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Precision measurements of Photon Detection Efficiency for SiPM detectors

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ABSTRACT

We present the preliminary results of the characterization of silicon detectors in terms of Photon Detection Efficiency (PDE). The precision measurements are performed at controlled temperature, using a specially suited setup based on a monochromator, an integrating sphere to randomize the incident light and a calibrated reference photodiode. We exploit a measurement technique that we recently devised, based on single photon counting with subtraction of dark noise, and avoiding as much as possible cross-talk and afterpulses. We describe in detail the experimental setups and the techniques utilized to measure the PDE. The achieved results are here discussed in order to establish a methodology capable to give very precise PDE values for solid-state photomultiplier detectors.

1. Introduction

The availability of suitable detectors capable of counting the arriving photons at the maximum speed possible and with a Photon Detection Efficiency (PDE) as good as possible in a wide spectral range is of great importance in applications like Nuclear Physics and Astrophysics that require devices with adequate characteristics.

Recently, efficient devices with different total sensitive area and single element dimensions for these applications have been manufactured by the silicon industries. Such detectors are named silicon photon multipliers (SiPMs) or multi-pixel photon counters (MPPCs). To understand the real applicability in the selected field, a very accurate experimental setup and a well-defined methodology in measuring the electro-optical characteristics are needed.

In this paper, we briefly describe the detectors characterized, and the adopted equipments and techniques for the measurements. We also show that carefully accounting for dark noise, cross-talk and afterpulses is fundamental in order to quantify the true efficiency of the photon counting detectors.

2. Detectors

The characterization activity carried out by our group regards two kinds of detectors operating in photon counting regime in continuous mode: SiPMs manufactured by ST Microelectronics and MPPCs manufactured by Hamamatsu.

Both sensors are based on a single photon avalanche diode (SPAD) cell that is a p–n junction operating in Geiger mode. The junction is biased slightly above the breakdown by an overvoltage (around 10% for the STM and about a few percent for the Hamamatsu) and remains quiescent until a carrier, generated either thermally or by a photon, triggers an avalanche in the depletion region. A passive quenching circuit, constituted essentially by a resistor integrated on the cell itself (the cathode for the STM and the anode for the Hamamatsu), extinguishes the avalanche and makes the pixel ready for another detection.

By replicating the elementary cell, can be produced detectors of various dimensions and architecture. In particular we have concentrated our attention on 10×10 cells STM SiPMs, 10×10 cells and 20×20 cells Hamamatsu MPPCs.

The STM SiPM 100-cells has dimensions of $0.5 \times 0.5\,\mathrm{mm}^2$ with each cell squared and with a $50\,\mu\mathrm{m}/30\,\mu\mathrm{m}$ side over active area ratio giving a 36% fill factor.

The Hamamatsu 100-cells MPPC (S10362-11-100C) has a pitch of $100\,\mu\mathrm{m}$ over a squared millimeter giving a fill factor of 78.5%, while the 400-cells MPPC (S10362-11-050C) has a pitch of $50\,\mu\mathrm{m}$ over the same area and then a fill factor of 61.5%.

The STM SiPM has a breakdown voltage around 29.5 V at room temperature, with a variation coefficient of 35 mV/°C, while both Hamamatsu MPPCs have a breakdown voltage around 68.6 V at room temperature.

Each SiPM cell is surrounded by a suitable trench filled with opaque material, to drastically reduce the probability of optical cross-talk between neighbouring cells but none of the MPPC cells have trench.

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3. Experimental setups used for gain and photon detection efficiency measurements

We carried out two kinds of PDE measurements, one by considering the output current from the SiPM and the other by counting the output pulses.

The first method requires the knowledge of the detector gain *G* and for this we implemented the equipment sketched in the left panel of Fig. 1.

The second method needs simply a classical front-end electronics constituted by an amplifier, a discriminator and a counter as sketched in the right panel of Fig. 1. More details can be found in Refs. [1,2]. For the *G* measurements we placed each detector into a light-tight box and positioned the fibre coming from the laser (a 671 nm pulsed laser with FWHM pulse width of 40 ps) just in front of it, making sure that the laser spot was covering the whole active area. The detector output is connected to an amplifier (a FTA810B, with gain 200 and rise time below 1 ns) that produces a voltage signal and forms the input signal of the QDC (a Silena 4418/Q). The laser TTL output trigger signal is sent to a discriminator (a Lecroy 4608) to generate the gate for the QDC. The optical apparatus used for PDE measurements is one of the available facilities at "INAF-Catania" laboratory. Its schematic is shown in Fig. 2.

A detailed description of the system is reported in Refs. [3–5] and here the main parts are briefly described. A xenon lamp is

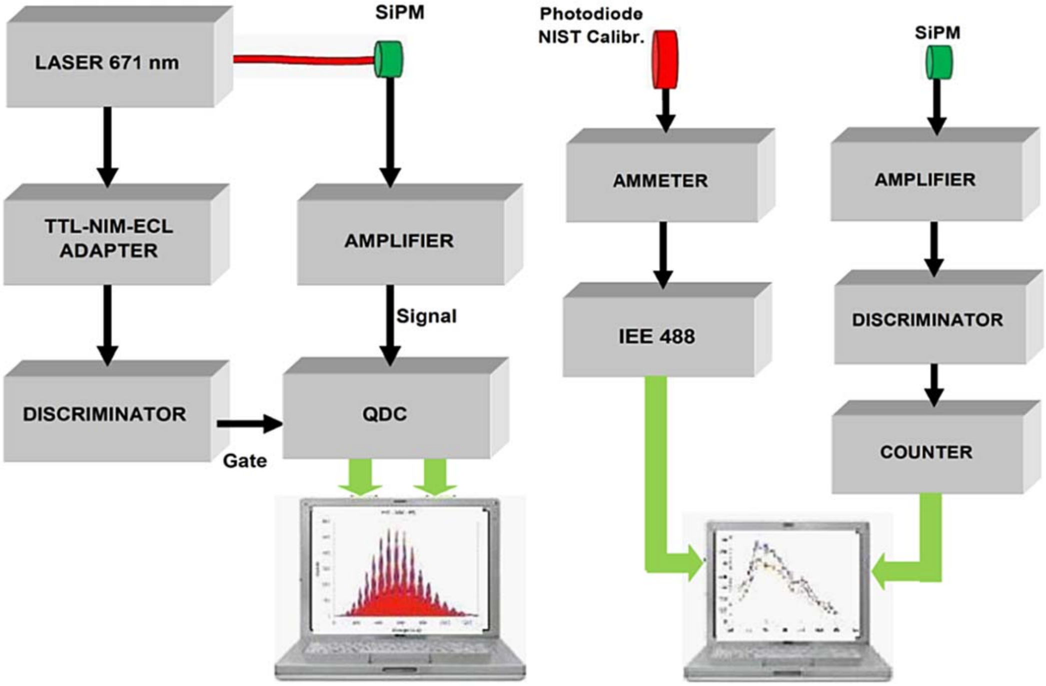

Fig. 1. Sketch of the electronics implemented for the charge gain measurements (left) and PDE measurement in counting mode (right).

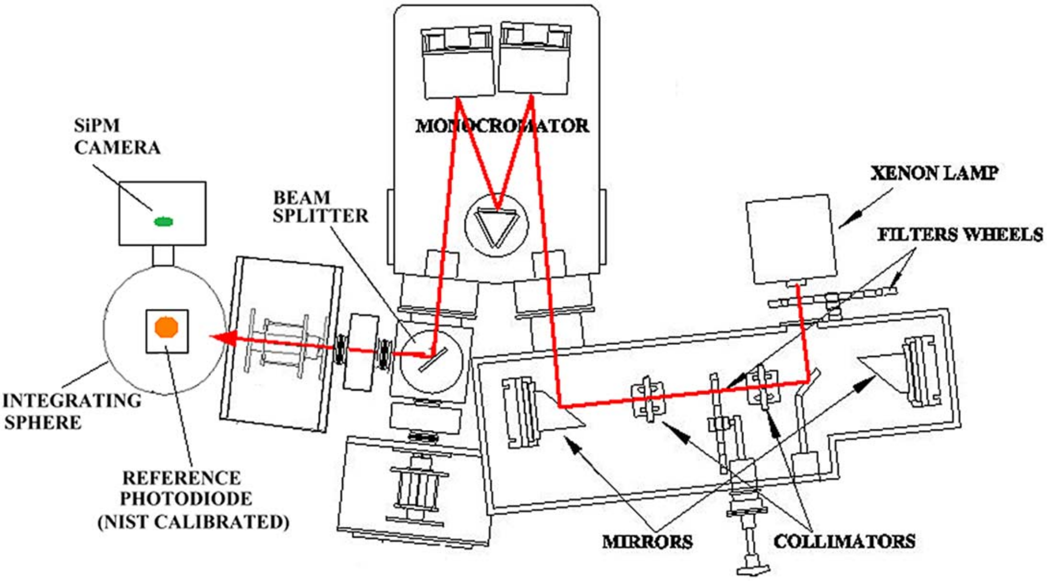

Fig. 2. Schematic of the optical apparatus used for PDE measurements. The light path is also shown. Details are in the text.

used as radiation source, the wavelength selection is performed by a Czerny–Turner monochromator (FWHM 1 nm in the 130–1100 nm spectral range) and a beam splitter directs the monochromatic radiation towards an integrating sphere that guarantees a spatial integration of the radiant flux on a 1 cm^2 reference photodiode (NIST traced) and on the detector to be characterized. Furthermore, we designed the detector housings, in such a way to have same aperture and distance from the centre of the sphere. The calibrated photodiode allows to evaluate the absolute number of photons per unit area, and then, after proper rescaling, the number of photons on the detectors.

4. Gain measurements

The gain measurements are of fundamental importance in computing the PDE considered as a ratio between the photocurrent of the tested detector and that of the calibrated one. Uncertainties on the gain measurement directly affect the PDE values.

As each cell of the devices operates in Geiger mode, the interaction of one photon produces an electron–hole pair followed by an avalanche multiplication [5] The avalanche multiplication factor is the gain and depends on the bias voltage. By using the setup described in the previous section and setting the laser intensity at various levels, we acquired the charge spectrum for each detector. The G has been obtained by computing the average spacing between two consecutive peaks in terms of QDC channels. Values in 10^4–10^5 range have been found.

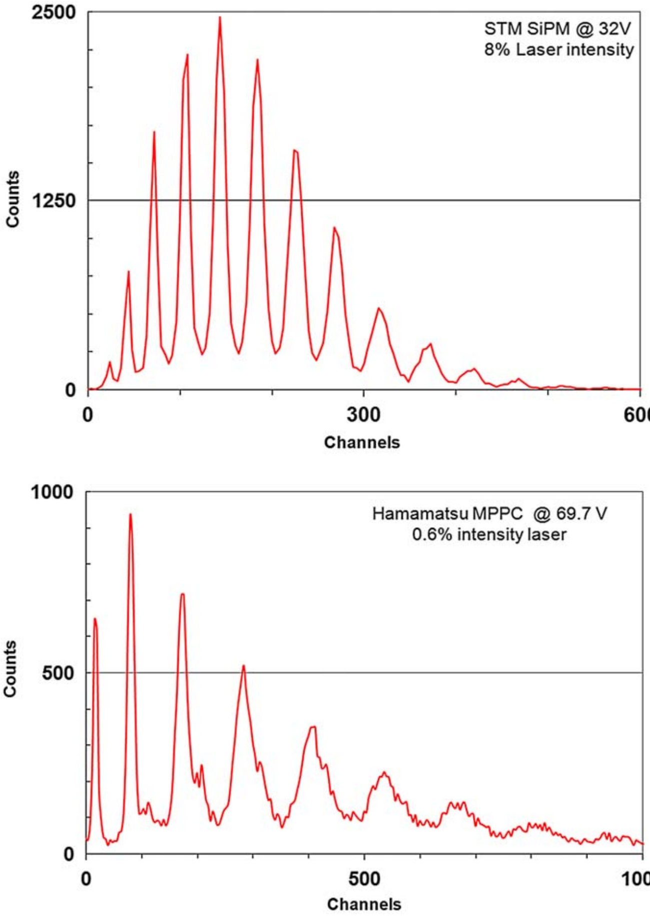

Fig. 3. On the upper panel is plotted the charge spectrum from the STM SiPM 100-cells. On the bottom panel is plotted the charge spectrum from Hamamatsu MPPC 100-cells.

As an example in Fig. 3 the STM SiPM and the Hamamatsu 100-cells charge spectra are shown.

Surprisingly for the Hamamatsu devices we have found values of G about one order of magnitude less with respect to those provided with the detectors. To locate the error sources, we also checked the amplifier by using a calibrated source. Different configurations are investigated and measurements are still in progress.

5. PDE measurements

Two approaches can be envisaged to measure the detector PDE: the "Photocurrent" method, consisting in measuring the generated charges considered as current and the "Counting" method, consisting in counting each produced event.

Considering that the reference photodiode is 1 cm^2 (leakage current less than 1 pA) while the tested devices have dimensions of squared millimeter, in the "Counting" case, we adjusted the photon flux level (from about 10^5 to about 10^7 $phs\,mm^{-2}\,s^{-1}$) in such a way that the reference detector was still sensitive and the detectors were safe in the single photon regime with negligible pile-up.

5.1. *The "Photocurrent" method*

The "Photocurrent" method consists in comparing the photocurrent of the characterized detectors with respect to that of the NIST calibrated photodiode. In this case the setup apparatus shown in the right panel of Fig. 1 is simplified by substituting the amplifier, the discriminator and the counter with an ammeter. The following formula explains how the method works:

$$PDE = (I_{Det} - I_{DarkDet})/(I_{PhD} - I_{DarkPhD}) \times 1/G \times PDE_{PhD} \times (A_{PhD}/A_{Det})$$

where I_{Det}–$I_{DarkDet}$ is the current measured in the detector, I_{PhD}–$I_{DarkPhD}$ is the current measured in the calibrated photodiode, G is the gain (N_{el}/e), PDE_{PhD} is the PDE of the calibrated photodiode and A_{PhD}/A_{Det} is the detectors area ratio.

We operated the detectors at room temperature and measured the PDE of the STM SiPM biased at 32.5 V (10% OV) and that of the 100- and 400-cells MPPC biased respectively at 69.8 V (~2% OV) and at 69.4 V (~2% OV). Using the G values obtained with our measurements, we found unreasonable PDE values (higher than expected). We suspected that this was mainly due to one of the used instruments (the Silena QDC) having a different performance from that specified on the data sheet. Thus, we decided to compute the PDE using the G values given by Hamamatsu. The obtained values are plotted in Fig. 4.

As can be noted, the PDE of the 100-cells MPPC at 450 nm has a peak of about 50%, while the 400-cells MPPC has a peak of 30% (essentially due to the different fill factor). It is well known, of course, that this technique, based on photocurrent measurements, is unable to discriminate from extra charges, i.e. afterpulses and optical cross-talk pulses, and this can lead to overestimate the PDE. To have more accurate measurements will be better to use a method that can account for extra charges.

5.2. *The "Counting" method*

The "Counting" method is based on measuring the count rate due to the real signal and comparing it to the photocurrent measured by the ammeter converted in number of electrons per second. The formula of this method is

$$PDE = (CR_{Det} - CR_{DarkDet})/(I_{PhD} - I_{DarkPhD})PDE_{PhD} \times e^{-}(A_{PhD}/A_{Det})$$

where CR_{Det}–$CR_{DarkDet}$ is the measured count rate, e^{-} is the electron charge and I_{PhD}–$I_{DarkPhD}$, PDE_{PhD}, A_{PhD}/A_{Det} are the same as in the previous formula.

By using this method the afterpulse and the cross-talk can be characterized and taken into account in the right way (see details in Refs. [1,2]). Furthermore as the measured counts could be affected by the front-end discriminator threshold setting, we analyzed the count rates as a function of the threshold (see Refs. [1,2]) and we selected a threshold equivalent to 0.5 photons that is in a safe plateau region. In the tested devices we found that the afterpulse probability is not appreciable after $\approx$100 ns and thus we settled the duration of output logic signal from the discriminator greater than this value.

We counted the number of pulses per unit time both in dark conditions ($\sim$600 KCnts/s for the 100-pixels MPPC, $\sim$500 KCnts/s for the 400-pixels MPPC, $\sim$500 KCnts/s for the 100-pixels STM) and with monochromatic light conditions (photon signal ranging from $\sim$100 to $\sim$500 KCnts/s), recording at the same time the light level seen by the reference detector, for several wavelengths. We also carefully tuned the light intensity to keep at negligible levels the pile-up probability.

For the STM SiPM we measured the PDE with two gate logic signal durations of 50 and 500 ns and accounted for the dead time. The result is shown in Fig. 5. The unappreciable difference between the two sets of measurements strongly supports the correctness of this method.

In Fig. 6 the resulting PDE plots for the 100 cells MPPC obtained with gate logic signal durations of 100 and 1000 ns are also shown. A negligible difference can be found.

6. Photocurrent versus photon counting

In order to compare the photocurrent method with the counting method, we have plotted in Fig. 7 the two MPPC 100-cells PDEs obtained with the two operating modes.

As can be seen from Fig. 7, the PDE obtained with the photocurrent method is systematically higher than that measured with the photon-counting mode in all spectral range. Moreover the error-bars associated to the PDE values are very low (not exceeding the point itself) demonstrating the high accuracy of measurements and the real difference between the two PDE curves.

Fig. 7 shows unequivocally that each PDE value obtained using the photocurrent method doubles that of the counting–operating mode, but to better evaluate the difference between the two methods, we decided to represent the two PDE plots in another way. In fact in Fig. 8 we placed on the left axis the PDE values obtained with the "Photocurrent" method, while on the right axis we reported the PDE values obtained in "Counting" mode. Note

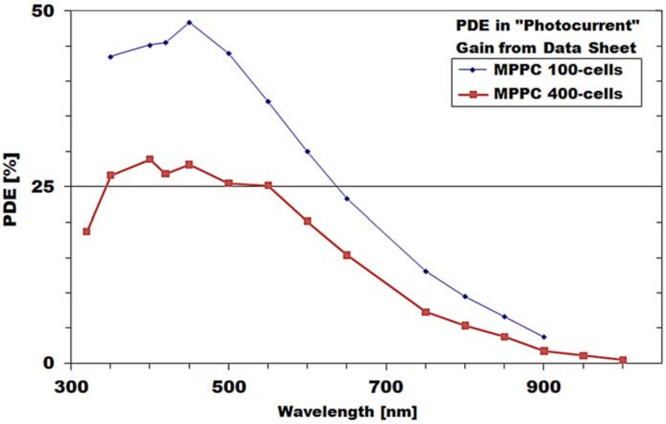

Fig. 4. PDE plots of the Hamamatsu MPPC 100-cells and 400-cells devices by using the "Photocurrent" method.

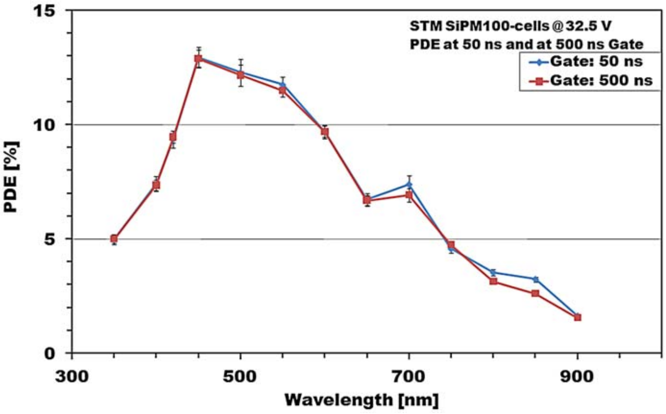

Fig. 5. "Counting" method: PDE of the STM device biased at 32.5 V, measured and reconstructed with our method using logic signal durations of 50 and 500 ns, respectively.

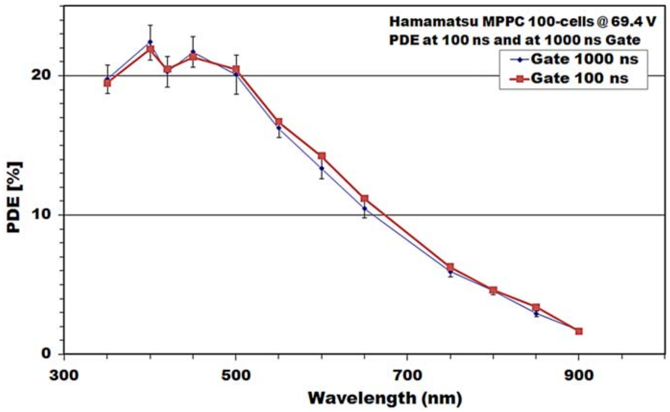

Fig. 6. "Counting" method: PDE measured for the Hamamatsu 100-cells biased at 69.4 V using gate signals of 100 and 1000 ns.

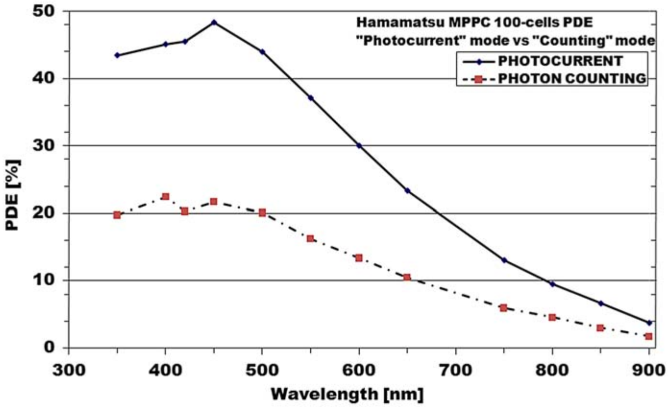

Fig. 7. PDE measurements for Hamamatsu MPPC 100-cells. The "solid line" refers to the PDE obtained with the "Photocurrent" method, while the "dashed line" refers to the PDE obtained in the "Counting" case.

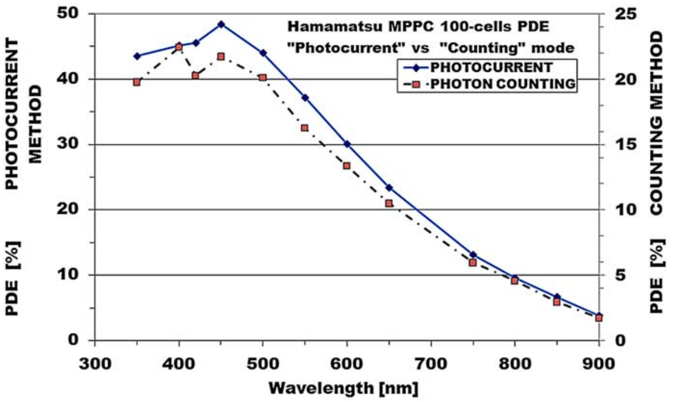

Fig. 8. "Photocurrent" method versus "Counting" method: The "solid line" refers to the PDE (values on the left axis) obtained with the photocurrent method, while the "dashed line" refers to the PDE (values on the right axis) in the "Counting" case.

that in this figure the solid line refers to the photocurrent method (values are on the left axis) while the dashed line refers to the counting method (values are on the right axis). Even the two PDE plots came from different methods, an amazing over-position is clearly evident. This demonstrates that at each wavelength the PDE values obtained with the two different methods can be related between themselves, and by noting the scale of the left axis with respect to the right axis, the relation is that each value almost doubles the corresponding value.

From this analysis we can easily conclude that the "Photocurrent" method fails in measuring the PDE accurately. In fact, as can be seen from Figs. 7 and 8 the PDE data obtained with the "Photocurrent" method are overestimated with respect to those obtained with the "Counting" method, and this can be certainly due to the extra charges (afterpulses and cross-talk pulses) that are impossible to avoid on the measurements of the "Photocurrent" method.

7. Conclusions

As seen in the previous section the comparison between the two methods has pointed out the vulnerability of the "Photocurrent" method that gives PDE values overestimated with respect to that of "Photon Counting". This is essentially due to the fact that the technique cannot discriminate the afterpulse and the cross-talk effects.

The "Counting" method allows to characterize and accurately discriminate the two effects giving PDE values quite close to the real ones, but needs to operate in appropriate signal conditions; in fact, very fast events can be lost and the total counted events can be lower than those expected. The "Counting" is a method well-suited for PDE measurements as it finally deals with true photons, reducing the contribution of extra charges as much as possible.

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