SPECTROSCOPIC CHARACTERIZATION OF NOVEL SILICON PHOTOMULTIPLIERS*

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Abstract

Most of the presently used systems for loss detection and EM radiation spectroscopy are still based on classical photomultiplier tubes. The more recent Silicon Photomultiplier (SiPM) is a good candidate to take their place thanks to some of its fundamental features such as its insensitivity to magnetic fields, robustness, compactness and relatively low voltage working regime. This device can be coupled to very different kinds of light generators, such as scintillators or Cherenkov radiators, thus making it extremely flexible in its use. To evaluate the possible range of applications of a specific SiPM, it is necessary to quantify its fundamental parameters including noise, time resolution and dynamic range. In this contribution an experimental and analytical characterization of some SiPMs is presented. Particular focus is given to a SiPM from ST Microelectronics

INTRODUCTION

Most systems used for the detection and spectroscopy of electromagnetic radiation are based on the use of photomultiplier tubes (PMT). In the last decade a new type of detector based on silicon avalanche photodiodes working in Geiger mode (GM-APD) has been developed, which seems to be a reliable candidate to replace existing systems [1]. The limitation of a single GM-APD is the output signal, which is the same regardless of the number of interacting photons. To solve this limitation, the diode can be segmented in thin microcells connected in parallel to have a unique output. Each single element when activated by a photon, produces the same current response. Thus, the output signal is proportional to the number of involved cells. The dynamic range is then limited by the number of elements which make up the device and the probability that two or more photons hit the same cell depends on its size. This array of GM-APDs is called a Silicon photomultiplier (SiPM). Some advantages of using this configuration are that it is compact, insensitive to magnetic fields and has a low operational voltage of the order of some tens of Volts. Furthermore, this technology facilitates the connection between the detector and the readout electronics. The range of applications of SiPMs is wide and expanding with the evolution of this technology. The detection of light emitted by scintillators or other light sources that are particle-triggered is some of the most interesting examples. In this frame, SiPMs are successfully used as sensors for radiation detectors. More noisy, but still reliable and interesting because of their comparably low costs, is the application of SiPMs for a beam loss monitoring system for a particle accelerator, especially in case of extensive use, as in case of very big facilities such as LHC [2] or CLIC [3]. Moreover, SiPMs also are an interesting tool for signal detection in low energy storage rings, in particular when it comes to the detection of annihilation events in a low energy antiproton ring, such as the Ultra-low energy storage ring (USR) [4].

This contribution describes a systematic study of some fundamental parameters which characterize a SiPM for prototypes developed by both, ST Microelectronics (model 'H') and Hamamatsu (model S10362-11-100C). Furthermore, the same parameters have been determined for the case of these SiPMs coupled to a 100 meters long multimodal optical fiber with a 1 mm section diameter. This allowed checking the possibility to place the sensor a long distance away from the particle detection part. The general features of both prototypes are summarized in Table 1.

Table 1: SiPM Prototype Features

SiPM	Array Size	Number of Cells	Cell Pitch	Fill Factor
ST (H)	1x1 mm²	17x17	58µm	45%
Ham.(100C)	1x1 mm²	10x10	100µm	78.5%

INVESTIGATED PARAMETERS

A SiPM used as a beam loss detector can provide two pieces of information: the output count rate and its signal amplitude. The count rate of the single cell signals can give information on the average radiation level, and the signal amplitude can give information on the light intensity and timing. To obtain information about a beam loss without destroying the SiPM, it is advisable to avoid direct triggering especially in case of high energy particles. A common solution is to convert the particles energy to photons by means of a well known phenomenon such as scintillation [5] or the Cherenkov Effect [6], and using heavy shielding apparatus to protect the SiPM from direct particle exposition. An optical fiber (scintillating and/or common) can resolve both of these problems by generating a number of photons that is proportional to the initial particles energy and allowing the SiPM to be safely placed outside the beam hall. Obviously, the presence of the fiber affects the SiPM's parameters, requiring a reestablishment of the sensor's features. Furthermore, by creating this additional step in the beam loss detection

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process, it is necessary to study all problems related to electron production triggered by charged particles in optical fibers, such as attenuation and the interface of the fiber and SiPM.

To give an evaluation of the above-mentioned parameters it is crucial to perform a spectroscopic characterization of the SiPM. It consists of the analysis of the response of a detector, in charge and in time, to a well known light or particle source to calculate two fundamental parameters: the photon resolving power and the time resolution. The performance of a detector based on SiPMs is also defined by the dark noise, which is separately evaluated.

Photon Resolution

The charge spectra produced by the SiPM output are a convolution of a discrete number of Poisson distributions, where the variance (σ) of the distributions gives a good estimate of the resolution of the detector. The SiPM photon resolution is affected by statistical noise which is the main and unavoidable unwanted contribution to the output signal, this contribution is directly related to environmental variables such as the temperature. There are several sources of noise which include drifts in the operational characteristics of the device during a measurement, intrinsic count rate and statistical noise due to the discrete nature of the charge generation process.

Noise Evaluation

This noise is a fundamental parameter that needs to be measured for having a good characterization of a SiPM and a key to understanding the output signal. Depending on the resolution required by the application, the importance of a good noise evaluation is more crucial or less. In general, for low energy and low frequency events, a better noise evaluation and correction is required. There are 3 main elements in the SiPM noise: non-correlated (statistical), correlated and external contributions.

For SiPMs, the biggest statistical contribution to the noise is the dark count which appears as output pulses in the absence of a photon source. In fact, Silicon is characterized by several statistical processes as the thermal equilibrium between electrons and holes, that cause the spontaneous creation of charge carriers which may trigger an avalanche [7]. The importance of this effect is that it is not distinguishable from the impulses arising from real events, which means a limitation in the minimum count rate of the SiPMs.

A second source of noise that can increase the dark count rate is the so-called 'after pulsing'. It is the probability that during an avalanche a carrier is trapped into lattice defects introduced by impurities, and then released after a characteristic time. The main difference to dark noise is that this effect is correlated to a previous avalanche, hence its distribution is not statistical [8]. The probability of after pulsing is related to the dead time of the device. If the dead time is high enough, the probability that a released carrier triggers a new avalanche is low. The SiPM microcells do not have a fixed dead time and the probability that a carrier released by a trap generates an avalanche is hence not negligible.

Crosstalk is a secondary effect that occurs when an avalanche in a cell triggers the production of photons which reach a neighboring cell and causes an avalanche also in this cell. This secondary effect can compromise the final result, since the total count will be affected by crosstalk which occurs simultaneously to the true signal and it is not possible to distinguish this from the former [8]. A solution to minimize this problem is to isolate the cells by means of physical trench, usually made of aluminum, but its contribution is never negligible.

Time Resolution

Another fundamental parameter of SiPMs is given by the time spectrum. The standard deviation σ of the Gaussian distribution obtained during time measurements gives a measure of the temporal uncertainty and is defined as the sensors time resolution. The intrinsic uncertainty shown by time distributions is due to the different charge concentrations in the active volume which can trigger avalanches. Therefore, considering an ideal light source, devoid of statistical fluctuations, incident on a SiPM, the time responses of the cells are not identical to each other. This occurs because the triggering of an avalanche can be more or less rapid according to the point in the active volume in which the primary charge carriers are generated. The time between the quiescent state of the SiPM and the production of an avalanche coincides with the falling edge of the output signal and defines the time of arrival of the photon which is dominated by the uncertainty discussed above.

MEASUREMENTS

Noise Measurements

Regardless of the kind of application that is to be performed, the SiPM noise measurement gives crucial information for data interpretation. Especially in case of very low intensity light pulses, with very few photons, it is necessary for a SiPM to generate a signal which is distinguishable from intrinsic events resulting from the emission of thermal electrons or other phenomena. The dark count has a certain average value of events per second $<N>$, and a variance derived from Poisson statistics $\sigma = \sqrt{<N>}$. The total dark count rate can then be expressed as: $N = <N> \pm \sqrt{<N>}$

In the presence of light pulses, the dark count is a part of the total number of events counted by a SiPM and to distinguish the number of useful events with a certain percentage of error one should refer to the variance on the average dark count and Gaussian distribution. If a light signal with a specified frequency is detected by a SiPM and a count rate higher than the dark count is found at the output, indicated by N_c the difference between the measured count rate and the dark count, two cases can be distinguished: if $N_c > \sqrt{<N>}$, one can deduce that N_c

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indicates the optical pulse seen by the photo detector; if $N_c < \sqrt{<N>}$, the noise fluctuations outweigh the optical pulses counted. When the number of events is big enough and information on all the involved particles is not necessary to the experiment, the dark noise is filtered by applying a threshold voltage. However, in both cases accurate noise measurements are necessary to avoid information loss or bad interpretation. Since the dark rate is proportional to the amplitude of the supply voltage and temperature [9], the number of pulses as a function of a voltage threshold was recorded for three different values of the bias voltage. Furthermore, all measurements were made at identical temperature (26^{0}C) to avoid introducing errors due to temperature variations. In addition to the intrinsic noise, the electronic noise introduced by the readout circuitry must also be taken into account, which is very important in case of count rates evaluation. This is usually a white noise whose contribution to the output voltage amplitude can be higher than 20% of a single cell signal, and is related to electromagnetic interferences. It should be noted that even with low thresholds (the equivalent of half of a single cell signal) this noise can be minimized. The setup for this experiment consists of two main devices: a leading edge discriminator (threshold from +10 mV to -200 mV) to select the output signal threshold level and a digital counter to determine the count rate. The signal from the SiPM is first amplified and inverted to match the NIM discriminator module standard input, by means of a NIM multichannel fast amplifier (gain: 200). The output NIM logic signals (rectangular pulses of 8 ns time width), are then counted by a digital counter. The error associated to this procedure is 0.8 %, related to the uncertainty induced by the start-stop manual system, negligible if compared to the variance of the Poisson distribution.

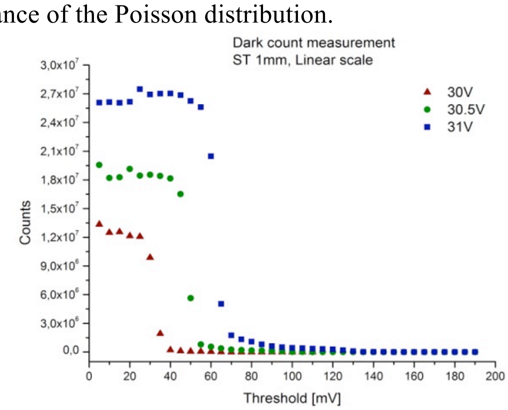

Figure 1: Dark count for the ST SiPM, for three different values of the bias voltage.

The plots represent the dark noise count rate for the two SiPMs that were analyzed, for three different bias voltages, in linear and logarithmic scale. Since the probability of a single cell dark signal is much higher than multiple cells, the linear plot has a stepwise shape. Considering the ST SiPM the single amplified cell signal is 40 mV for a bias voltage of 30.5 V. From the green curve in fig.1 one can deduce that the number of events lost even in case of a threshold next to the single cell value, is negligible. This constitutes important information, when removing electronic noise without affecting the measurement in count rate regime [10].

The logarithmic plot in fig.2 makes it possible to distinguish multiple cell activations, where the plateaus between steps represent a region in which two or more cell signals are superimposed. Since the one cell signal is represented by the first plateau, for the ST SiPM it can be distinguished until four cells are activated simultaneously in the allowed range of the discriminator (200 mV).

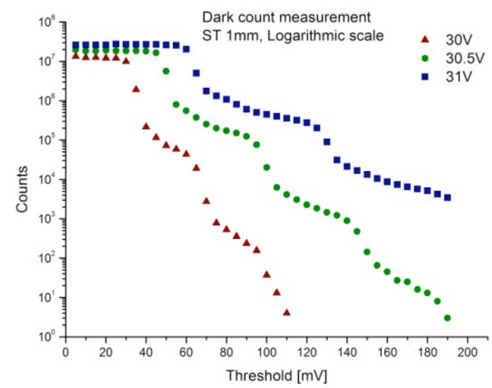

Figure 2: Dark count from the SiPM ST, for three different values of the bias voltage, in logarithmic scale.

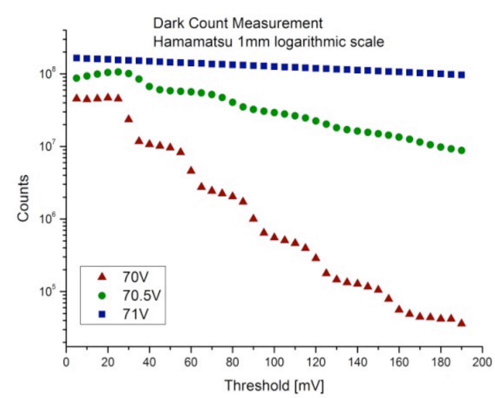

Figure 3: Dark count measurement from the Hamamatsu SiPM, for three different values of the bias voltage.

For the Hamamatsu SiPM this distinction is not as evident as in case of the ST SiPM. For this SiPM it is possible to distinguish even the six cell plateau as shown in fig.3, but only for one value of the bias voltage. The absence of a clear distinction of the plateaus for some bias voltages is due to the different architecture of the two SiPMs. The Hamamatsu used for this experiment is more affected by crosstalk than the ST one, increasing the probability of a multiple and partial cell activation. This effect, being proportional to the bias voltage, is more evident for higher voltages curves. In Table 2 the single cell dark count rates for the two SiPMs at varying bias voltage are summarized. Since it is the sum of the contribution of dark pulses by each single cell, it can reach frequencies of some MHz.

The total dark count rate appears to increase linearly with the voltage applied, confirming results from other

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similar experiments [11]. Furthermore, there is a higher count rate for the Hamamatsu SiPM. This means the ST SiPM has a better sensitivity for lower count rates than the Hamamatsu SiPM, in despite of its higher number of cells. However, in applications characterized by high light intensity output where it is not interesting to make measurements of single photon spectra, the dark count can be drastically reduced by applying a voltage threshold equal to 2-3 cells signal amplitude, without affecting the measurements [12].

Table 2: SiPM Dark Count Rates

Bias Voltage	**Dark count rate [20 mV th.]**
ST 30 V	203 kHz ± 7%
ST 30.5V	317 kHz ± 6%
ST 31 V	435 kHz ± 5%
Hamamatsu 70 V	777 kHz ± 4%
Hamamatsu 70.5 V	1.733 MHz ± 3%
Hamamatsu 71 V	2.642 MHz ± 2%

Time and Spatial Resolution

SiPMs can achieve a time resolution (R_t) in the order of hundreds of picoseconds, defined by the contribution of three main parameters:

1. The time of collection of the charge carriers in the drift region. If the field is very high (more than 10^5 V/cm), the electrons and holes drift velocity are about the same and very close to 10^7 cm/s. For a drift region of 5 μm the collection time is approximately 10 ps.
2. The time of propagation of the avalanche. This is the time required to an avalanche so that the entire junction reaches the breakdown. Since there is a charge gradient between the start point of the avalanche and the rest of the junction, this generates a side scattering of the avalanche. This propagation time is relevant to the shape of the signal, since it is the largest contributor. Depending on where the photon interacts with the active area (cell borders) a different time would be needed for the whole junction to reach the breakdown. Since a single cell area is in the order of μm^2, this effect does not affect the time resolution too much and the total breakdown propagation time is some tens of ps.
3. The drift time of electrons through the depletion region. This is the time necessary for a carrier produced by a deep interaction of a photon in the active region to reach the drift region.

Since the intrinsic contributions to the time resolution are very small, the only real limit is given by the readout electronics, which play a crucial role for SiPM applications, more than for standard PMs. However, the three contributors listed above give an upper limit despite of any sophisticated electronics adopted.

To perform R_t measurements, the SiPM is directly connected to a light source, such as a laser or a LED, pulsing at a certain frequency defined by a pulse generator (dependent by the available sampling rate). The difference in time between the trigger and the SiPM signal is then sampled by a TDC. As shown in fig.4, the shape of the collection is a Gaussian, whose σrepresents the time resolution [13].

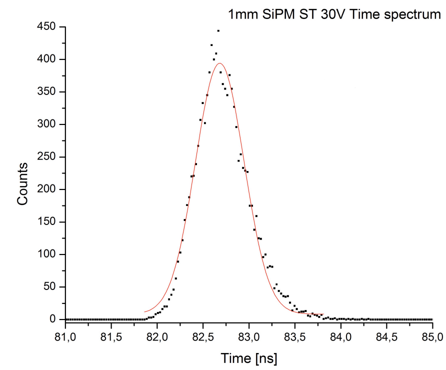

Figure 4: ST SiPM Time spectrum, V_B = 30 V.

From the characteristics of the contributors to the time resolution, a proportional dependency on the bias voltage can be expected. This is correct in the ideal case, but for the measurements it must also be taken into account that the dark noise is proportional to the applied voltage, increasing the uncertainty and then the σ. This multiple dependency means that the best solution in terms of time and noise rate needs to be sought as a function of the application. In case of the combination SiPM-fiber, the expected time resolution is less favorable because of the statistical uncertainty introduced by multiple reflections which characterize the light transport in an optical fiber. This must be considered as an intrinsic R_t of the detector and is dependent on the fiber length. The data shown in table 3 indicates that there is one order of magnitude difference between the two configurations for both SiPMs. The R_t is directly related to the linear space resolution (R_d). Thus, the length of the detector should be chosen under consideration of this requirement for the machine on which it shall be used.

Table 3: Time Resolution and Spatial Resolution Range

SiPM	**R_t no fiber**	**R_t with fiber**	**R_d [cm] fib. (0-100)m**
ST	264 ps	1,230 ps	7.9 < d < 37
Hamamatsu	143 ps	903 ps	4.3 < d < 27

Considering the exposed cases a spatial resolution of less of 40 cm in the worst case (in case of light in vacuum) is observed, which is enough to satisfy the requirements in most of high energy machines.

Charge Spectrum

The ideal charge output of the SiPM should be a signal which is an integer multiple of the elementary cell output, depending on the number of detected photons. Unfortunately the real signal suffers the contribution of some non negligible secondary effects such as dark noise,

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uneven cells, electrical noise, etc. The sum of these effects is well represented in a charge spectrum as a Gaussian convolution, which is modulated by the Poisson distributions related to discrete photon detection. To obtain a charge spectrum, a SiPM is exposed to a time-coherent tunable light source such as a laser head (I_L), sampling and collecting the SiPM output charge signal. In Fig. 5 a charge spectrum from the ST SiPM is represented, together with its fit. The width of each peak, and thus its variance, is expected to fundamentally depend on two main factors: the overall electronic noise induced by the detector and the electronics, and the combination of fluctuations between all the elementary cells.

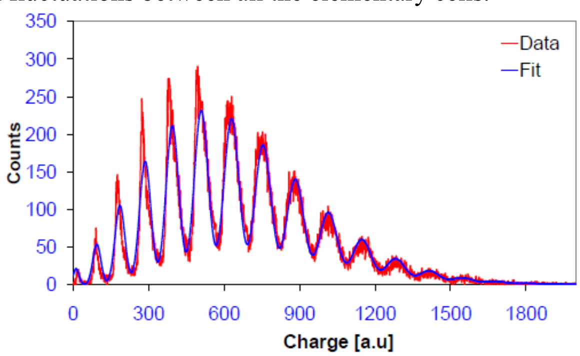

Figure 5: ST charge spectrum. V_B = 30V; I_L=2.4%.

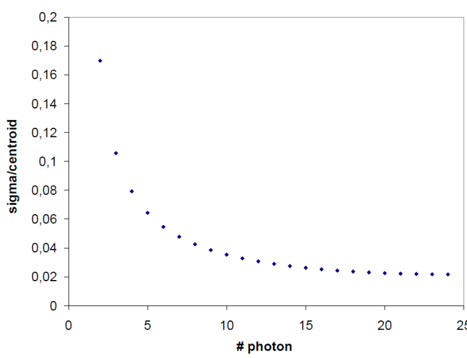

Figure 6: ST SiPM. Charge relative variance as a function of the detected photons. V_B = 30V; I_L=2.4%.

These factors can be calculated and then used to determine the charge resolution and resolving power of the SiPM [13].

In Fig. 6 the relative SiPM resolution as a function of the number of detected photons is shown. The resolving power can be defined as the number of measured photons, where the separation between two consecutive peaks *d* is three times σ. This is the condition for a clear peak separation, while it is still possible to resolve peaks until *d* = 2σ. Table 4 summarizes the resolution power for the two SiPMs alone and when coupled with a 100 m long fiber.

CONCLUSION

SiPMs are an interesting and competitive solution for several applications related to particle detection in an accelerator environment, such as beam loss monitoring. An accurate study of the main parameters of this device

Table 4: Resolving Power

SiPM	$R_{3\sigma}$	$R_{2\sigma}$
ST	13	29
ST 100 m fiber	5	11
Hamamatsu	14	31
Hamamatsu 100 m fiber	6	13

was performed for two SiPM types. These are characterized by two different architectures and bias voltages, whilst having similar wavelengths interval sensitivities. The parameter determination was performed for the SiPMs alone and when coupled with an optical fiber to explore the possibility to exploit scintillation or Cherenkov Effect phenomenon even for long distance photon transmission. From the results obtained by dark noise evaluation, the dark count rate of the Hamamatsu device was three times larger than the ST SiPM and thus it would be preferable to use the latter in cases of low frequency events or poor photon production. With regard to time and spatial resolution, better results were obtained with the Hamamatsu, especially in case of a need for good spatial resolution. If the SiPM is coupled to a fiber, this parameter gets worse proportionally to the light path length. For beam loss applications, even with a 100 m fiber both SiPMs show a spatial resolution of less of 50 cm. The data collected from the charge spectra show again a better resolving power in the case of the Hamamatsu SiPM, maintaining a resolution of around 13 photons even when coupled with a 100 m long fiber. The general performances of the SiPMs are deeply affected by the electronics which picks up, amplifies and analyses the signal. Recently developed amplifiers have shown an outstanding improvement in time and charge resolution, reaching resolutions in the order of 50 ps and 100 photons respectively in preliminary tests [14]. Further tests and experiment to confirm this statement are ongoing and will be published soon.

REFERENCES

[1] D. Renker, Nucl. Instr. Meth. A **567** (2006).
[2] E.B. Holzer et al., Nucl. Sc. Symp., IEEE (2005).
[3] M. Sapinski et al., Proc. IPAC11, p.2869 (2011).
[4] C.P. Welsch et al., Nucl. Instr. Meth. A **546** (2005).
[5] V. Saveliev et al., IEEE Trans. Nucl. Sc., **53** vol.1, (2006).
[6] J. V. Jelley, , British J. of Appl. Phys. 6, p. 227 (1955).
[7] W. Shockley, T. Read. Phys. Rev. **87** p.835 (1952).
[8] F. Zappa et al., Sens. Act. A Phys. **140**, p. 103 (2007).
[9] M. Boscardin et al., Nucl. Sc. Symp., 41(2) (2007).
[10] P. Finocchiaro et al., IEEE Trans. Elec. Dev., **55**, p. 2757 (2008).
[11] [V. Golovin et al., Nucl. Instr. Meth. A **447**, p.486 (2003).
[12] N. Dinu. Nucl. Inst. and Meth. A **572**, p.422 (2007).
[13] P. Finocchiaro et al., IEEE Trans. Elec. Dev. **55**, p. 2765 (2008).
[14] www.microsensor.it

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