Characterization of SiPM: temperature dependencies.

Marco Ramilli

Abstract—**Within RAPSODI[1] novel types of Silicon Photo-Multiplier (SiPM) from different suppliers were investigated. The main parameters: dark count rate, amplification, dynamic range, quantum detection efficiency and optical cross-talk have been studied to qualify the detectors. Results demonstrate the possibility to apply this detection technology to intense photon fluxes detection as well as to low plurality ones. Characterization protocol for a full SiPM qualification was developed. The most important result is the demonstration of temperature independence of SiPM gain versus over voltage.**

Index Terms—**Silicon Photo Multipliers, Temperature dependance, Characterization**

I. Introduction

THE Silicon Photomultiplier (SiPM) is a detection technology originally developed in Russia [1] and consisting in a high density ($\sim 10^3/\mathrm{mm}^2$) matrix of diodes with a common output load. Each diode is operated in a limited Geiger-Müller mode, in order to achieve gain at the level of 10^6 and comparable to PMT's. As a consequence, these devices are sensitive to single photons even at room temperature and feature a dynamic range well above 100 photons/burst, matching the boundary conditions in many processes of radio-diagnostics and radio-detection. Moreover, the SiPM measures the light intensity simply by the number of fired diodes, with an unprecedented time resolution at the 100 ps level and a dead time per diode limited to 100 ns. All of the above advantages imply that Silicon Photo-Multipliers are an enabling technology for integration, miniaturization, and array formats in photon counting. Preserving the analogue information that relates to the deposited energy would add a considerable value in photons flux measurements. RAPSODI is a research project funded by the European Commission within the sixth framework program. The aim of the project is the development of a set of new radiation detectors for three well defined applications: real-time dosimetry in mammography, Radon concentration monitoring and radioactive material detection.

II. SiPM characterization protocol

Tests have been performed on existing devices with the main goal to define an exhaustive protocol and to produce a comparative study. Three kind of detectors were under test, from different manufacturers: SensL [2] (2 generations and 2 different topologies), Hamamatsu [3] (2 different topologies) and CPTA [4] (2 generations). The characterization of detectors is a major task for all of the applications where SiPM are used, on the other hand the definition of main parameters is strongly application dependent. For example the Dark Counting Rate (DCR) is an important parameter for low event rate application and thermal stability is essential for dosimetry in medical fields. For this reason the following exhaustive protocol has been developed with the intention to focus on subsets of it, depending on the considered application.

- Geometrical parameters (number of cells, size of detectors and occupancy factor);
- I - V measurements;
- Noise measurements:
  - Dark Counting Rate (DCR);
  - Optical cross-talk;
  - Dependence on the environmental parameters;
- Analysis of photon spectra:
  - Resolution power;
  - Gain;
  - Working point optimization (at low and large flux);
  - Electronic noise measurement;
  - Dependence on the environmental parameters (Temperature);
- Linearity and dynamic range;
- Spectral response measurement:
  - Photon Detection Efficiency.

III. Experimental setup

In order to carry on this characterization protocol, a complete experimental setup has been put in place in the Silicon detector laboratory at the Università degli Studi dell' Insubria in Como.

As a light source, a green-emitting LED (λ = 510 nm) has been used, coupled to a fast pulse generator *PDL800-B PicoQuant*. The SiPM output signal has been delivered using the following acquisition chain and digital electronics:

- a first stage amplification board provided by SensL directly connceted to the SiPM; occasionally, as a second stage of amplification has been used a *ZFL-1000LN* amplifier;
- an amplitude discriminator *Lecroy 821* with a user-defined voltage threshold which SiPM output has to exceed in order to provide a triggering signal;
- in case of frequency measurements (e.g. DCR measurements), discriminator output has been directly delivered to a scaler;
- output of SiPM has been integrated by a *V171816ch QDC CAEN V792N* using the triggering signal from the discriminator as a gating window;

M. Ramilli is with the Università degli Studi dell'Insubria, Dipartimento di Fisica e Matematica, Via Valleggio 11, 22100 Como, Italy

Corresponding author: marco.ramilli@uninsubria.it

[1]European founded project - COOP 32993 - RAdiation Protection with Silicon Optoelectronic Devices and Instruments

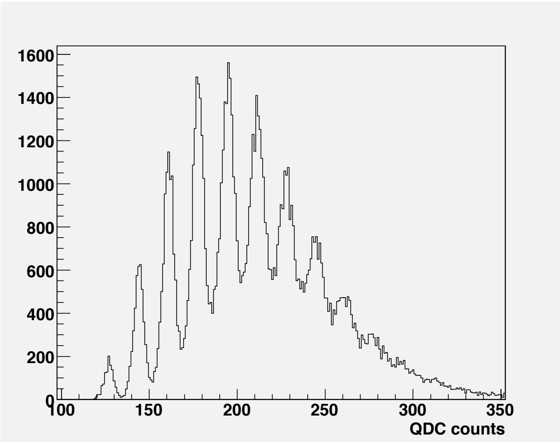

Fig. 1. Exemple of low flux spectrum of a SiPM.

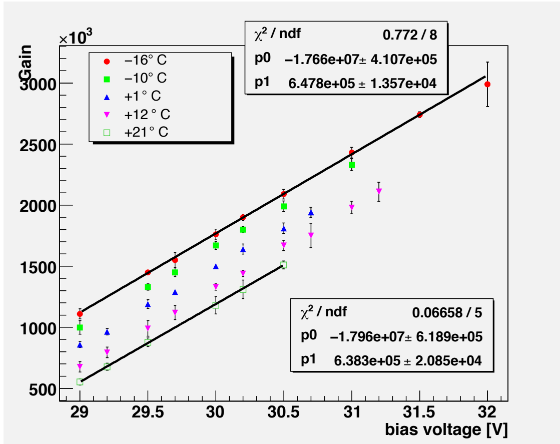

Fig. 2. Gain dependance vs. bias voltage for different temperatures.

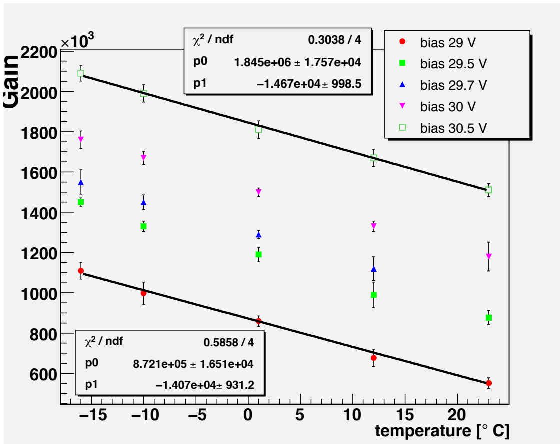

Fig. 3. Gain dependance vs. temperature for different bias voltages.

- digital information has been trasferred to the equippement computer through a *USB-VME Bridge CAEN* .

The system composed by the investigated SiPM and a first-stage amplification board, has been set in metal box sealed with grease, in which air has been replaced with helium. Cooling fluid has been pumped into the box through a copper pipe. Temperaure of the system has been measured by a *PT 100 resistor*.

IV. Results

In the following subsections the methods for analyze data and the principal results are going to be presented. Measurements have been performed in a temperature range varying from -20 °C to room temperature.

A. Gain

Gain has been evaluated by illuminating the SiPM with low photon flux, thus obtaining a spectrum whose peaks are clearly recognizable: an exemple is depicted in Fig. 1. As the *n*-th peak corresponds to the mean charge released by *n* Geiger-Müller avalanches, gain calculation has been straightforward, using the following relation:

$$G = \frac{QDC_{cal}}{e^{-} K_{amp}} \Delta_{PP}, \tag{1}$$

where G is the gain, QDC_{cal} = 0.11 pC is the charge corresponding to one QDC unit, e^{-} is the elementary charge, K_{amp} is the global amplification factor of the electronic setup, and Δ_{PP} is distance in QDC units between two adjacent peaks of the collected spectra.

In Fig. 2 the behavior of gain with bias voltage, at fixed temperatures, is shown: a linear dependence in the range of interest is clearly observable and varying temperature does not affect the slope of the extrapolated curves, within the experimental errors. In Fig. 3 the same gain values are presented as function of the temperature, for fixed bias voltage: a linear behavior is still clearly recognizable; in this case as well slope is not affected by the change of applied bias.

This analysis suggests that gain can be expressed as a linear function of a variable which can be re-scaled with temperature; since it is well known that breakdown voltage has, in our range of interest, a linear dependence from temperature [5], the over voltage, defined as the difference between the applied bias voltage and the breakdown, is thus a suitable candidate.

The mentioned condition can be summarized in the equations

$$G(V,T) = \frac{dG}{dV}(V - V_{BD}(T)), \tag{2}$$

$$G(V,T) = \frac{dG}{dT}T + G(T_0, V), \tag{3}$$

$$\tag{4}$$

where $\frac{dG}{dV}$ and $\frac{dG}{dT}$ are the slopes of curves representing the gain as function, respectively, of the bias voltage and of the temperature, while $V_{BD}(T)$ is the breakdown voltage and T_0 is a reference temperature. Solving simultaneously these equations for $V_{BD}(T)$, the rate of change of the breakown voltage with temperature has been found as given by

$$\frac{dV_{BD}}{dT} = -dG/dT \frac{1}{dG/dV}. \tag{5}$$

Using a linear law, value of breakdown voltage has thus

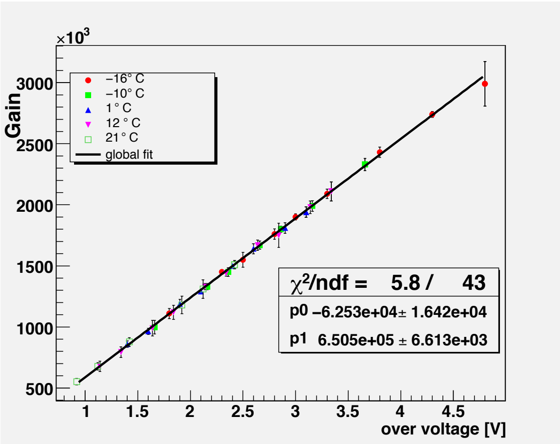

Fig. 4. Gain dependance vs. the over voltage.

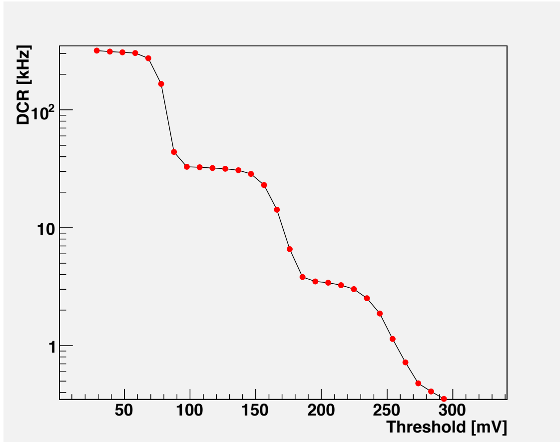

Fig. 5. Exemple of *staircase function*, obtained after three-stage amplification.

been calculated for each temperature and it made possible to express the gain as a function of the over voltage: in Fig. 4 gain has been plotted versus over voltage, showing a global linear behavior indipendent from the temperature.

B. Dark Count Rate

Dark Count Rate (DCR hereon), is the frequency of the Geiger-Müller avalnches triggered by thermally extracted carriers. A scan of the DCR at different threshold can be done, and the resulting plot (an exemple is shown in Fig. 5) is characterized by a serie of plateaus whose value decreases sharply (tipically an order of magnitude in frequency) for precise thresholds: this corresponds to settings of the discriminator higher than the output signal respectively of the first photon, the second and so on: this kind of plots are usually referred to as *staircase functions*.
DCR has been measured at different voltages and different temperatures, also setting different discrimination thresholds; in Fig 6, for exemple, results for *"half photon threshold"*[2] are shown. A clear and expected dependance from temperature is recognizable; probability of thermally produce electron-hole pairs is, infact a well-known function of temperature:

$$p(T) \ = \ CT^{3/2} \exp\left(-\frac{E_g}{2k_B T}\right) \quad (6)$$

where T is the absolute temperature, E_g is the bandgap energy, k_B is the Boltzmann constant and C is a proportionality constant depending on the material and the tecnological parameters.
The importance of these measurements is twofold:

- first, precise DCR measurements are fundamental to a complete characterization of the system;
- taking into account Eq. 6, and knowing the value of C, allow a direct estimation of the Geiger-Müller avalanche probability.

[2]The discriminator has been regulated with a threshold corresponding to half the output signal of the first photon.

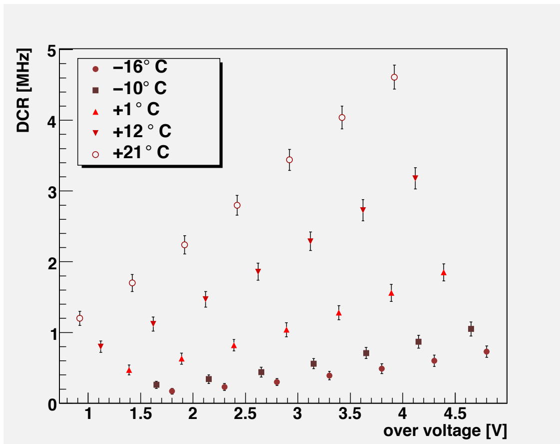

Fig. 6. DCR at different temperatures rescaled as function of the over voltage, for a SensL SiPM.

C. Optical cross-talk

An electron avalanche is modelized as a microplasma; photons emitted by plasma during this event have a certain probability to reach the neighbour cell diodes and trigger a second avalanche: thus, the quantity named optical cross-talk (for brevity simply cross-talk or X_{talk} hereon) is simply the percentage of avalanches triggered by such a mechanism.
Cross-talk has been calculated starting from DCR measurements:

$$X_{talk} \ = \ \frac{DCR_{1.5p}}{DCR_{0.5p}}, \quad (7)$$

where $DCR_{1.5p}$ and $DCR_{0.5p}$ are the DCR frequencies measured setting the discriminator threshold respectively at *"one-and-half photon"* and at *"half photon"*. This method is based on the assumption that the probability that two uncorrelated avalanches are triggered within the same rise time is negligible, so that all the second photon events are due to cross-talk.
In Fig. 7 results of cross-talk evaluation are depicted: it is worth noticing that, within experimental errors, cross-talk does not seem to possess a strong temperature dependance.

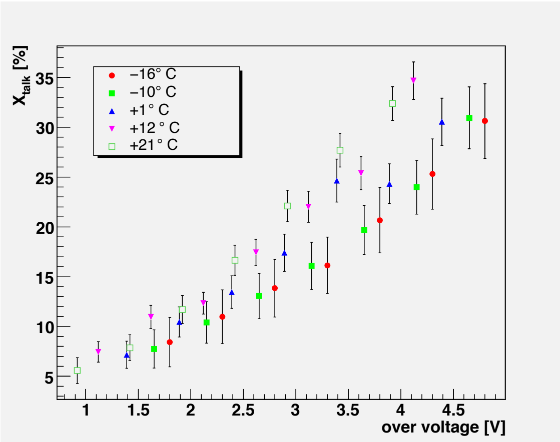

Fig. 7. Cross-talk rescaled on the over voltage, at different temperatures, for a SensL SiPM.

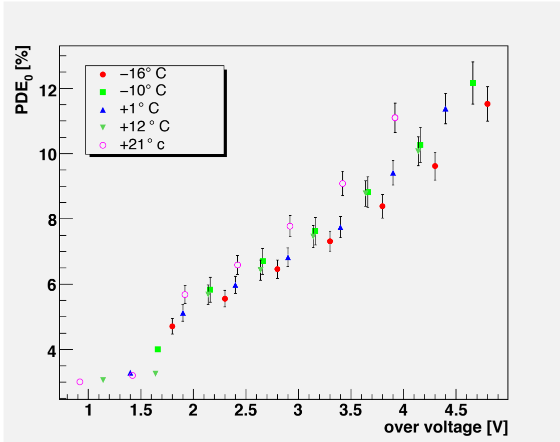

Fig. 8. PDE values corrected taking into account cross-talk effects, for a SensL SiPM. Wavelenght of impinging light is 510 nm.

D. Photo-Detection Efficency

Photo-Detection Efficiency (PDE) is a key parameter for every light detector and it is defined as the product of three terms:

- Quantum Efficiency (QE), the probability that the impinging photon produces a charge carrier and it is a function of the incoming light wavelenght;
- the Geiger-Müller probability that the extracted carrier generates an avalanche, and depends on the over voltage;
- the so called Fill Factor (FF), a geometrical factor which express the fraction of the active area of the sensor, respect to the total area;

or, in formula:

$$PDE = FF \times QE(\lambda) \times P_{GM}(V); \tag{8}$$

this value thus represents the fraction of impinging photons that are detected.

To measure this quantity, SiPMs have been illuminated with a known flux of light Φ (measured with a calibrated PMT) and then resulting spectra have been acquired; PDE has thus been evaluated estimating the mean number of measured photons $<n>_{meas}$ divided it by the incoming light flux:

$$PDE = \frac{<n>_{meas}}{\Phi}. \tag{9}$$

In case of spectra where each photon peak could be resolved, $<n>_{meas}$ has been evaluated by fitting the peak positions with a Poissonian curve and then evaluating the mean value of the fit result distribution. In case peaks could not have been resolved, $<n>_{meas}$ has been extimated using

$$<n>_{meas} = \frac{QDC_{cal}}{e^- \, G \, K_{amp}} \Delta QDC, \tag{10}$$

where G is the proper gain value, e^- is the elementary charge, $QDC_{cal} = 0.11$ pC is the charge per QDC unit, K_{amp} is the amplification factor of the electronic chain, and ΔQDC is the difference between the mean value of the obtained spectrum and the pedestal position.

This method, however, provides a zero-order approximation of the PDE because it does not take into account cross-talk effects that can be as large as 40% (see again Fig. 7 as a reference). To properly estimate the *"real"* number $<n>_0$ of impinging photons triggering an avalanche,the following relation has been used:

$$<n>_{meas} = <n>_o (1 + X_{talk}); \tag{11}$$

PDE values previously obtained have thus been corrected using $<n>_0$ as the mean number of detected photons as shown in Fig. 8. Again, PDE_0 does not seem to have any remarkable temperature dependance, thus confirming the consistency of our results with the definition of PDE.

V. Conclusion

An exhaustive procedure to characterize the parameters of a SiPM has been presented. Over voltage, instead of bias voltage, has been demonstrated to be the real physical parameter involved in the characterization of a SiPM performances: infact, gain as function of over voltage has been shown to be independent from temperature, as well as other relevant parameters as cross-talk and PDE. A method to cancel out cross-talk effect from PDE evaluation has also been shown.

All these measurements have been performed with green light; in order to fully characterize SiPM properties, a study of the wavelength dependence of all the presented parameters has already been planned.

References

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