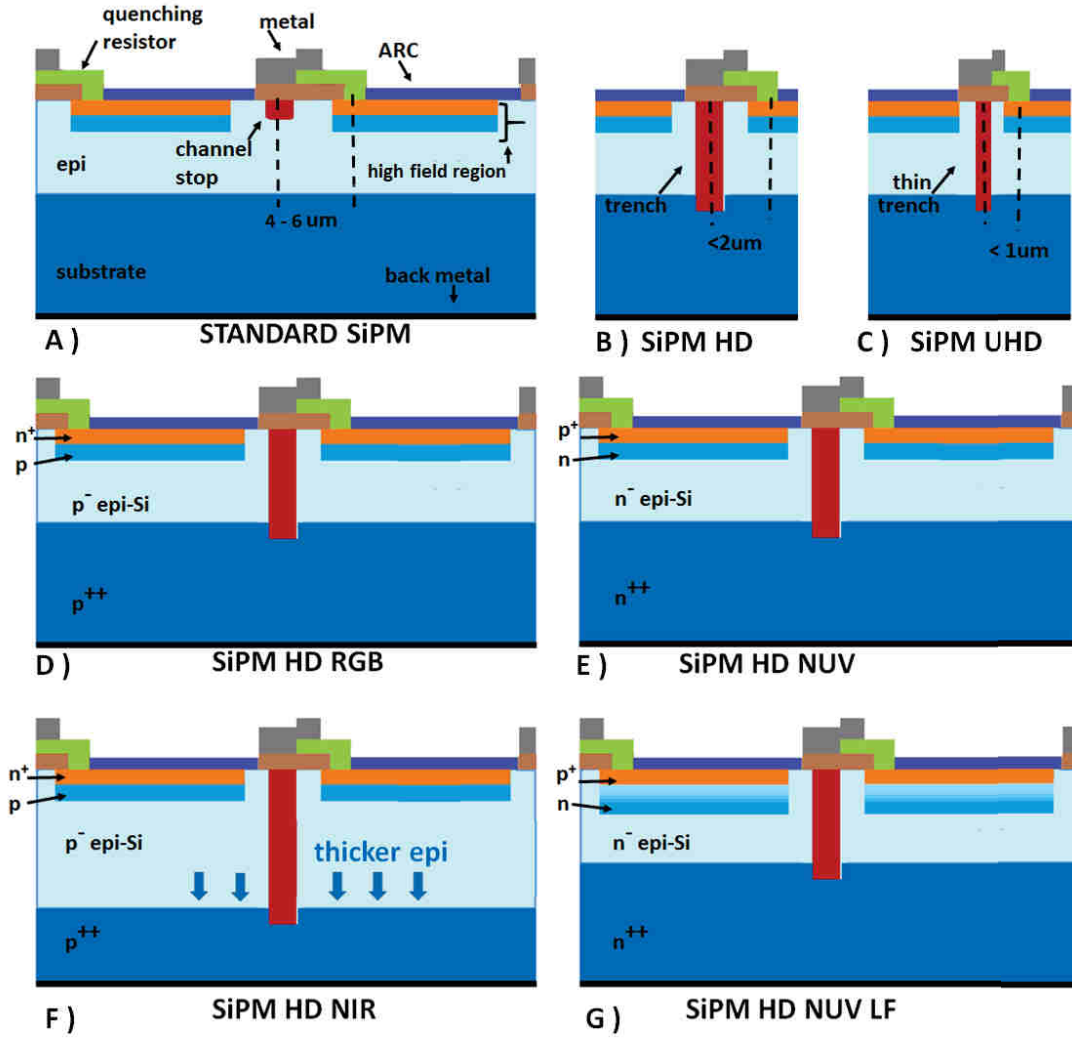


FIGURE 3.2: Cross-section of cells of some main technologies of SiPM developed in FBK. Fig. A), B) and C) are generic cells, while Fig. D), E), F) and G) are specific technologies

from $4 - 7 \mu m$ to $2 \mu m$. The name of this new, improved technology was high density SiPM or SiPM-HD, with this implementation, the FF reached was significantly improved. For example, a non-HD SiPM with CS of $50 \mu m$ has FF of $\sim 48\%$ (with border region of $7 \mu m$) [123], while a SiPM-HD with a CS of $15 \mu m$ features FF about 56% [52].

At same PDE, HD-SiPMs compared to standard SiPM have three main advantages:

- reduction of correlated noise (AP and CT) at the same level of PDE, because the average carrier trapped of AP and the average photon number that are emitted during an avalanche are proportional to the gain, which depends on CS, as will be demonstrated in section 4.4.

- The high cell density significantly improves SiPM linearity, allowing them to measure higher photon flow without saturating.
- it has been demonstrated that SiPMs with smaller CS, when all other parameters are equal, have an increased resistance to radiation damage [124]. Therefore, HD technology is useful for space, medical and particles physics researches.

The HD-SiPM approach is at the basis of development of several SiPM technologies, as described in the following:

- **RGB-HD** was successfully employed for the readout of crystal scintillators in ToF-PET applications. A scintillator is a material that when struck by an incoming particle (γ -rays to 511 keV in ToF-PET applications), absorbs its energy and in a second time re-emits the absorbed energy as scintillation light, with wavelength and emission-time that depend on scintillator type. In [125], RGB-HD-SiPMs (CS = $30 \mu m^2$, area = $4 \times 4 mm^2$) were using two types of scintillators (Ce:LYSO and Ce:GAGG). Significant results were obtained with Ce:LYSO, energy resolution of 9.0% FWHM at 511 keV and a coincidence resolving time (CRT) of 125 ps FWHM at $-20^\circ C$. PDE of RGB devices is particularly suitable for the emission wavelength of GAGG scintillator (emission peak 540 nm [126]).

Initially, it was characterized at cryogenic temperature for DarkSide-20k, in two versions: RGB-HD-LR_q (low quenching resistor) and RGB-HD-HR_q (High R_q). The results of characterization are reported in [127].

In [128], RGB-HDs were also tested against neutron irradiation at moderate neutron fluences were irradiated up to $10^{11} n/cm^2$ (1 MeV eq). The dark current increases by two orders of magnitude when the neutron fluence goes from $10^9 n/cm^2$ to $10^{11} n/cm^2$, while single photoelectron sensitivity is lost at a fluence above $3 \cdot 10^9 n/cm^2$.

- **NUV-HD**, similarly to RGB-HD, is the evolution of previous NUV technology. Over the years, it had different improvements like: reduction of the DeCT [129], reduction of Ap at environmental temperature [130] and increase of maximum SiPM area to $1 cm^2$. With an overvoltage (OV) operating range more than doubled than in the old NUV, the PDE_{420 nm} for a SiPM with CS of $30 \mu m$ (FF of $\sim 75\%$) is 50% with OV = 4 V and $\sim 60\%$ with OV = 10 V [81]. Among the main potential applications we can list:

- ToF-PET because the PDE peak of NUV is well matched to the emission of LYSO (435 nm [131]), used to convert the γ -photons to 511 keV in to visible light [130] [132].

- A second field of application is for CTA (Cherenkov Telescope Array) [133], thanks to the high sensitivity of NUV-HD on characteristic emission spectrum of Cherenkov radiation in the atmosphere between 350 nm and 450 nm.
- The **LG-SiPM** (linearly-graded) work is already explained in section 1.1. Its main feature is the possibility of tracking the 2D position of photon detected, but at the cost of an increment of readout channels from 1 (standard SiPM) to 4. This property is exploited to study an high resolution (100 – 200 μm without crystal scintillators) depth-encoding PET detector module using LG-SiPM arrays, as in the recent work [134].
- **NIR-HD** (near-infrared) technology, as suggested by its name, is a series of optimizations to increase the PDE in wavelength range between 700 nm and 950 nm. At 850 nm, for example, the absorption length of silicon is about 18 μm , so it is necessary to increase the epitaxial layer thickness (Fig. 3.2F) to increase the internal quantum efficiency [116]. Using circular SPADs with edge of active area shielded by metal to eliminate border effect, with CS of 25 μm and with OV of 8 V, the PDE(850 nm) of NIR-HD is 20 % compared to standard RGB-HD that is 15 %, while if CS= 35 μm the PDE(850 nm) is 30 % (NIR-HD) and 20 % (RGB-HD) [135].

This region is very interesting for LIDAR (light detection and ranging or laser imaging detection and ranging) applications like: automotive, industrial and atmospheric LIDAARs [136]. Moreover, NIR region is attractive for fluorescence light detector [137] and low light levels near-infrared spectroscopy [138].

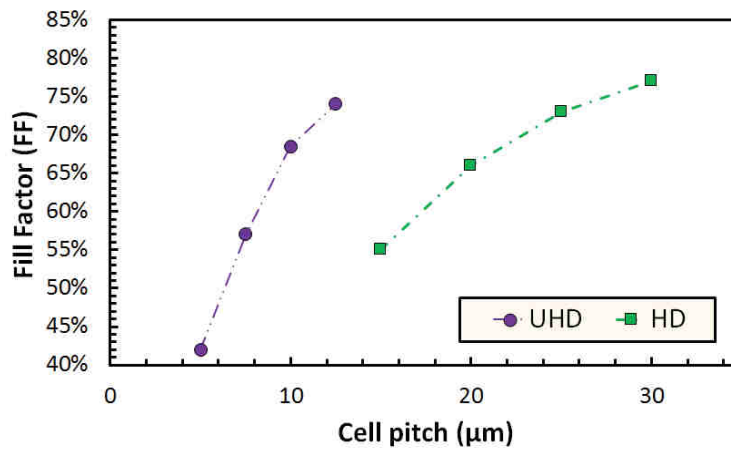


FIGURE 3.3: Fill factor as function of cell size for the HD and the UHD technologies

- **UHD-SiPM** (ultra high density), trench technology was obtained by further improved reducing dead border from 2 μm to 1 μm , Fig. 3.2C. Together with

a modified hexagonal cell layout, these features allowed to make CS between $12.5\ \mu\text{m}$ and $5\ \mu\text{m}$ with reasonably high FF (Fig. 3.3), considering the cell size, and density up to $\sim 40000\ \text{cell}/\text{mm}^2$. SiPM-UHD has a very high linearity up to high photon flux and low correlated noise but typically smaller PDE [117].

Potential applications of UHD technology are in medical hadron therapy [132], calorimeter detectors for particles physics [128] and more generally applications with radiation damage [139].

- **NUV-HD-LF** (low field) is a specific technology developed for cryogenic temperature and is very well suited for DarkSide-20k. Thanks to a deeper implantation (see Fig. 3.2G), a reduction of the peak electric field at breakdown was obtained. This allowed a reduction of the tunneling component of DCR generation, which determines the SiPM DCR at cryogenic temperatures. The result is a reduction of DCR from few Hz/mm^2 (standard field) up to few mHz/mm^2 (low field) at 77 K [140].
- **VUV-HD-LF** (vacuum ultraviolet) technology was developed for scientific experiments using liquid Xenon as a scintillator (emission at $175\ \text{nm}$), particularly for the nEXO experiment [141]. Photons at $175\ \text{nm}$ are absorbed in the first nanometers below the surface, where there is a neutral region. Then, the ARC (anti reflective coating) is modified to improve the transmission coefficient for this region of wavelengths. Actually, the PDE max ($\lambda = 175\ \text{nm}$) for VUV-HD-LF with CS of $35\ \mu\text{m}$ is of 22 % with OV of 3 V [81] [135].
- **NUV-HD-LAP** (low afterpulsing) is the second main technology split aimed at improving performance at cryogenic temperatures. When operated below 100 K, previous SiPM technologies showed a significant increase of correlated noise, in particular of afterpulsing. This severely limited the maximum operating overvoltage range (OV_{Max}) to 3 – 4 V at low temperature. The physical process is currently under investigation, but the most plausible explanation is that the release time constant of trapped carriers increases at low temperature, especially in certain parts of the device. The increment of AP can be controlled by implantation of a specific process-dopant. The dopant efficiently reduces AP at low temperature and increments OV_{Max} almost to values that can be obtained at room temperature. The results are published in [81] and will be discussed later.
- **NUV-HD-Cryo** is the technology includes all the technology splits useful for cryogenic operations, developed by FBK until 2018, and is the one selected for DarkSide-20k. It includes features from the following, previous technologies: NUV, HD, LF, LAP and, in addition, a quenching resistor (R_q) with low dependence on temperature. This last feature is realized changing the doping level of the polysilicon, implementing the quenching resistor. In this way, LAP

technology allows using low R_q values at cryogenic temperature compared to SiPM without LAP, thanks to the reduction of afterpulsing. Therefore, it is possible to decrease the recharge time constant that improving the performance of readout. The characterization is showed in next chapter [81].

NUV-HD-Cryo represents an enabling technology for future large-scale LAr-based of dark matter and neutrino experiments, like: DarkSide-20k (chapter) and DUNE (deep underground neutrino experiment) [142].

Different technologies can be implemented or combined to realize specific features as Fig. 3.1 shows.

Chapter 4

Results

In this chapter, we show and discuss the main results of characterization of the following: High-Density Near-Ultra-Violet (HD-NUV) , HD-NUV Low Field (LF) and HD-NUV-LF Low Afterpulsing (LAP) SiPMs, where SiPMHD-NUV-LF-LAP is also called with suffix -cryo. The performances are obtained measuring a few samples that are representative of different technologies. The first part of the characterization (sec.4.1) concerns the stability and the uniformity of SiPMs at low temperatures. In section 4.2, the output capacitance of SiPMs will be shown. In section 4.3, second divergence of reverse I-V is discussed depending on different parameters, while in sections 4.4¹ and 4.5, a full characterization focused on noise, gain, and PDE is presented, with an accent on the comparison of different SiPM technologies. Final section describes my personal contribution to the realization of first prototypes of motherboards.

4.1 Stability and uniformity of devices

In the first phases of cryogenic technology development, we did not know how SiPMs would have behaved in cryogenic conditions in terms of mechanical effects (delamination and cracking) and electrical effects (performance, stability and uniformity). Moreover, it was necessary to test a large number of devices to establish some types of trend. For these reasons, a series of measurements and stress tests in liquid nitrogen (LN) was made. LN has boiling temperature of 77.3 K, while DarkSide-20k will work with argon liquid at 87.3 K, thus we can consider the LN representative of LAr. For these tests, a full silicon to 6 *inch* wafer of SiPMs-HD-LF has been used.

In the table below, the sequence of measurements and immersions in LN are shown.

¹Errors in section 4.4 and section 4.5 are calculated like average value of errors obtained by single measurements of a quantity with relative methods described in chapter 2. This choice is justified by the fact that errors a certain measured quantity result similar. Errors are indicated with absolute errors or relative errors according to quantity considered. Sometimes, errors are indicated within a range depending on measure conditions. Among equal devices there could be fluctuations of parameters due to manufacture process and method of measurement.

Chronology of operations	measurement
Automatic wafer test at Room T	A
Slow immersion in LN for 10 <i>min</i>	
Automatic wafer test at Room T	B
Slow immersion in LN for 2 <i>h</i>	
Automatic wafer test at Room T	C
Fast immersion in LN for 10 cycles x 2 <i>min</i> each	
Automatic wafer test at Room T	D

IV curves of all working devices on the wafer were made four time (indicated with captions A, B, C and D) at room temperature. The measurement A was performed before the first immersion in LN. The wafer was manually immersed in a dewar as shown in Fig. 4.1.



FIGURE 4.1: Manual immersion of a SiPM wafer in dewar filled of liquid nitrogen

First two immersions were made with slow cooling in LN (keeping the wafer some minutes to few cm above LN). In first immersion, wafer was immersed for 10 minutes, while in second time for 2 hours. In third test, wafer was stressed with 10 fast immersions in LN for 2 minutes every time and with a pause of ~ 5 minutes between two consecutive immersions to warm the wafer. After each test, the wafer was optically inspected to research defects as cracks.

On these tests, no device resulted damaged to an optical inspections. SiPMs in the wafer had four types of cell: fast R_q with cell size of $20 \mu m$ (F20), F25, slow R_q with cell size of $25 \mu m$ (S25) and S35. Fast R_q means with nominal $R_q(77K) \sim 0.8 - 1.2 M\Omega$ and slow R_q means with nominal $R_q(77K) \sim 11 M\Omega$.

In Fig. 4.2, the resistors were shown for all four measurements made, where equivalent resistances (parallel of all R_q) were measured with method explained in section 1.4. The values of measurement "A" in blue seem to be those with higher dispersion, while in the following measurements, values have more uniformity and stability. Then, first measurement could have a conditioning effect that eliminated

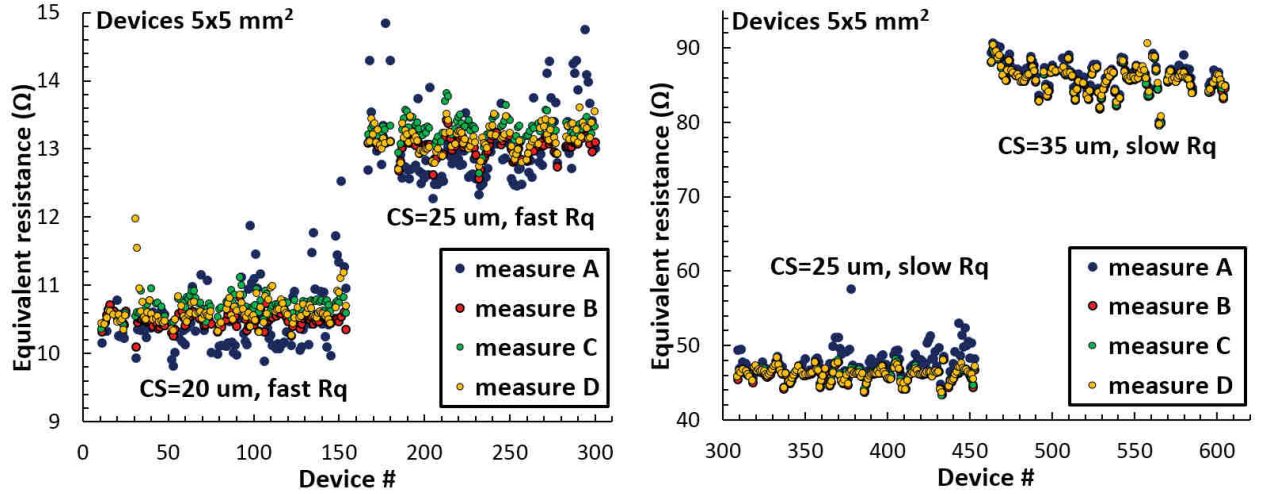


FIGURE 4.2: Equivalent resistor values of working SiPMs measured four times. Each color matches with one specific measurement as described in table. On the left, there are equivalent resistors of SiPM with fast R_q , on the right SiPMs with slow R_q

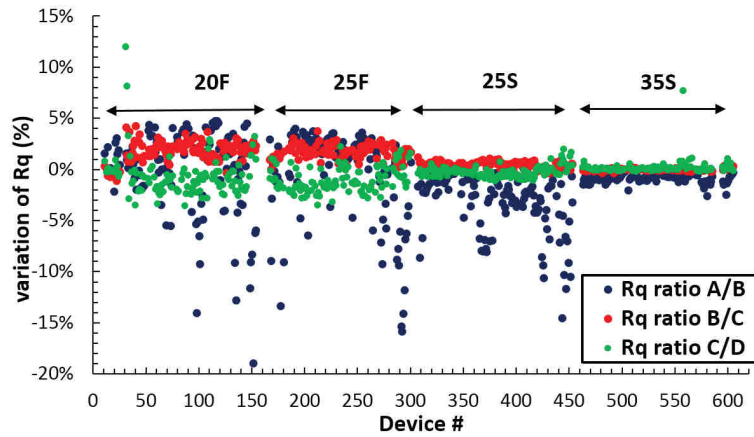


FIGURE 4.3: Percentage variation of R_q is given by ratio between two consecutive measurements of same device

static charges accumulated during manufacturing. The value dispersion is more evident for fast R_q and small cell size, because equivalent resistance is lower and is more influenced on parasitic series resistors due to setup, like cables and bad electrical contacts.

In Fig. 4.3, the percentage variations of R_q s for each SiPM are shown. SiPMs are ordered by type (F20, F25, S25 and S35) and the percentage variation is given by ratio between two consecutive measurements of same device. As in Fig. 4.2, the effect probably due to static charges is highlighted in Fig. 4.3 by the ratio A/B for devices: F20, F25 and S25, while subsequent ratios B/C and C/D have lower and more uniform dispersion values.

F20 and F25 show higher dispersion, moreover, an offset is visible in all devices

between ratio B/C and C/D . The offset effect can be due to a little variation of parasitic series resistors generated by setup. All initially working devices (475) were operative after all stress tests. In conclusion, we can say that LN temperature and fast temperature variations toward low temperatures do not have appreciable effect on device functionality after warm-up at room temperature.

At low temperatures, the uniformity may change, so automatic IV curves on entire wafer production have been made at lower temperature in addition to the usual measurements carried out at 20°C . The reverse and the forward measurements of IV are made to extract values of R_q and breakdown voltage (V_{BD}). Automatic prober used in FBK can operate at minimum temperature of -40°C which is far from LN temperature, but can still give indications on temperature trends. These trends show that the yield changes slightly, a result that supported the choice of the DarkSide collaboration to equip itself with a cryogenic prober to additionally investigate.

Fig. 4.4 sums up all R_q of three SiPM productions carried out at FBK during 2017 for DarkSide-20k with area of 1 cm^2 . Compared to previous layout, different splits of R_q and cell size were introduced. At same R_q value, SiPMs with large cell size have lower dispersion due to lower number of quenching resistors connected in parallel so higher parallel equivalent resistance is measured. Among wafers of the same type, there is a good uniformity of average value of R_q . The box width increases at -40°C but the relative error is averagely the same between two temperatures.

In Fig. 4.5, all V_{BD} at -40°C of working SiPMs are represented. The graph shows a certain discretization in Y-axis because voltage step is limited to 100 mV to maintain reasonable total measurement time of automatic prober. Lot2 and Lot3 have an excellent compatibility of average value of V_{BD} . Lot1 has average value of V_{BD} that differs of $\sim 0.78\text{ V}$ from others Lot2-3, but similar standard deviation. V_{BD} difference could be due to a setting offset of implant dopant machine. In any case, the average relative variation of V_{BD} at -40°C is lower than 0.6% .

In addition to stress tests in LN and the automatic IV curves at -40°C , a direct confirmation it was necessary to confirm the correct functionality of SiPMs at cryogenic temperature on a representative number of devices. In collaboration with DarkSide group of University of Federico II (Napoli), we measured IV curves of two tiles with 68 NUV HD LF SiPMs, both tiles have 90 SiMP slots singly read and protected by a glass, tiles were realized in Princeton. Pictures in Fig. 4.6 shows Napoli cryostat setup and one of tiles. The adapter board under tile separated SiPM signals with 3 connectors (externally switchable) by 24 channels each one with a configuration of $24+24+20$ SiPMs.

Signals were acquired by an automatic switching matrix with 24:1 channels. First tile was composed by 68 SiPMs $5\times 5\text{ mm}^2$ with a cell size of $25\text{ }\mu\text{m}$ and slow R_q , while second tile has SiPMs with cell size of $35\text{ }\mu\text{m}$ and slow R_q . From IV curves, R_q and

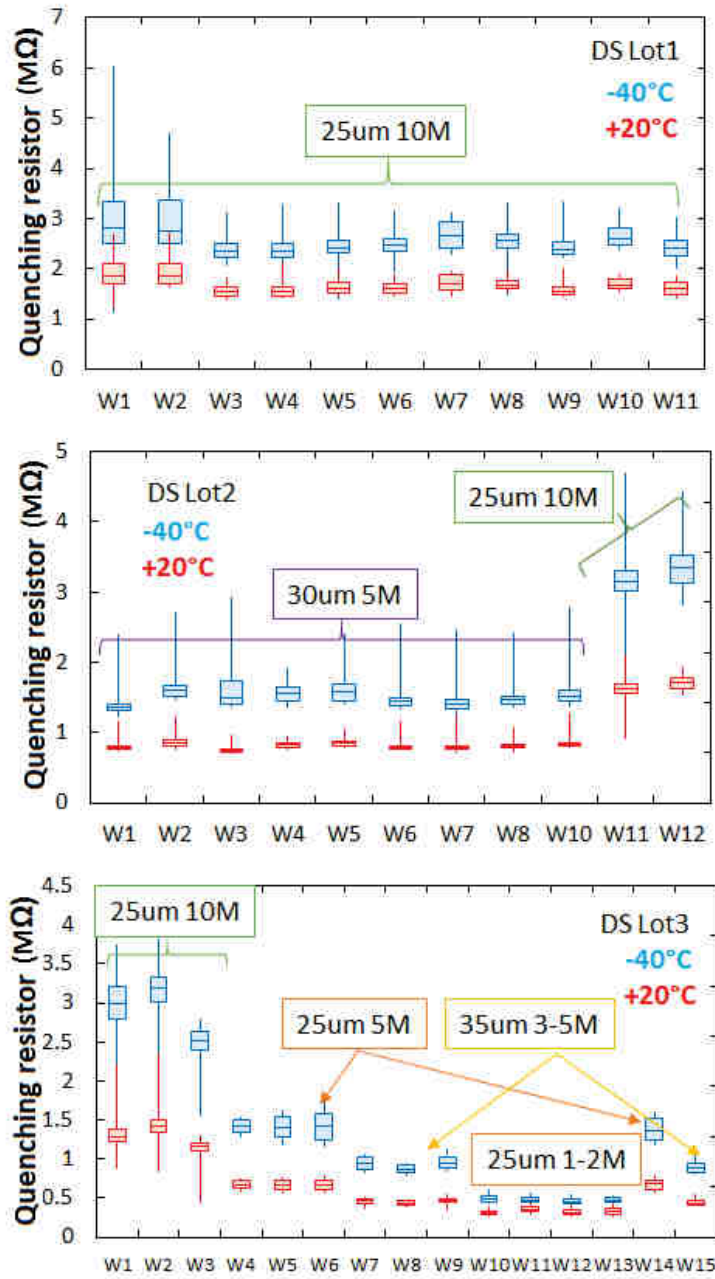


FIGURE 4.4: In all figures, quenching resistors are represented for all working SiPMs (of 1 cm^2) of three different productions of R&D (Lot1-Lot2-Lot3) that were made for DarkSide-20k. Each box includes 90% of the population of working devices, while box bars include 99% of the population. Red boxes correspond to measurements at 20°C , while blue boxes are those at -40°C . The labels indicate cell size and nominal R_q value in LN

V_{BD} for each single SiPM are always calculated with same technique explained in section 1.7.

In Fig. 4.7, SiPM resistors of two tiles are plotted at room temperature and at 94 K. In tile-1, 7 SiPMs were broken during the build of tiles. Moreover, a channel of

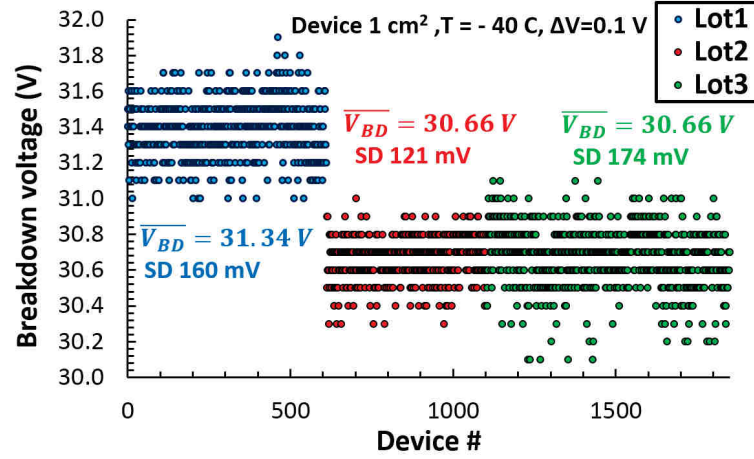


FIGURE 4.5: V_{BD} of all working SiPMs of the three production DS Lot1-2-3 divided by colors, the measurements are made at -40°C

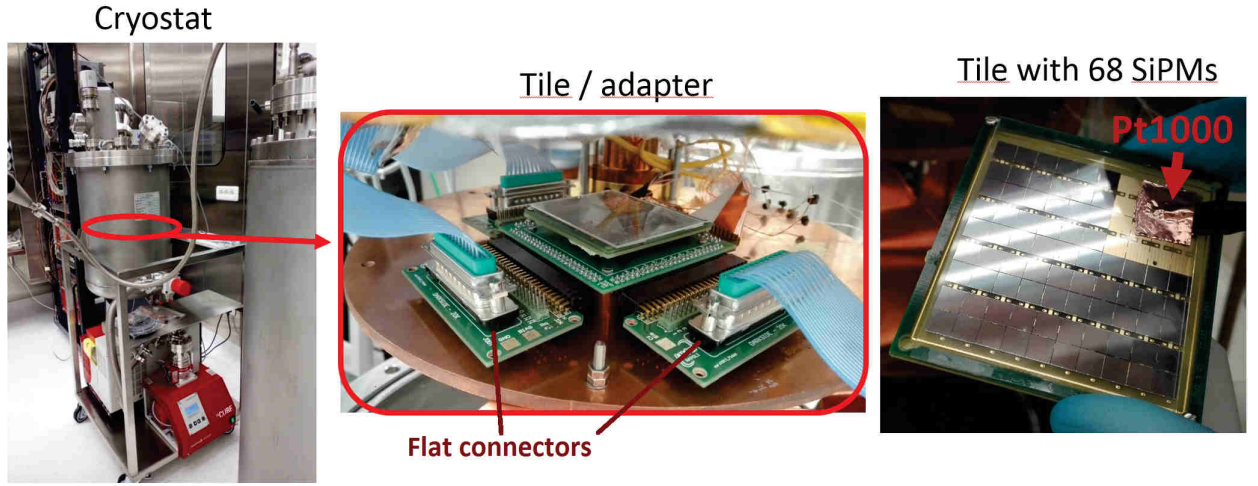


FIGURE 4.6: The first two pictures show the cryostat setup at the University Federico II of Napoli used to measure IV curves of two SiPM tiles at cryogenic temperature. On the right, one of tiles realized in FBK with 68 SiPMs

switching matrix seemed to have high series resistance because tiles at both temperatures have 4 SiPMs that are slightly out of distribution toward higher values (green circles in Fig. 4.7). Although the setup was not optimized, we obtained a relative variation of $\sim 6\%$ at 94 K.

Fig. 4.8 shows the V_{BD} measurements of two tiles for both temperatures. At low temperature, an optical fiber was used to illuminate SiPMs with faint light, this was made to well distinguish multiplied current ($V > V_{BD}$) from non multiplied leakage current ($V < V_{BD}$) and so improving the breakdown voltage estimate. If we sum both distributions of V_{BD} , we obtain on 129 devices: $\overline{V_{BD}}(296\text{ K}) = 33.95\text{ V}$ with relative variation of 0.44 % and $\overline{V_{BD}}(94\text{ K}) = 28.08\text{ V}$ with relative variation of 0.25 %.

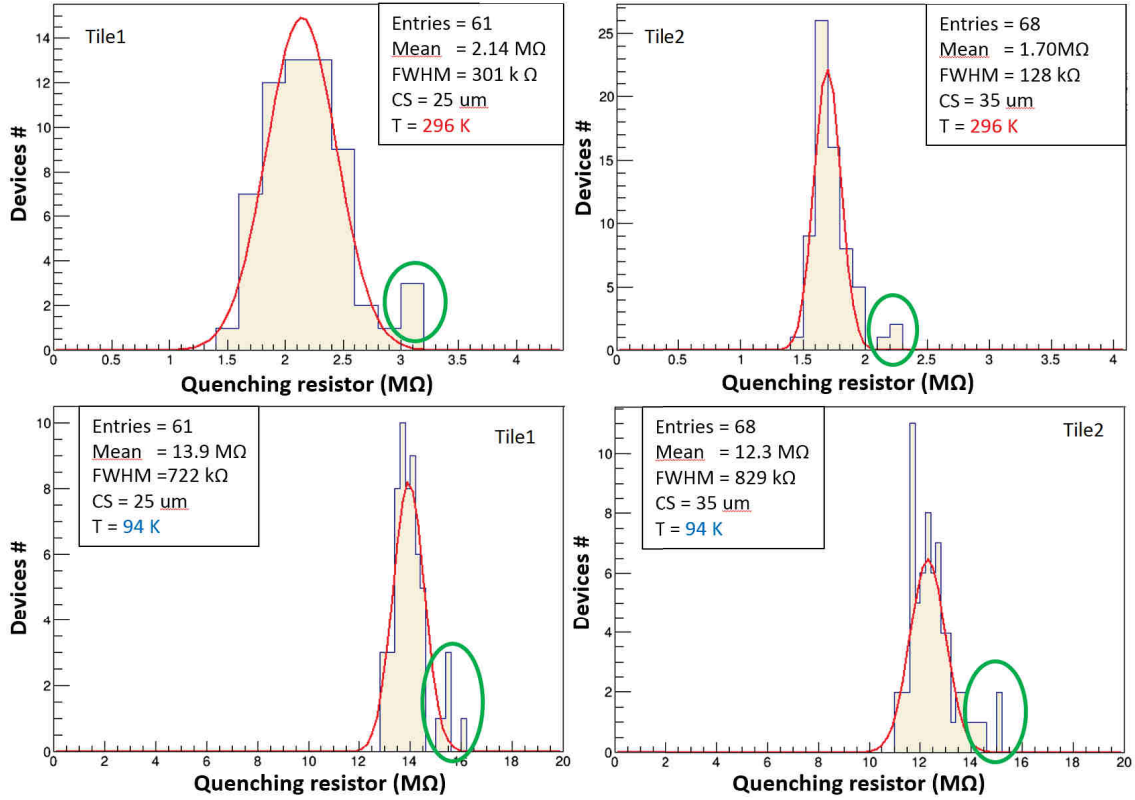


FIGURE 4.7: On the top, quenching resistors of tile-1 and tile-2 are measured at room temperature. On the bottom, the same R_q measured at 94 K

4.2 Measurements of output impedance of SiPMs

To design the front-end electronics, it is important to know the input impedance of the circuit, which is dominated by the SiPM output impedance.

We have done measurements of: Capacitance-Frequency (C-f), Resistance-Frequency (R-f) and Capacitance-Voltage (C-V). The used electric model was of type RC-series discussed in section 1.4, while used setup is described in section 2.4. All devices have an area almost of 1 cm^2 to minimize the effects of measurement fluctuation and parasitic capacitances.

The aim of frequency measurements is to estimate SiPM components like: cell capacitances C_d , parasitic capacitances of R_q which we call C_q and grid capacitance C_{grid} . However, if C_{grid} is enough small (true in case of High Density SiPM) as shown in sec.1.4, output capacitance C_{output} in first approximation is $\sim C_d \cdot N_c$ at intermediate frequency, where N_c = cell number, while at higher frequency ($\omega \gg 1/R_q C_q$), $C_{output} \sim N_c / (C_q^{-1} + C_d^{-1})$ [74].

In Fig. 4.9, C-f and R-f of different device (Low Field) are compared at 300 K and at 77 K. All measurements are made with at bias voltage of $V_{BD} = 1V$ to be as close as possible to the working conditions but without the DCR events. In Fig. 4.9A and B, around 1 – 3 MHz a resonance depends on SiPM parameters and allows

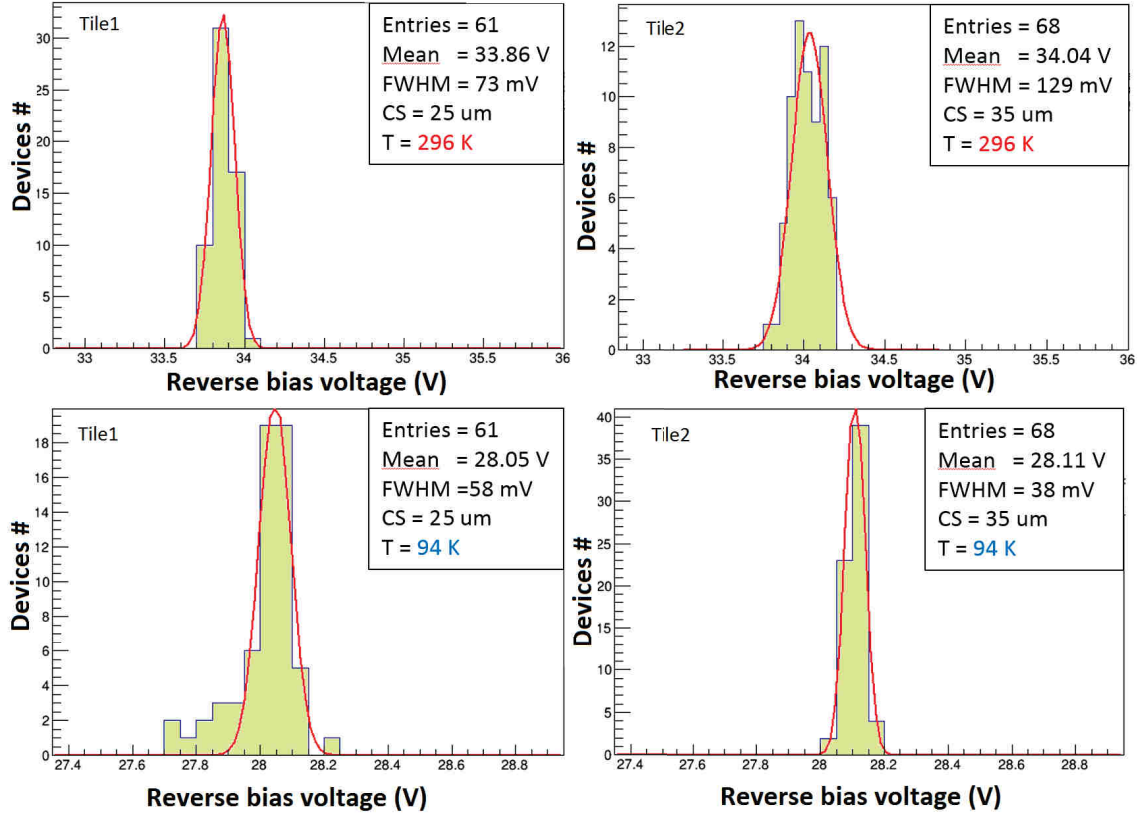


FIGURE 4.8: On the top, breakdown voltages of tile-1 and tile-2 are measured at room temperature. Lower, the same V_{BD} measured at 94 K

cell size	cell/ mm^2	nominal R_q _{77K}	Estimated R_q	
			300K	77K
25 μm	1600	10 M Ω	2 M Ω	10 M Ω
25 μm	1600	5 M Ω	1.5 M Ω	6 M Ω
25 μm	1600	1-2 M Ω	0.9 M Ω	1.3 M Ω
35 μm	816	5 M Ω	0.9 M Ω	3.5 M Ω

TABLE 4.1: Estimate of R_q obtained on Fig. 4.9C and 4.9D with $f = 100 \text{ kHz}$

we would assume that used RC-series model lose its validity, probably due to the adapters chain of setup used to measure capacitance in liquid nitrogen (see section 2.4).

Therefore, we can not estimate C_q via C- f measurements at high frequency but SiPM model is still valid at lower frequency so we can measure C_d via C-V measurements at fixed frequency of 100 kHz.

On Fig. 4.9C and 4.9D, R_q of different devices can be estimate through resistances measured at low frequency because are roughly $R_q \cdot N_c$ [74]. In legend, cell sizes (CS) and nominal (according to the layout) values of R_q (77 K) are reported, to know SiPM

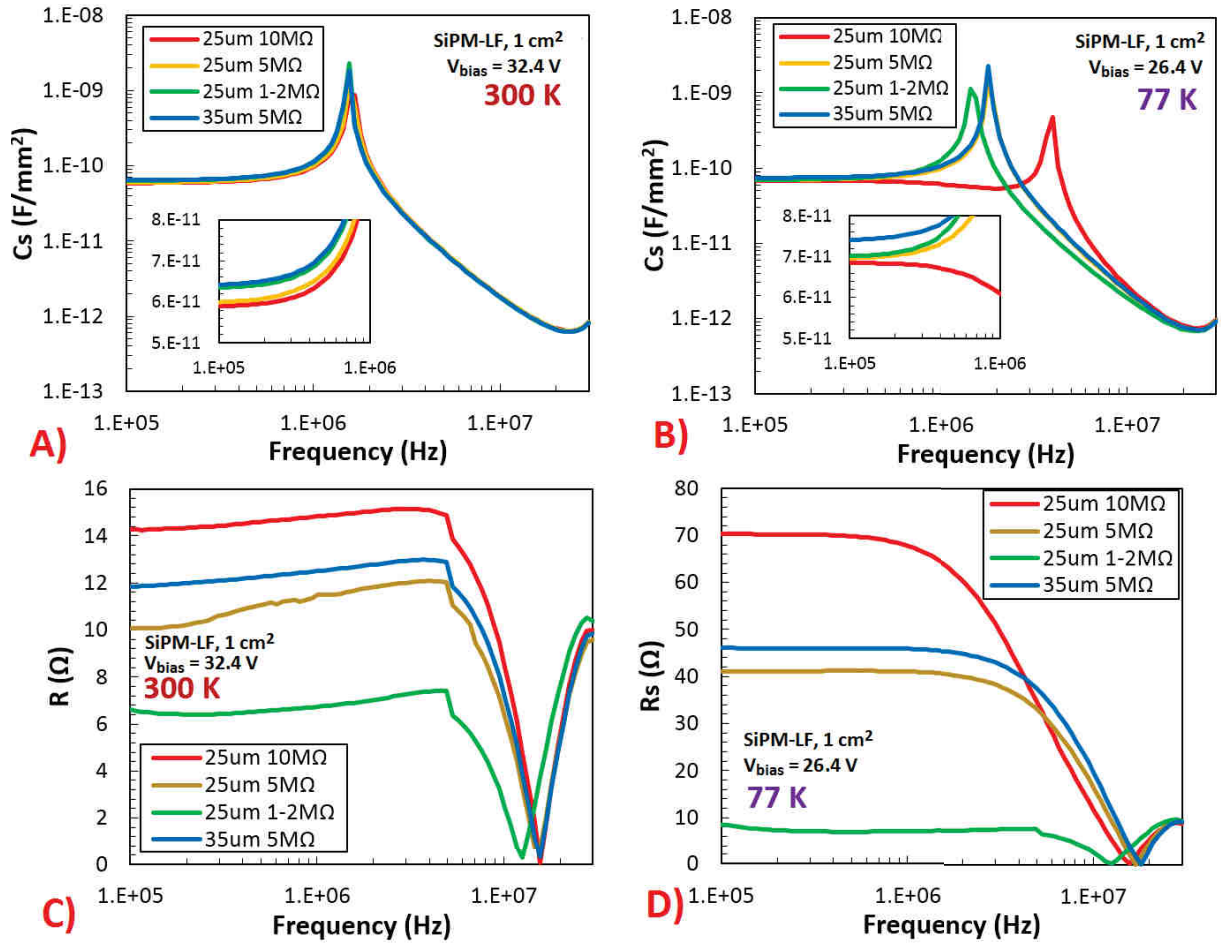


FIGURE 4.9: C_s - f (on the top) and R_s - f (lower) curves are plotted. On the left, there are measurements at 300 K; on the right, there are those at 77 K

area we obtain estimates of R_q that are reported in table 4.1.

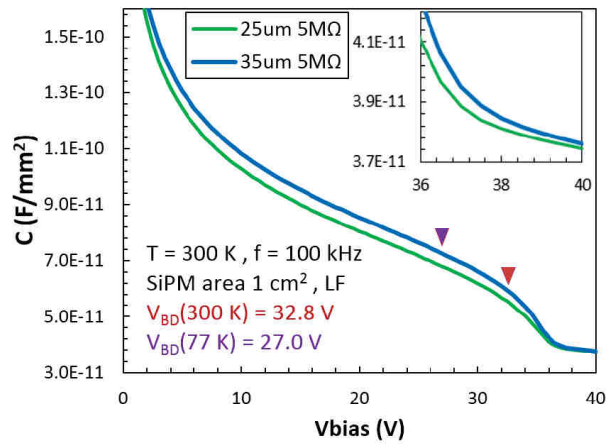


FIGURE 4.10: C-V curves are compared among SiPMs that differ for cell size at same conditions. $V_{BD}(300 K)$ and $V_{BD}(77 K)$ are indicated by colored triangles.

SiPM #	SiPM area	cell size	cell/mm ²	Technology	C _d (OV=6V)		C _{output} /mm ² (OV=6V)	
					300K	77K	300K	77K
1	97.7 mm ²	25 μ m	1600	LF	24 fF	34 fF	38 pF	54 pF
2		35 μ m	816		47 fF	71 fF	38 pF	58 pF

TABLE 4.2: Estimate of C_d and of C_{output} obtained on Fig. 4.10 at $OV = 6 V$ and $f = 100 kHz$

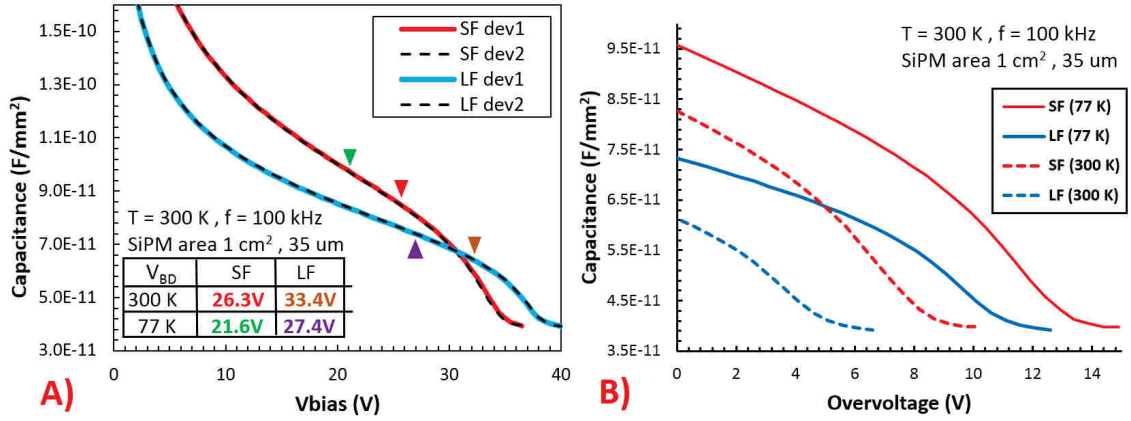


FIGURE 4.11: On the left, C-V curves are compared among SiPM-SF and SiPM-LF. V_{BD} (300 K) and V_{BD} (77 K) are indicated by colored triangles. On the right, the same measurements as a function of OV depending on temperature.

SiPM #	SiPM area	cell size	cell/mm ²	Technology	C _d (OV=6V)		C _{output} /mm ² (OV=6V)	
					300K	77K	300K	77K
3	93.2 mm ²	35 μ m	816	LF	49 fF	75 fF	40 pF	61 pF
4				SF	66 fF	97 fF	56 pF	79 pF

TABLE 4.3: Estimate of C_d and of C_{output} obtained on Fig. 4.11 at $OV = 6 V$ and $f = 100 kHz$

In Fig. 4.10, C-V comparison of different cell sizes is made at fixed frequency (100 kHz) and at room temperature. In LN, the shape of C-V does not change compared to one at room temperature. Generally, the capacitance decreases with increasing of reverse bias voltage because the depletion width of the junction, composing each microcell, changes with bias. At approximately 36 V, measured capacitance reaches a plateau because the edge of the depletion region reaches the interface between epitaxial layer and highly-doped substrate and, thus, cannot increase further. Triangles indicate V_{BD} at room temperature (red) and LN temperature (violet). The same device at fixed overvoltage has a higher output capacitance at lower temperature. Capacitance difference between the two cells is reduced when depletion region

achieves interface. To know SiPM area, CS and $C_{output}(100\text{ kHz}) \sim C_d N_c$, we can estimate C_d at $OV = 6\text{ V}$ (OV probably used in DarkSide) as reported in table 4.2.

In Fig. 4.11A, the C-V of two SiPM-SF (Standard Filed) and of two SiPM-LF are compared. C-V of same type of devices are well overlapping. The LF capacitance decreases less rapidly compared to SF capacitance, but it achieves the flatting at higher overvoltage. These difference depend on profile of pn -junction. The differences are highlighted if shown as function of overvoltage, Fig. 4.11B. In conclusion, if we observe breakdown voltages indicated by colored triangles, SiPM-LF compared to SiPM-SF at same overvoltage and temperature has lower output capacitance. C_d calculated of devices at $OV = 6\text{ V}$ are reported in table 4.3.

Device #1 and #2 of table 4.2 have not same technology of #3, in particular #1 and #2 are NUV-HD-LF while devices #3 and #4 are VUV-HD-LF and VUV-HD-SF respectively (technologies described in chapter 3). This could explain differences of V_{BD} and of capacitance between #2 and #3 at same CS and LF profile.

In conclusion, as seen in fig4.11B, the SF and the LF devices working far from depletion, especially in LN, where SF depletion happens for $OV \sim 14\text{ V}$ while LF depletion happens for $OV \sim 10\text{ V}$. Moreover, the capacitance increases because V_{BD} decreases with decreasing of temperature.

4.3 IV characterization in LN

In this section, the characterization is focused on the second divergence of reverse IV curves due to correlated noise (see section 1.7) in LN. The overvoltage where second divergence starts is usually indicated as the maximum operating voltage range (OV_{Max}).

All IV curves that are shown in the following plots are aligned so that all curves have $V_{BD} = 0\text{ V}$. This eases the comparison of second divergences among different devices. Furthermore, to accentuate breakdown voltage, IVs taken in LN are measured in faint light condition, otherwise in darkness condition, multiplied current ($I^{V_{bias} > V_{BD}}$) can not be distinguished on leakage current ($I_{leakage}^{V_{bias} < V_{BD}}$), because multiplied current decreases faster than the leakage current with decreasing temperature.

The second divergence depends on correlated noise ($AP + CT$), that, among other factors, depends on gain (Fig. 4.19F) and then on cell size (Fig. 4.19E). Fig. 4.12 shows a series of IV curves with cell size from $30\text{ }\mu\text{m}$ up to $40\text{ }\mu\text{m}$ for standard field (SF) and low field (LF) devices. As expected, OV_{Max} decreases with large cell size because gain at the same OV is higher. On the other hand, for any given cell size, LF technology reduces AP as it will be shown in section 4.4, increasing OV_{Max} by nearly a factor of two.

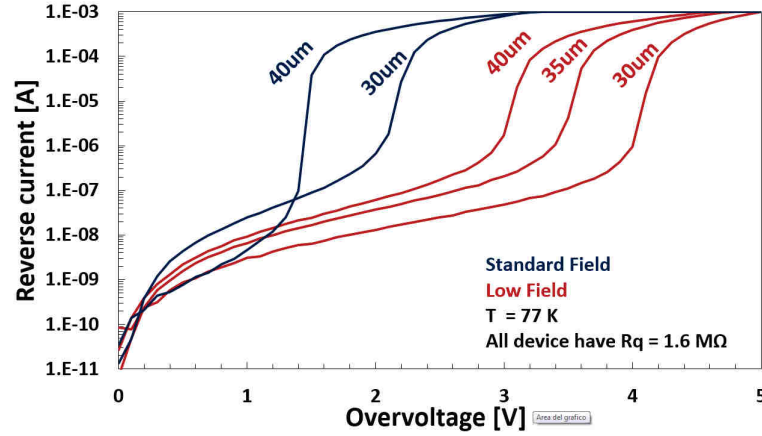


FIGURE 4.12: OV_{Max} comparisons between SiPM-LF (blue curves) and SiPM-SF (red curves) with different cell size

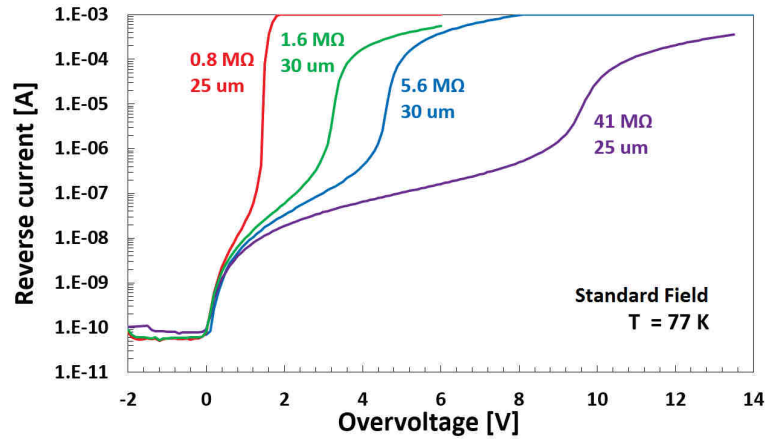


FIGURE 4.13: OV_{Max} dependence on quenching resistor in LN

The second divergence also depends on value of quenching resistor (Fig. 4.13). If the cell size is fixed, OV_{Max} increases with increasing recharge time constant, i.e. increasing R_q . If the life time of trapped carriers becomes sufficiently small compared to the recharge time constant, the trapped carriers are mostly released when the microcell is still partially discharged and, the probability that these carriers trigger an avalanche, i.e. the probability of having an afterpulse, is reduced. Indeed, we can observe a clear trend in Fig. 4.13, in which different comparable cell sizes with very different values of quenching resistor at LN show very different values of OV_{Max} : for example with R_q equal to $0.8 \text{ M}\Omega$, we obtain $OV_{Max}(CS = 25 \mu\text{m}) \sim 1.5 \text{ V}$, while with $R_q = 41 \text{ M}\Omega$ we obtain $OV_{Max}(CS = 25 \mu\text{m}) \sim 9 \text{ V}$. The main disadvantage is the increase of recharge time constant τ_{RC} , that in turn, reduces the SNR of signals amplitude and of cell gain, because it decreases signal amplitude and increases the integration time to estimate the gain, as explained in section 2.2.

Low Afterpulsing (LAP) technology was developed to reduce AP at cryogenic temperature. Several process splits were tried (with gradual doses of the process

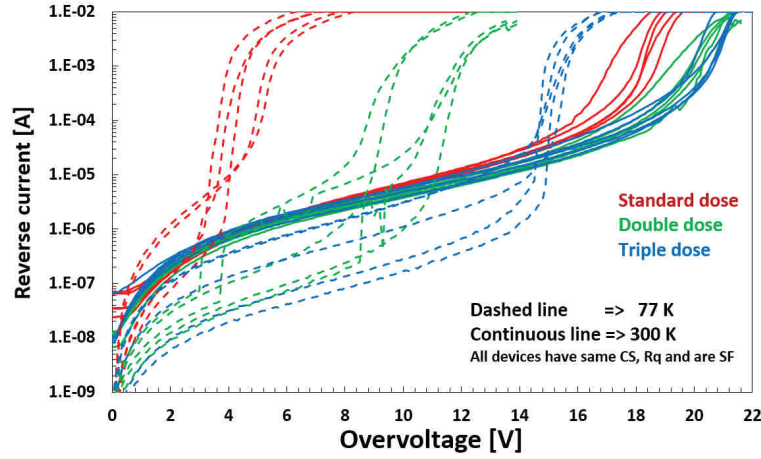


FIGURE 4.14: Five devices for each split of process-dopant dose are measured at 300 K and 77 K

dopant) and the last, the triple dose, the most effective at cryogenic temperatures was called LAP. In Fig. 4.14, the effect due to this technology is clearly visible. At room temperature (continuous lines), OV_{Max} is over 16 V in all three splits of process dopant and seems weakly dependent on process dopant dose.

On the other hand at cryogenic temperature, OV_{Max} of non LAP devices is severely limited by AP. Dashed curves, of Fig. 4.14, show as OV_{Max} is strongly influenced by dopant concentration. Comparing standard dose and triple dose in the same conditions of cell size ($30 \mu m$) and R_q ($\sim 6 M\Omega$), OV_{Max} increases from $\sim 3 - 4 V$ up to 14 V.

We can observe in Fig. 4.14 that OV_{Max} has some variations from sample to sample, within the same technology split. Thanks to LAP technology, SiPMs can be operated far from this region.

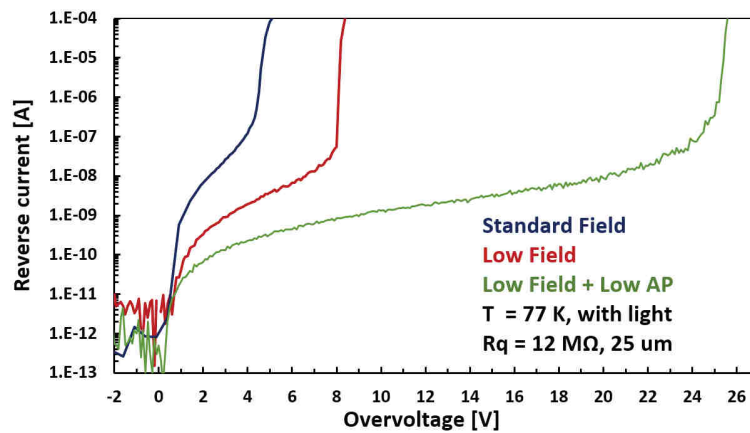


FIGURE 4.15: Second divergence comparison among technologies: SiPM-HD-SF, SiPM-HD-LF and SiPM-HD-LF-LAP

SiPM-NUV-HD-Cryo combines the benefits of LF and LAP technologies, which

are both effective in reducing the AP. The combined effect is shown in Fig. 4.15. Measured devices have same cell size ($25\ \mu\text{m}$) and R_q ($12\ \text{M}\Omega$) in LN. Cryo-device compared to standard one extends OV_{Max} of a factor of 5 times.

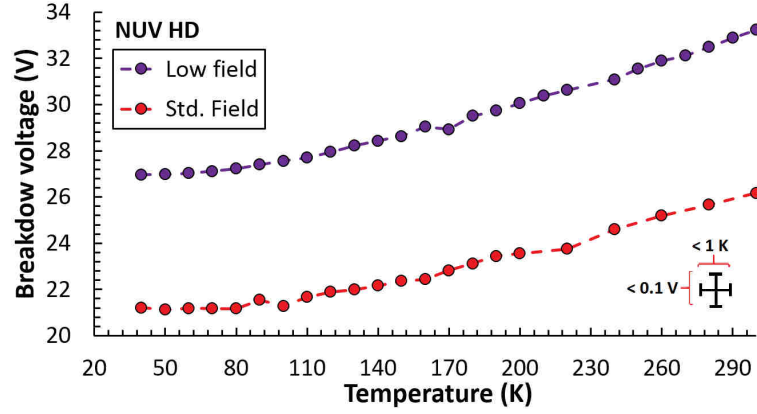


FIGURE 4.16: V_{BD} as a function of temperature

V_{BD} and breakdown voltage temperature coefficient, which we call C_T^{BD} , change with dopants profile. In Fig. 4.16, V_{BD} of LF and SF devices are compared as function of temperature. The two V_{BD} differ by about 3 V at any given temperature. From 300 K up to ~ 100 K, C_T^{BD} is approximately constant with $\sim 30\ \text{mV/K}$ (LF) and $\sim 25\ \text{mV/K}$ (SF). At temperatures lower than ~ 100 K, V_{BD} temperature dependence is significantly reduced and C_T^{BD} is reduced to $\sim 10\ \text{mV/K}$ (LF) and $\sim 4\ \text{mV/K}$ (SF).

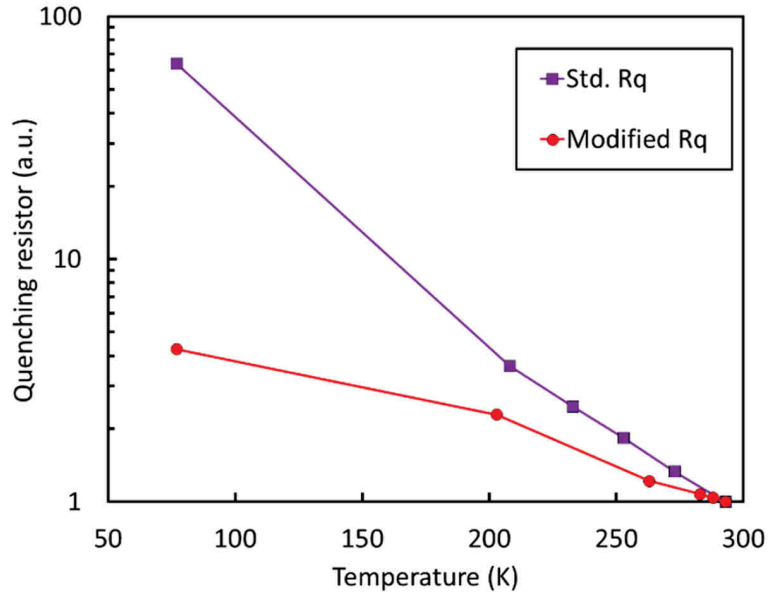


FIGURE 4.17: Comparison between quenching resistors with different dependence on temperature. Original figure taken from [81]

Thanks to the reduction of AP provided by LF+LAP technologies, it was possible to start a development aimed at obtaining a SiPM with relatively low value

of quenching resistance and of recharge time constant at LN, comparable or not excessively larger than the values at room temperature. As already discussed in this section, this provides advantages in terms of improved *SNR*, for a given design of the front-end.

As already mentioned in chapter 3, R_q temperature variations are dependent on the doping level of the polysilicon used to build the resistor and, in general, higher doping corresponds to lower value of resistance with lower temperature coefficient. Details of the process employed cannot be disclosed, for NUV-HD-Cryo FBK developed a resistor whose value that is $1.5 \text{ M}\Omega$ at 300 K and increases to $6.5 \text{ M}\Omega$ at 77 K , see Fig. 4.17. The variation is ~ 4.3 times, and compares favorably to the previous generation of the resistor, whose temperature variations were ~ 64 times.

4.4 Noise, Gain and recharge time constant

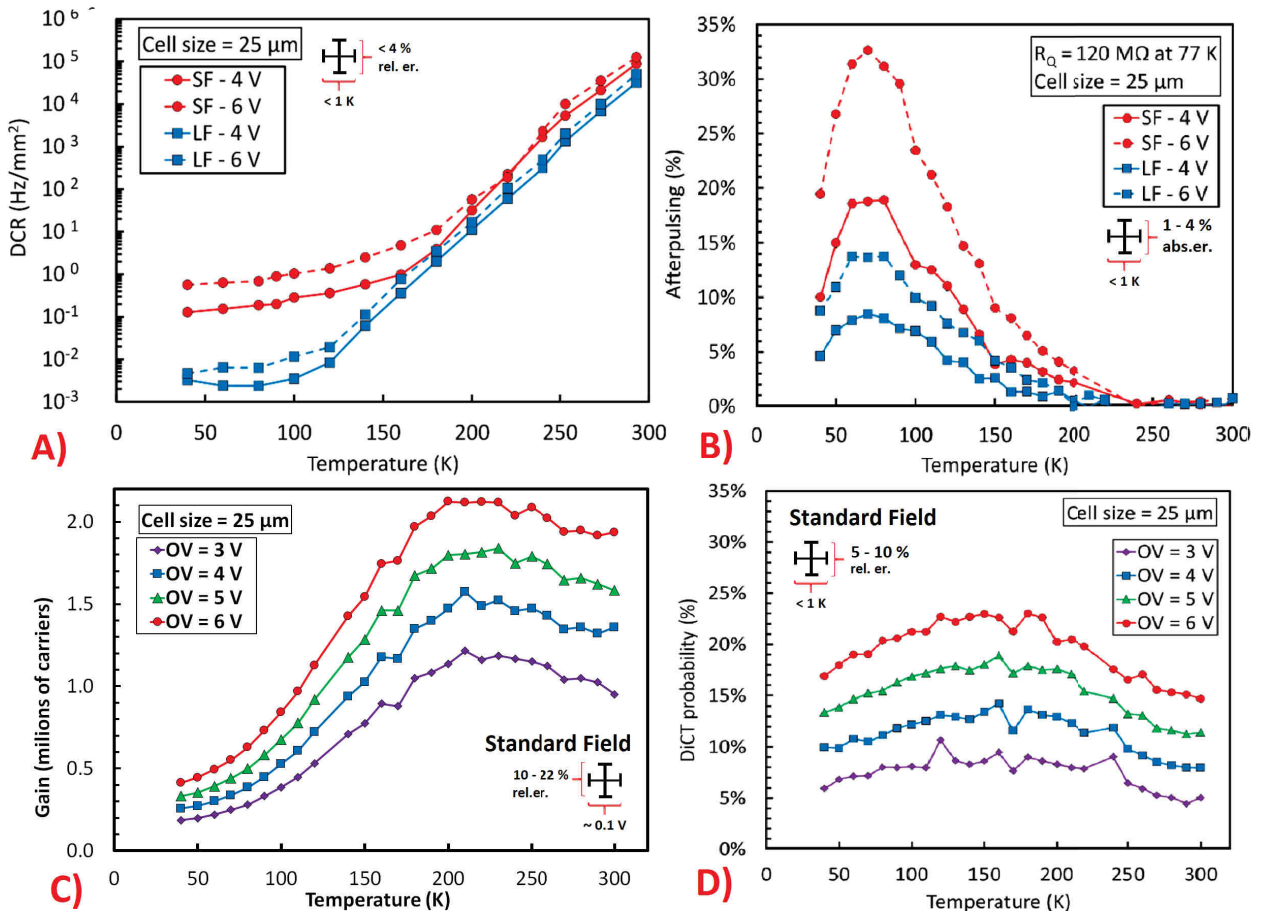


FIGURE 4.18: Comparison between LF and SF technologies for DCR, AP and Gain. In Fig.D DiCT is characterized as function of temperature. Original DCR, AP and DiCT figures are taken from [140]

In this first part, NUV-HD-LF and NUV-HD-SF technologies are compared to show benefits due to LF devices at cryogenic temperature. Fig. 4.18A and B show

comparison of DCR and AP for two overvoltage (OV) values in a temperature range between 40 K and 290 K. In DCR figure, two regimes are evident as explained in section 1.5. At high temperature, DCR of LF is slightly lower than SF but they have the same order of magnitude. Below of 150 K generation by tunneling effect in SF devices starts to be dominant with respect to on thermal generation, because peak electric field and, thus, band to band tunneling probability is lower in LF devices, corner temperature is lower, at 100 K. At LN temperature, if we make the ratio between DCR of LF device and DCR of SF device we have $DCR_{SF}/DCR_{LF} \sim 100$ for a fixed OV.

Considering afterpulsing (AP), Fig. 4.18B shows that the peak of AP is around 70 – 80 K for both technologies. The behaviour is consistent with OV_{Max} reduction with decreasing temperature (Fig. 1.26 and Fig. 1.28). We point out that, at the same OV, LF device has an AP reduction of ~ 2 times, especially at low temperature. To be able to use these devices up to OV of 6 V at cryogenic temperatures, we need to suppress AP by increasing of the microcell recharge time constant τ_{RC} to $\sim 6 \mu s$, which requires a value of the quenching resistor of $\sim 120 M\Omega$.

From 300 K up to 200 K, as expected, the gain of SF device in Fig. 4.18C confirms trends of C-V (Fig. 4.11), i.e. gain slowly increases with decreasing temperature because cell capacitance increases. For this device, at 300 K, $\tau_{RC} = 70 ns$ while from 200 K up to 40 K, it increases from 300 ns up to 6 μs . Measurements were not made with updated method described in section 2.2, moreover, integration time of signal was fixed to 500 ns. The combination of τ_{RC} increase and old measurement method cut part of charge during avalanche with decreasing temperature, thus, underestimating the gain.

The DiCT, in Fig. 4.18D, weakly depends on temperature. A constant OV, we observe a slight increase of DiCT, when cooling, followed by a decrease. A possible hypothesis to explain this behaviour is that, when going from room temperature to 150 K gain increases (Fig. 4.18C) and, thus, also the number of secondary photons emitted by the avalanche increases. Under the hypothesis that depletion and charge collection properties of the microcell are not significantly changed, we observe an increase of CT. On the other hand, below 150 K, depletion, even at high OV, is reduced, together with the collection efficiency of secondary photons. Thus, even though the gain of the cell is still increasing, DiCT probability is slightly reduced.

In the second part of this section, we report on the full characterization of SiPM-NUV-HD-Cryo technology developed by FBK after the R&D of different technology splits, described above. In Fig. 4.19, we show the results of the characterization for different cell size (CS) from 15 μm up to 45 μm at room temperature, SiPMs have same R_q value. In Fig. 4.19A, τ_{RC} is plotted as function of OV. If CS is fixed, τ_{RC} slowly decreases with increasing of OV because depleted region extends toward EPI layer and cell capacitance (C_d) decreases. In Fig. 4.19B for large CS, DCRs are similar,

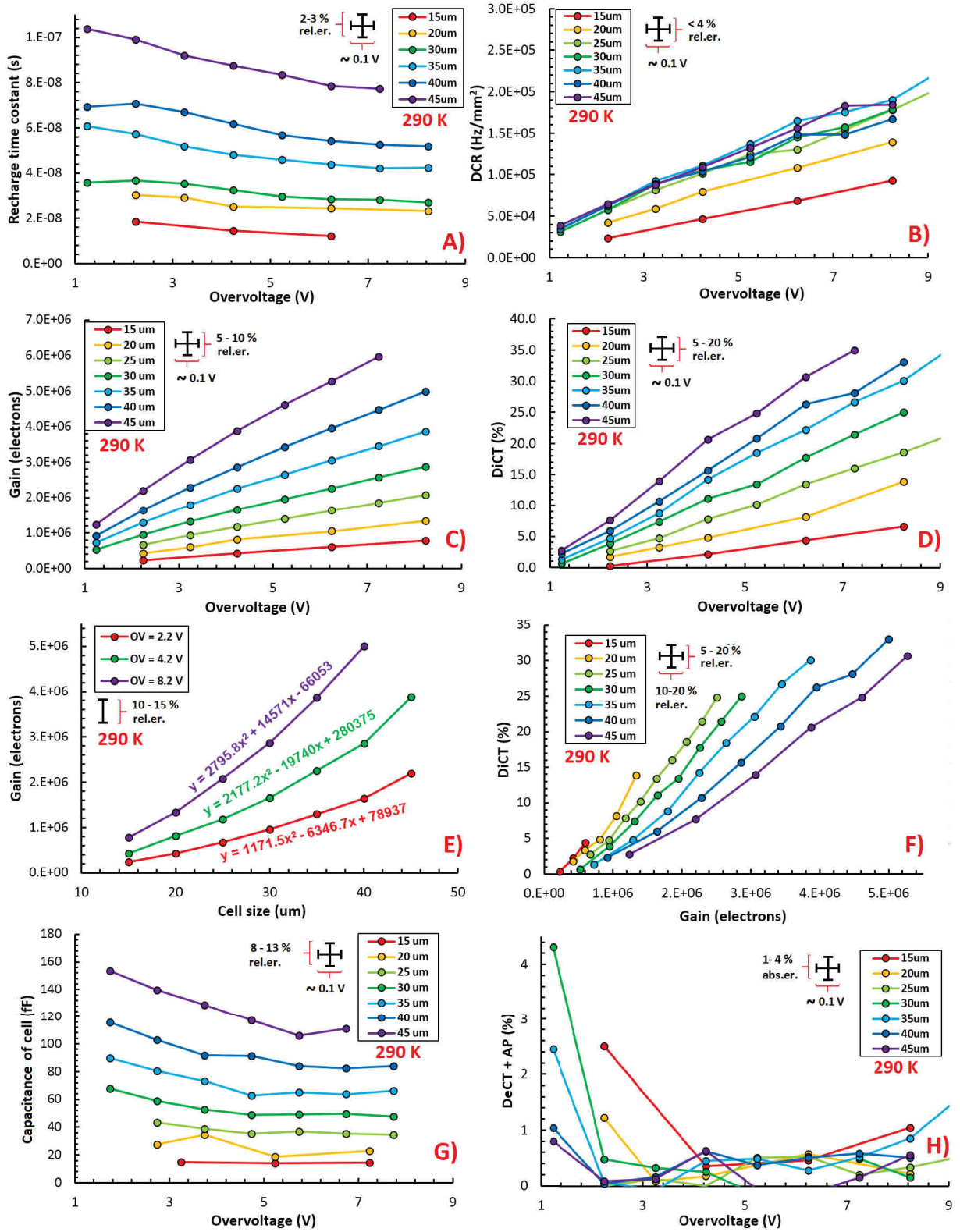


FIGURE 4.19: Complete dynamic characterization of SiPM-NUV-HD-Cryo (or SiPM HD NUV LF LAP) for different cell sizes at room temperature

while for lower CS DCRs decrease up to an half. This happens because between CS as $45\ \mu\text{m}$ and $15\ \mu\text{m}$ there is a large difference of fill factor ($\sim 80\%$ vs $\sim 55\%$). Therefore, effective active area of SiPM that can collect DCR events is enough different (see Fig. 3.3), while for the larger cell sizes this difference is much smaller. The gain dependence on OV (Fig. 4.19C) is approximately linear for each CS, while gain increases with square of CS (Fig. 4.19E). As expected, DiCT is roughly linear with OV and increases for large CS at same OV (Fig. 4.19D). It is interesting to note that, at the same level of gain, DiCT is lower for larger CS (Fig. 4.19F). In large cells, on average the avalanche is farther from the first neighboring cell, therefore, there is a probability non negligible that the secondary photons are absorbed in the same cell, thus, reducing the DiCT. [143]. By derivative of gain on OV (Fig. 4.19C), $C_d + C_q$ can be calculated from the derivative of the Gain vs OV curve (Fig. 4.19G), where C_q is parasitic capacitance of R_q that depends on layout and is typically 5 – 10 times smaller of C_d [74]. As observed on C-V in Fig. 4.10, C_d decreases if OV increases. If we take the value in Fig. 4.19G for devices with CS of $25\ \mu\text{m}$ and $35\ \mu\text{m}$ at room temperature and at $OV = 6\ \text{V}$ and we compare them to the table data in table 4.2 at same conditions, we obtain values similar, where the values in Fig. 4.19G are slightly higher of 20 – 30 %. Finally, Fig. 4.19H shows the sum of correlated noises DeCT+AP that can be considerate always negligible at room temperature.

In Fig. 4.20, we show the dependence on temperature of noise of NUV-HD-Cryo SiPMs, with $30\ \mu\text{m}$ and same R_q as devices in Fig. 4.19.

DCR of SiPM-LF (Fig. 4.18) at of SiPM-NUV-HD-Cryo (Fig. 4.20A) in LN temperature, are similar and under OV of $\sim 7 - 8\ \text{V}$ SiPM-NUV-HD-Cryo satisfies the requirement of DarkSide-20k experiment, setting a maximum acceptable level of DCR at 87 K of $80\ \text{Hz}/\text{mm}^2$. As expected from C-V in Fig. 4.10, the gain in Fig. 4.20B increases with decreasing temperature, at the same $OV = 6\ \text{V}$, the gain(77 K) is $\sim 18\%$ higher than gain(300 K). The gain over OV of $2.5\ \text{V}$ satisfies the project requirement of minimum gain of 1 M.

DiCT in Fig. 4.20D at low temperatures increases by a few percentage point, this effect is coherent with independent results of DiCT measurements in 4.18D, showing a slightly increasing of DiCT for decreasing temperature for fixed OV. DiCTs dependence on gain (Fig. 4.20C) is well overlapping for all temperatures, this supports the previous hypothesis that secondary photons emitted by the avalanche increases with increment of gain at low temperature. Further measurements at different low temperatures (with new cryostat) could confirm the reduction of CT below 150 K observed in Fig. 4.18D. Anyway the sum of total correlated noise ($\text{TCN} = \text{AP} + \text{DeCT} + \text{DiCT}$) is well under of project requirement with $\text{TCN}_{OV=7V} < 40\%$.

As seen in Fig. 4.18B, AP increases at low temperature. If we compare AP of SiPM-LF to one of SiPM-NUV-HD-Cryo in Fig. 4.20G, we have $\text{AP}_{LF} = 14\%$ and $\text{AP}_{Cryo} = 7\%$ with OV of $6\ \text{V}$ at LN temperature. In addition to the difference of

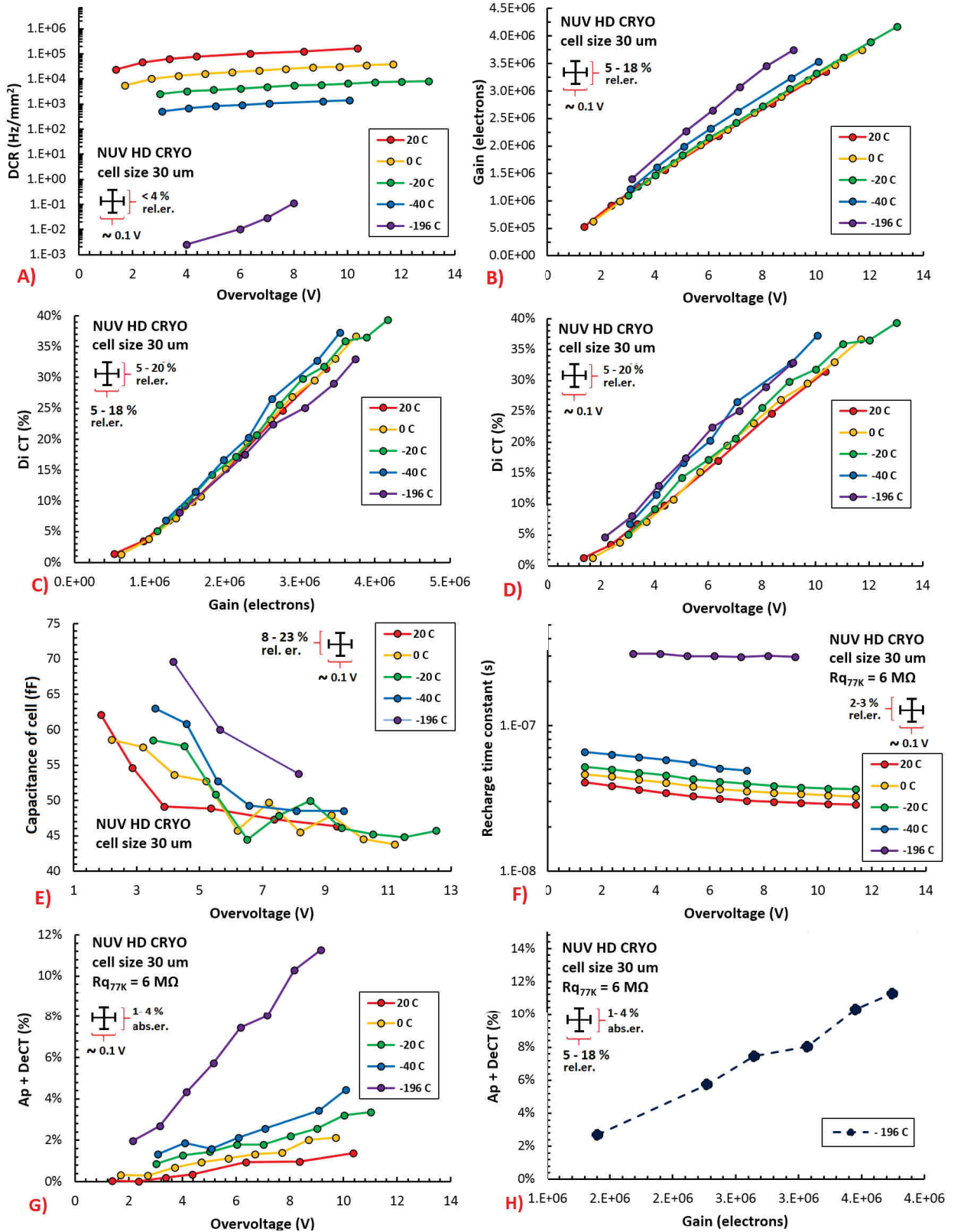


FIGURE 4.20: Complete dynamic characterization of SiPM-NUV-HD-Cryo technology with cell size of 30 μm , at different temperatures

cell size ($CS_{LF} = 25 \mu m$ and $CS_{Cryo} = 30 \mu m$), there is a very large difference of R_q in two devices: $R_{q_{LF}} \sim 120 M\Omega$ and $R_{q_{Cryo}} \sim 6 M\Omega$. Thanks to LAP technology in SiPM-NUV-HD-Cryo, we can obtain better AP but with $R_q \sim 20$ times smaller and consequently with a recharge time constant much faster. In fact, $\tau_{RC}(77 K)$ is $\sim 300 ns$ (Fig. 4.20F). In last Fig. 4.20H, we noted that AP is linearly depending on gain at same OV at LN temperature.

4.5 PDE

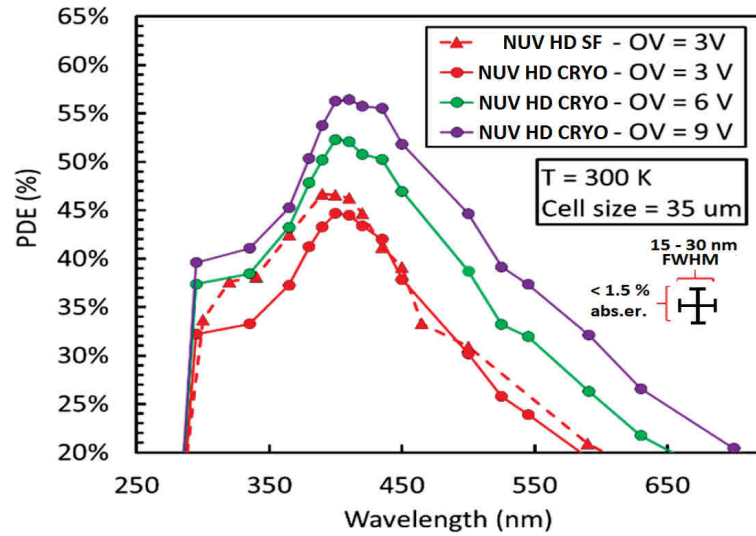


FIGURE 4.21: PDE comparison between NUV HD SF SiPM and NUV HD Cryo SiPM. Original figures taken from [81]

In Fig. 4.21, PDE comparison at room temperature (red curves) between SiPM-SF and SiPM-NUV-HD-Cryo is shown as function of wavelength (λ). For $\lambda > 430 nm$, PDE of two technologies are well overlapping, while for lower λ PDE_{SF} is systematically higher. At λ of interest of DarkSide project, PDE_{420 nm} of LF device is 2 – 3 % lower compared to PDE_{420 nm} of SF device. The cut-off at 290 nm is due to silicone resin used to coating the surface of SiPM with thickness of $\sim 200 \mu m$.

Coating has a double function: to protect active surface of device from damage and to average oscillations in PDE due to interference caused by the thin dielectric layers constituting the anti reflective coatings (ARCs) layer [144].

In Fig. 4.22A, PDE of NUV HD Cryo is plotted as function of OV with cell size from $15 \mu m$ up to $45 \mu m$ for $\lambda = 420 nm$ at room temperature. For different values of the OV, in Fig. 4.22B the same data are plotted as function of cell size. PDE increases due to increasing of fill factor for large cell size. Fig. 4.22C shows that large cells have higher gain compared to smaller cells at the same value of PDE, while the PDE curves as function of DiCT (Fig. 4.22D) have similar trends for different cell sizes.

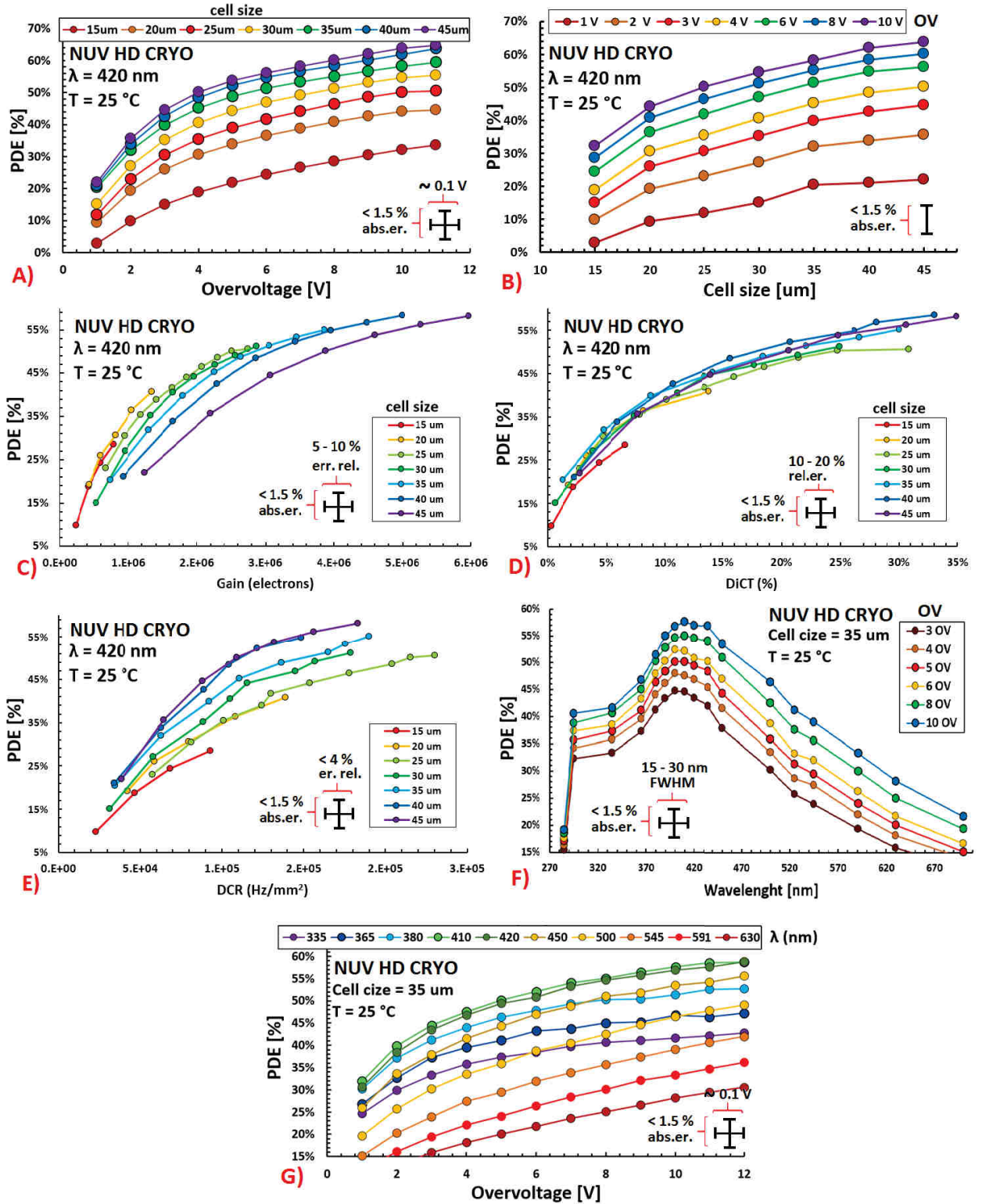


FIGURE 4.22: Complete characterization of SiPM-NUV-HD-Cryo in light

Fig. 4.22E compares PDE as function of DCR for different cell sizes from which it results that DCR is lower for large cells at the same PDE. This happens because the

PDE is more sensitive on FF compared to DCR. In fact, observing DCR vs OV (Fig. 4.19B) and PDE vs OV (Fig. 4.22A), DCR is already almost fully insensitive on the larger cell of $25\ \mu\text{m}$ at the same OV, while PDE increases with increasing of CS up to $45\ \mu\text{m}$ at the same OV.

In Fig. 4.22F, full PDE spectrum as function of λ of NUV HD Cryo SiPM is shown. In particular, NUV technology has PDE peak between $390\ \text{nm}$ and $430\ \text{nm}$. DarkSide project constraint is $\text{PDE}_{420\ \text{nm}} > 42 - 45\%$, the requirement is satisfied when $\text{OV} > 5.5 - 6\ \text{V}$ for cell size of $30\ \mu\text{m}$ and $\text{OV} > 4\ \text{V}$ for cell size of $40\ \mu\text{m}$ (Fig. 4.22B). The last Fig. 4.22G, PDE as function of OV curves for different λ and fixed cell size are compared (PDE theory in section 1.6).

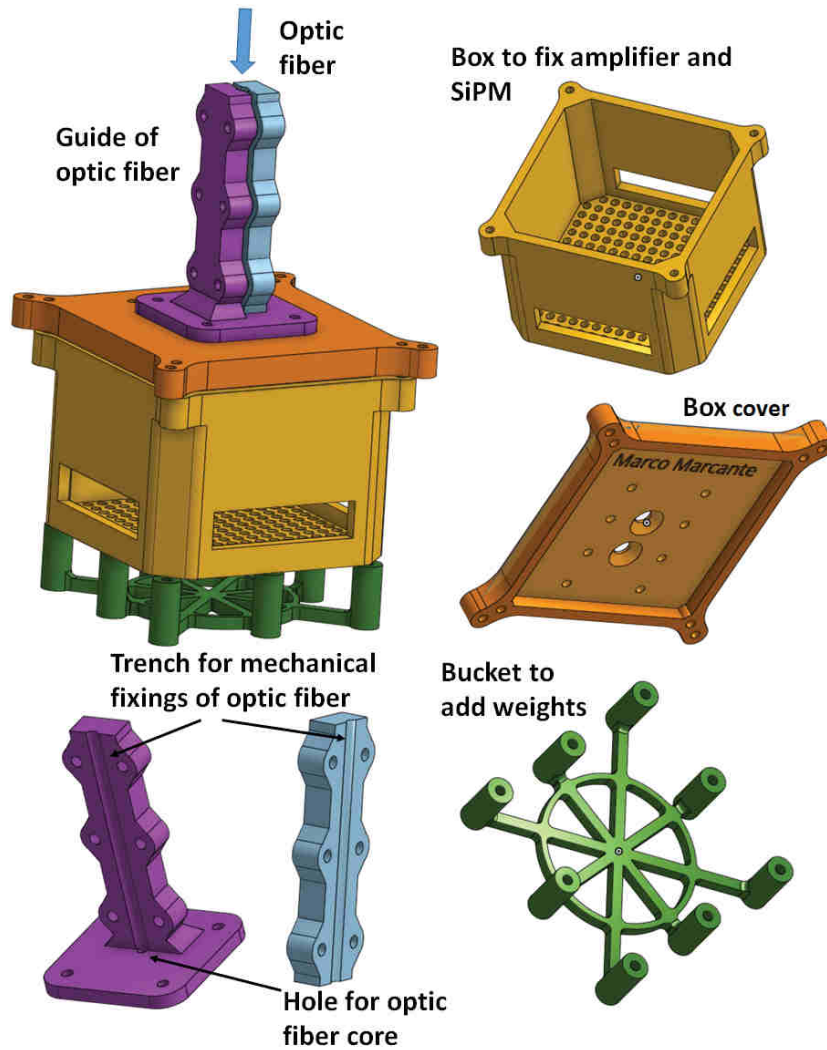


FIGURE 4.23: 3D plots of setup for relative PDE measured in liquid nitrogen

Construction of a suitable setup (section 2.3.1) at FBK to perform PDE measurements at cryogenic temperatures is not finished yet, at the time of writing this thesis.

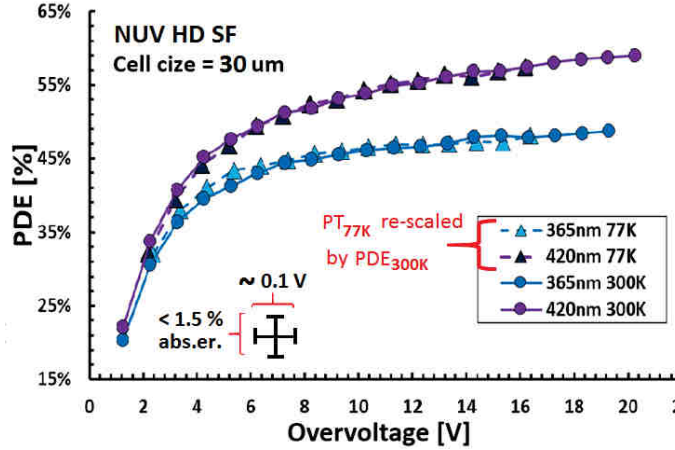


FIGURE 4.24: Extrapolation of $PDE_{420\text{ nm}}$ and $PDE_{365\text{ nm}}$ at LN temperature for SiPM-NUV-HD

Anyway, preliminary measurement of uncalibrated PDE in liquid nitrogen has been done.

Then, by comparing the obtained results to the calibrated, absolute PDE measured at room temperature, we obtain a preliminary, first indication of the absolute PDE at 77 K. In particular, we assume that the neither fill factor (FF) nor quantum efficiency (QE), especially at shorter wavelengths, do not change significantly between 300 K and 77 K. Under these assumptions, we calculate a calibration factor for the PDE measurements carried out at 77 K such as the saturation values of the PDE, i.e. the PDE achieved at high OV, match at both temperatures.

To carry out this measurement, the setup is similar to the one shown in Fig. 2.29. Instead of using an integrating sphere, with 3D-print an holder box that can be immersed in liquid nitrogen was realized (see Fig. 4.23). It consists of a pitted box where both amplifier and SiPM are housed, while under the box a bucket can be placed to add weights (because pieces are hollow). Over the box cover, two mechanical pieces guide the optical fiber and keeping it in a stable position. All pieces are connected by screws. Using this method, precise information on the quantity of light hitting device is missing because reference diode is not present. Consequently, it is not possible to measure absolute PDE ($PDE_{abs.}$) but only the PDE dependence on OV ($PDE_{rel.}$) given by eq.4.1:

$$PDE^{77\text{ K}} = \alpha \cdot PDE_{rel} \quad (4.1)$$

with α =calibration factor. However, it is possible to compare shapes of $PDE_{abs.}^{300\text{ K}}$ to $PDE_{rel.}^{77\text{ K}}$ that depends on trigger probability (T_P). $PDE_{rel.}^{77\text{ K}}$ is normalized with maximum value of $PDE_{abs.}^{300\text{ K}}$ when achieves saturation that means to achieves T_P^{max} .

We underline that this measurement is possible if, at high OV, correlated noise (especially AP) is under control (only with LAP technology), otherwise, it would

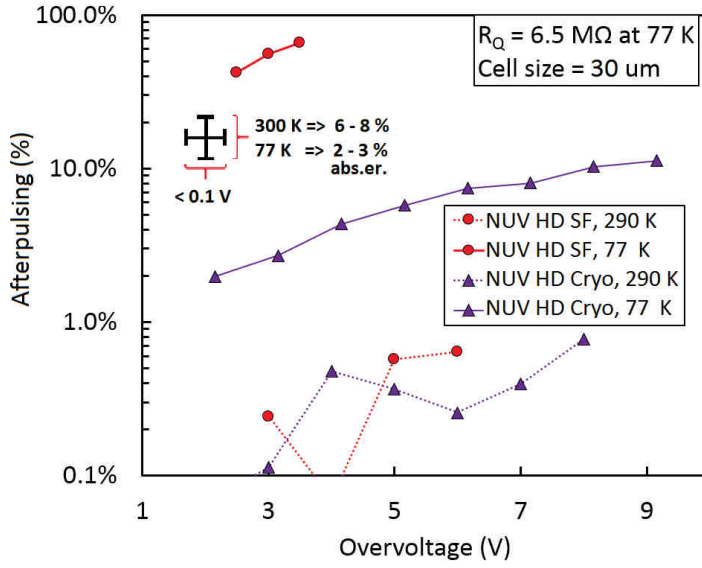


FIGURE 4.25: Comparison between DCR and OV in Fig.A and between AP and OV in Fig.B. Original figures taken from [81]

artificially increase PDE. The results are reported in Fig. 4.24, for a SiPM-HD-NUV-SF-LAP with cell size of $30\ \mu\text{m}$ at $420\ \text{nm}$ and $365\ \text{nm}$. The shapes of $\text{PDE}_{rel.}^{77\text{K}}$ and $\text{PDE}_{abs.}^{300\text{K}}$ are well overlapped at $420\ \text{nm}$, partly confirming the initial hypothesis that it would be possible to normalize PDE at $77\ \text{K}$ with data measured at $300\ \text{K}$. We also observe that $\text{PDE}_{rel.}^{77\text{K}}$ at $365\ \text{nm}$ increase a little faster for low OV, this probably happens because change shallow triggering probability due to higher mobility of electrons.

To complete the NUV HD Cryo SiPM characterization, in Fig. 4.25, DCR as function of OV and AP as function of OV are plotted to show improvements obtained from NUV HD SF SiPM to NUV HD Cryo SiPM at $300\ \text{K}$ and $77\ \text{K}$. DCR of NUV HD Cryo in LN is reduced of ~ 7 order of magnitude and of 1 order of magnitude compared to SF device (Fig. 4.25A). With same R_q at LN temperature, AP of NUV HD Cryo is reduced of more 1 order of magnitude compared to NUV HD SF (Fig. 4.25A).

In Fig. 4.4², main features and performances of NUV HD Cryo SiPM are summed up and compared between $300\ \text{K}$ and $77\ \text{K}$. Plotted parameters are related to device with CS of $30\ \mu\text{m}$ that operates with OV of $6\ \text{V}$.

4.6 Photo detector module

During the thesis activity, I have contributed to realization of first prototypes of motherboard used to cover the top and the bottom surface of DarkSide-20k TPC

²The measurements were made on different devices of same NUV HD Cryo technology, because the packaging and SiPM size change depending on type of measurement

SiPM-cryo with cell size of 30 μm , OV = 6 V		
	300 K	77 K
SiPM size	7.94 x 11.74 mm ²	
total cell number	102238 cells	
cell density	1100 cell/mm ²	
fill factor	77%	
R _q	1.5 M Ω	6.5 M Ω
V _{BD}	32.8 V	27.1 V
temperature coef.	30 mV/K (T>100 K)	10 mV/K (T<100 K)
cell capacitance by gain	49 $\pm$ 5 fF	58 $\pm$ 8 fF
2 nd divergence or OV _{max}	$\sim$ 25 V	$\sim$ 20 V
DCR	104 $\pm$ 5 kHz/mm ²	10.2 $\pm$ 0.4 mHz/mm ²
cell gain	2.0 $\pm$ 0.2 M	2.6 $\pm$ 0.4 M
DiCT probability	17 $\pm$ 2%	22 $\pm$ 2%
DeCT+AP probability	< 1 $\pm$ 1 %	8 $\pm$ 1 %
Recharge time constant	32 $\pm$ 1 ns	300 $\pm$ 8 ns
PDE (6V, 420 nm)	47 $\pm$ 1 %	/

TABLE 4.4: Main features of NUV HD Cryo SiPM

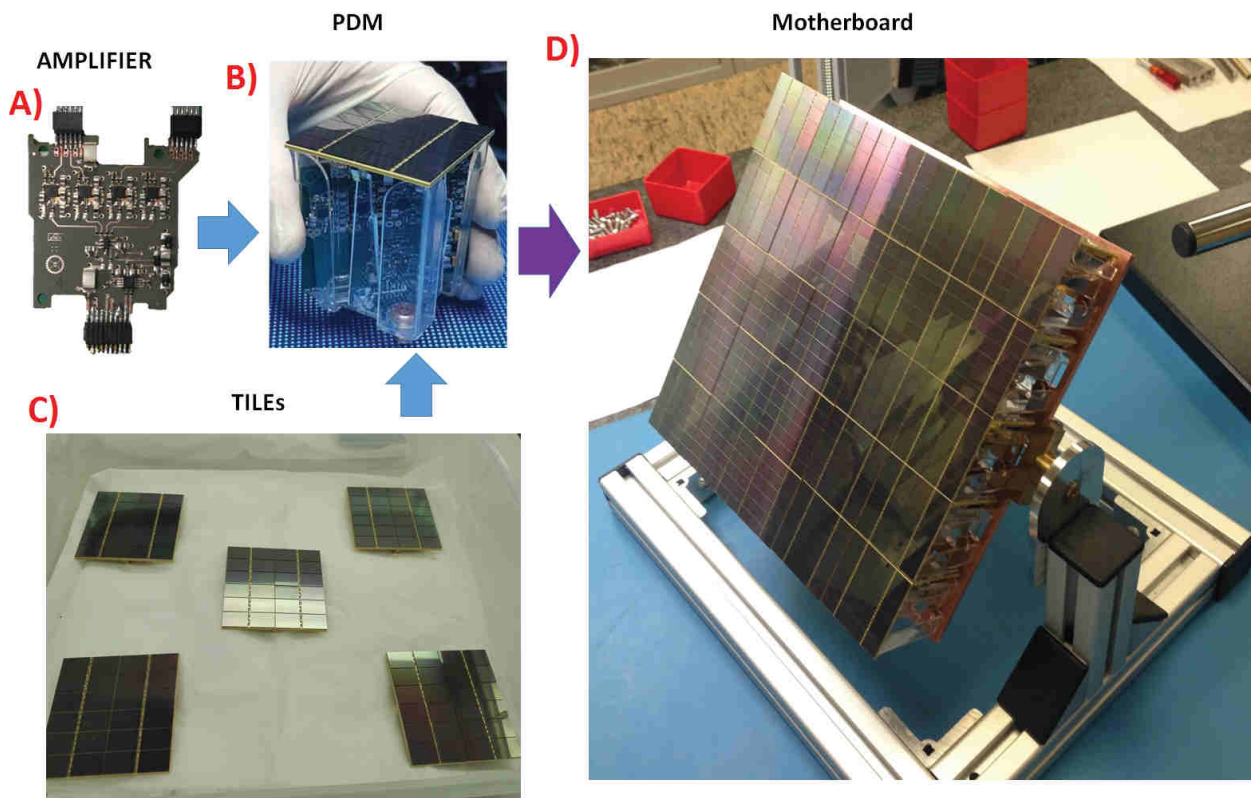


FIGURE 4.26: Original pictures A, B and D taken from [145]

Each motherboard has a size of $25 \times 25 \text{ cm}^2$ and is composed of 25 PDMs. More specifically, I spent two months at the University of Princeton (NJ, USA) to produce part of tiles that make up PDMs.

Single tile is composed of board designed by LNGS and array of 4×6 SiPMs realized in FBK. Board dimension is less than $5 \times 5 \text{ cm}^2$, while single SiPM is large $7.94 \times 11.74 \text{ mm}^2$. Dimensions should be taken into account for mechanical tolerance among PDM in the motherboard and among SiPMs in the tile.

Main operations to realize a tile are: selection of working devices on wafer; tracking wafer number and tile position of each SiPM to have history of all devices; Automated Fluid Dispensing Robot Nordson EFD EV2 [146] previously programmed by bi-component epoxy glue is precisely set down on contact pad of board to electrically connect and to glue SiPMs; SiPMs are manually oriented and placed by micro-positioner over board pads with a precision of $\sim 100 \mu\text{m}$; tile is put in oven between $100 - 150^\circ\text{C}$ to dry epoxy glue for about 1 hour depending on temperature; front connections are created among SiPMs and board pads by semi-automatic wedge-bonding machine.

Fig. 4.26 shows the main element of a motherboard: Front end Board (FEB) built at by LNGS to read 25 cm^2 of active area with single channel (Fig. 4.26A), some tiles that were realized in Princeton (Fig. 4.26C), a complete PDM (Fig. 4.26B) and the first motherboard assembled (4.26D).

Finally, in Fig. 4.27 you can see the energy resolution of single channel readout (25 cm^2 PDM area). The excellent result with $\text{SNR} = 24$ is obtained using a PDM with NUV-HD-cryo-SiPMs and it fully satisfies project requirement $\text{SNR} > 8$.

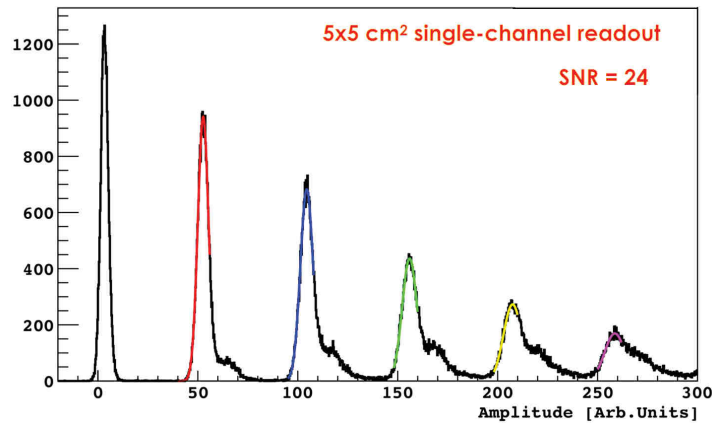


FIGURE 4.27: Energy spectrum of single PDM (25 cm^2) with NUV-HD-Cryo-SiPMs. Original picture taken from [44]

Conclusion

Silicon Photomultiplier (SiPM) is one of the key enabling technologies for large-scale dark matter experiments, such as DarkSide-20k, based on cryogenic noble liquid scintillators (LAr, in the case of DarkSide). It may also play an important role in next generation LAr-based neutrino detectors, such as DUNE, and liquid xenon based detectors for neutrinoless double beta decay (nEXO).

The research and development activity carried out during this thesis contributed to the realization of SiPMs with high performance at cryogenic temperature. SiPM is a pixelated photosensor, in which every single cell is made of a Geiger-mode Avalanche Photo Diode (G-APD), operated with a reverse bias voltage (V_{bias}) higher than the breakdown voltage (V_{BD}). Each G-APD includes a series resistor R_q that biases cell and quenches the avalanche. Optimization of detector characteristic at liquid nitrogen temperature (T_{LN}) required the development of a dedicated analysis software and experimental setup and the characterization of several technology splits, developed at FBK, each one of them aimed at optimizing a particular performance parameter. The result of this thesis can be divided in two parts.

The first part of thesis is focused on improvement and validation of analysis software to characterize SiPM nuisance parameters in a wide range of temperatures, obtaining, with high level of precision, dark count rate (DCR), correlated noises given on afterpulsing (AP) and optical crosstalk (CT), cell gain and recharge time constant (τ_{RC}).

Among all the software improvements that were made, the most important one is the extension of the functionality of the software to operate at cryogenic temperatures. When using the oscilloscope in the standard mode, acquisition window is triggered randomly (e.g. on the power supply line) and has a certain duration, usually in the order of a few milliseconds. The upper limit to its length is set by the memory depth of the instrument, considering that, in most cases, the sampling rate of the oscilloscope should not be reduced below 2 GS/s , in order to have a sufficiently accurate sampling of the SiPM signals. Subsequently, the software performs waveform analysis, using different pulse-finding techniques, and calculates amplitude and time distance between subsequent SiPM signals, also defined "inter-arrival time" within the same acquisition window. Processed data are represented in a signal amplitude vs. inter-arrival time scatter plot, in which components of noise are normally well distinguishable. With this technique, operating range of primary DCR measurement is from few tens of MHz/mm^2 (depending also on signal shape and

oscilloscope sampling rate), down to tens of kHz/mm^2 . Indeed, lower end of measurement sensitivity is set by the length of the acquisition window, as no timestamp is calculated if only one pulse is present in it. On the contrary, new analysis software combines the standard technique, used for high DCR, with a segmented memory acquisition mode, used for low and very low values of DCR. In the latter mode of operation, waveform acquisition is triggered by SiPM pulses and an accurate timestamp of the beginning of each windows is saved. By combining information from inter-arrival time of different acquisition windows and pulse finding within each window, a much broader DCR range can be measured. Indeed, if large SiPMs ($\geq 1 \text{ cm}^2$) are employed at low T and small SiPMs (1 mm^2) are used at high T, it is possible to characterize DCR of 9 order of magnitude from few MHz/mm^2 up to few mHz/mm^2 , which is a result never obtained before nor reported in literature before the beginning of this thesis work.

A second major improvement is the introduction of visual data filter, which can be applied from the software *GUI* and facilitates analysis of signals. The filter deletes data from analysis that are directly selected in scatter-plot. This strategy is convenient at cryogenic temperature, because at very DCR, time acquisition time can last for hours. Over this time, even few external noise events, such as fast dampen transients (few μs) and transitory oscillations (hundreds of μs) could generate hundreds of false events at one time. These false events have their discernable signature on the scatter plot and are usually confined in well-defined regions, so that they can be visually selected with a box and deleted by *GUI* filter.

Third major improvement of analysis software is measurement methods of cell gain, which is especially useful at cryogenic temperatures. Normally, gain measurement is calculated by integration of oscilloscope signal over a given time (t_{Int}), depending on τ_{RC} and, in order to integrate 99 % of charge $t_{\text{Int}} \simeq 5 \cdot \tau_{\text{RC}}$ is needed. Depending on the SiPM technology, τ_{RC} can increase by more than a factor of 65 at cryogenic temperatures, up to $10 \mu\text{s}$, thus significantly increasing the amount of electronic noise that is integrated and in some cases compromising the result of the measurement. Moreover, high AP probability at cryogenic temperatures can significantly affect gain measurement. Improved method allows reducing t_{Int} by a factor of 2 without changing the measurement result. In addition, filter selects signals that are integrated among those in which no afterpulsing has occurred within t_{Int} . By combination of these techniques, it results a reduction of relative uncertainty of gain up to $\sim 50 \%$ was achieved in the most demanding experimental conditions.

Among several improvements that were made to the cryogenic setup for SiPM characterization, a trans-impedance amplifier, operating with high speed and low-noise from T_{room} down to T_{LN} , was designed, realized and characterized. Moreover, dedicated SiPM holder and amplifier boards were designed and produced for new cryostat acquired by FBK.

The second part of the thesis is dedicated to characterizations and comparisons of several versions of Near Ultra-Violet (NUV) and High Density (HD) SiPM technologies (SiPM-HD-NUV). The peak of Photon Detection Efficiency (PDE) of NUV devices is between 400 nm and 430 nm , while HD technology improves the fill factor (FF), allowing small cell size with high FF: for example, $15\text{ }\mu\text{m}$ cell features 55 % FF and $40\text{ }\mu\text{m}$ cell features 83 %.

Among first results obtained, the reliability of SiPMs in LN was checked. A whole wafer with 475 working SiPMs ($5 \times 5\text{ mm}^2$) of different cell size (CS) and quenching resistor (R_q) were subjected to series of immersion cycles with different time lengths of immersion (from minutes up to hours) and transient times of immersion, adjusted with a special setup gradually lowering the wafer above the liquid nitrogen level (from minutes up to few seconds). After each cycle, optical inspection and IV measurement at room temperature (T_{room}) of all devices were made. At the end of all cycles, all initially working SiPMs were still operative and did not show visible cracks. Percentage variations of R_q between measurement made before and after an immersion in LN were within percentage variation due to parasitic series resistor of setup.

At 94 K (near to LAr temperature), the uniformity of V_{BD} and R_q were verified on 61 SiPMs with $CS = 25\text{ }\mu\text{m}$ and 68 with $CS = 35\text{ }\mu\text{m}$, all SiPMs had nominal (by layout) $R_q(77\text{ K}) = 10\text{ M}\Omega$ and are NUV-HD-LF (Low Field). Measurements were made in collaboration with University Federico II of Napoli and the results are: average quenching resistor $\overline{R_q}(94\text{ K})_{CS=25\text{ }\mu\text{m}} = 13.9\text{ M}\Omega$ with $FWHM = 0.7\text{ M}\Omega$ and $\overline{R_q}(94\text{ K})_{CS=35\text{ }\mu\text{m}} = 12.3\text{ M}\Omega$ with $FWHM = 0.8\text{ M}\Omega$, while average breakdown voltage $\overline{V_{BD}}(94\text{ K})_{\#SiPM=129} = 28.08\text{ V}$ with a relative variation of 0.25 %. Those values confirmed the good uniformity of two major SiPM parameters at cryogenic temperatures, which was never verified before and was necessary prerequisite to use this technology in the DarkSide experiment.

Measurements of capacitance vs. voltage (C-V) and capacitance vs. frequency were important to characterize other SiPM parameters, such as output capacitance, which was necessary for proper front-end design by other working groups within the DarkSide collaboration.

Moreover, measurements of capacitance vs. frequency (C-f) and resistance frequency (R-f) of SiPM gave values of cell capacitance and quenching resistor compatible with values calculated by cell gain and by forward IV measured at 290 K and 77 K .

V_{BD} temperature coefficient (C_T^{BD}) was measured for standard field (SF) devices and low field (LF) devices in a temperature range from 300 K up to 40 K . It result that $C_T^{BD}(LF)$ was 30 mV/K ($T > 100\text{ K}$) and 10 mV/K ($T < 100\text{ K}$), while $C_T^{BD}(SF)$ was 25 mV/K ($T > 100\text{ K}$) and 4 mV/K ($T < 100\text{ K}$). Two technology splits on the fabrication of the polysilicon quenching resistor (R_q) were tested: the standard version showed a high dependence (R_q^H) while an experimental version was engineered to

provide a low dependence (R_q^L) on temperature. The two splits were measured from 300 K up to 77 K. The resistance variations given by ratio of resistances measured between low temperature and high temperature obtained were: $\frac{R_q^H(77K)}{R_q^H(300K)} \simeq 64$ and $\frac{R_q^L(77K)}{R_q^L(300K)} \simeq 4.3$. Resistances with low dependence on temperature are implemented in latest version of cryogenic technology (SiPM-NUV-HD-Cryo), which will be used in the SiPM production for the experiment.

In reverse bias, IV characteristics features the so-called 2nd divergence after V_{BD} , due to divergence of correlated noise (AP+CT). The OV, where 2nd divergence starts, is indicated as the maximum operating OV (OV_{Max}). Characterization of $OV_{Max}(77\text{ K})$ was carried out investigating the effects of CS, R_Q , dopant profile (LF and SF) and specific process dopant concentration. In the same conditions, $OV_{Max}(77\text{ K})$ decreased with increasing CS because AP and CT are linearly proportional to gain (as a first approximation); on the other hand, $OV_{Max}(77\text{ K})$ increased with increasing R_q because high τ_{RC} suppressed AP probability. LF devices have higher $OV_{Max}(77\text{ K})$ compared to SF devices because, as shown on characterization, LF technology reduces AP probability. A dedicated process split, increasing a specific dopant concentration and aimed at reducing afterpulsing probability at cryogenic temperatures, was at the basis of the Low AP (LAP) technology at cryogenic temperature and it was implemented in combination with NUV-HD-LF technology in SiPM-NUV-HD-Cryo. An impressive result was the improvement of $OV_{Max}(77\text{ K})$ from 4 V in SiPM-HD-NUV-SF to 23 V in SiPM-NUV-HD-Cryo, at same condition with CS= 25 μm and $R_q = 12\text{ M}\Omega$. For SiPM-NUV-HD-Cryo, $OV_{Max}(77\text{ K})$ was reduced to 20 V if CS= 30 μm and $R_q = 6\text{ M}\Omega$. The higher overvoltage at which the SiPMs can be operated, allow saturating Photon Detection Efficiency at 420 nm, which is the wavelength of interest for the DarkSide experiment, and increasing gain, which improves SNR in few photon counting, which is one of the most important parameters of the photo-electronics of the experiment.

SiPM-NUV-HD-Cryo is the result of several technology optimizations, developed by FBK and carefully evaluated during this thesis, aimed at satisfying project requirements of DarkSide-20k experiment at liquid argon temperature (87 K), that are: $\text{DCR} < 80\text{ mHz/mm}^2$, $\text{cell gain} > 1\text{M}$, total correlated noise probability (TCNP) < 60 %, $\text{PDE}(420\text{ nm}) > 42 - 45\%$.

SiPM-NUV-HD-Cryo technology was characterized using devices with CS of 15, 20, 25, 30, 35, 40, 45 μm at 290 K. Quantities measured were: DCR, cell gain, cell capacitance, τ_{RC} , AP, CT, $\text{PDE}_{420\text{ nm}}$. Measurements were made as function of OV from $\sim 1\text{ V}$ up to $> 8\text{ V}$. For SiPM-NUV-HD-Cryo with CS= 35 μm , PDE was characterized from 300 nm up to 700 nm. Moreover, considering SiPM-NUV-HD-Cryo with CS= 30 μm , quantities like DCR, cell gain, cell capacitance, τ_{RC} , AP, CT were characterized at different temperatures: 290 K, 270 K, 250 K, 230 K and 77 K, with OV from 1 V up to $> 10\text{ V}$.

Now, we report the main results of SiPM-NUV-HD-Cryo characterizations, for $CS = 30 \mu m$, $OV = 6 V$ and $R_q(77 K) = 6 M\Omega$ are reported in the following. The most impressive result is the suppression of DCR from $0.1 MHz/mm^2$ (290 K) up to $10 mHz/mm^2$ (77 K), with a reduction of 7 order of magnitude. Cell gain and cell capacitance are $2 M$ and $58 fF$ at 77 K respectively, while DiCT probability weakly changes depending on temperature from 15 % (290 K) up to 22 % (77 K). A second impressive result is the suppression of AP probability thanks to LAP technology in SiPM-NUV-HD-Cryo. If we compare at 77 K a SiPM without LAP (AP_{nonLAP}) and one with LAP (AP_{LAP}), we obtain that AP_{nonLAP} diverges at $OV = 4 V$ and AP_{LAP} is 8 % at $OV = 6 V$. On the other hand, recharge time constance increases from $32 ns$ (290 K) up to $300 ns$ (77 K), while the $PDE_{420 nm}(290 K) = 47 \%$. Thus, SiPM-NUV-HD-Cryo, used with $CS = 30 \mu m$, $OV = 6 V$ and $R_q(77 K) = 6 M\Omega$ satisfies all requirements of DarkSide-20k project. The last necessary measurement, which is necessary to fully complete SiPM-NUV-HD-Cryo characterization, is $PDE_{420 nm}(87 K)$ that is planned in FBK in the next months.

FBK NUV-HD-Cryo SiPMs were used in combination with the latest revision of the cryogenic, discrete front-end developed at LNGS, in a mixed series parallel connection, so that a total of 24 SiPMs, covering a photo-sensitive area of $24 cm^2$, was read using a single front-end channel [48]. In this configuration, the charge histogram was measured with faint, pulsed-light illumination, obtaining a few-photon spectrum at 77 K. The SNR of the single photon peak was 24, calculated as the standard deviation of the peak, divided by it distance from the baseline peak. This value is exceptionally good, especially considering the very large photo-sensitive area and redefines the state-of-the art in the field. It confirms the very good development work carried out in the photo-electronics group within the DarkSide collaboration, which now provides a world-class, enabling technology for the experiment, to which this thesis gave a significant contribution.

List of publications

1. Martines E. *et al.* (2016). *The radiofrequency magnetic dipole discharge*. Physics of Plasmas, 23(5), 053511.
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3. Aalseth, C. E. *et al.* (2017). *Cryogenic Characterization of FBK RGB-HD SiPMs*. Journal of Instrumentation, 12(09), P09030.
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5. F.Getman *et al.* *Proceedings of the event IPSP2017 industrial problem solving with physics* (chapter1. "Analysis of the laser piercing process", Trento July 17 – 22, 2017, ISBN 978-88-8443-786-0
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