Nuclear Instruments and Methods in Physics Research A ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

# New method for evaluating effective recovery time and single photoelectron response in silicon photomultipliers

Martyna Grodzicka*, Tomasz Szczęśniak, Marek Moszyński, Marek Szawłowski, Krystian Grodzicki

*National Centre for Nuclear Research, A. Soltana 7, PL 05-400 Świerk, Otwock, Poland*

ARTICLE INFO

*Article history:*
Received 6 June 2014
Received in revised form 20 January 2015
Accepted 20 January 2015

*Keywords:*
Effective recovery time of SiPM
SiPM
MPPC
SPMMicro
Scintillation spectrometry

ABSTRACT

The linearity of a silicon photomultiplier (SiPM) response depends on the number of APD cells and its effective recovery time and it is related to the intensity and duration of the detected light pulses. The aim of this study was to determine the effective recovery time on the basis of the measured SiPM response to light pulses of different durations. A closer analysis of the SiPM response to the light pulses shorter than the effective recovery time of APD cells led to a method for the evaluation of the single photoelectron response of the devices where the single photoelectron peak cannot be clearly measured. This is necessary in the evaluation of the number of fired APD cells (or the number of photoelectrons) in measurements with light pulses of various durations. Measurements were done with SiPMs manufactured by two companies: Hamamatsu and SensL.



## 1. Introduction

A silicon photomultiplier (SiPM) belongs to the group of semiconductor photodetectors. It is made up of an array of parallel connected micro avalanche photodiodes (APD cells), working in Geiger mode. Each APD cell generates a constant signal after the detection of a single photon, or due to related phenomena such as cross-talks and after-pulses. The sum of the signals from all of the APD cells gives the SiPM output pulse. In consequence, the number of fired APD cells is generally larger than the number of detected/incident photons [1–9]. The details of the operating principles, the theoretical model and the analysis of the linearity and pulse height resolution of SiPMs have been extensively studied and can be found elsewhere in the literature [3,4,9–12].

Depending on the incident light flux, the response of SiPM can be non-linear or saturated for very high numbers of incident photons. These effects are the result of a limited number of APD cells in a device and its finite effective recovery time. The effective recovery time is the time needed for the APD cell to fully recharge after firing. For example, if two or more photons are incident at the same time on one APD cell, the signal will be equal to one photoelectron case: the linearity of the photon detection will be deteriorated. Assuming that each APD cell can fire only one time during one light pulse, the response of the SiPM can be described in the following way:

$$N_{fired} = N_{total} \times \left[1 - \exp\left(\frac{-N_{tpd}}{N_{total}}\right)\right] \quad (1)$$

where $N_{fired}$ is the number of excited APD cells; $N_{total}$ is the total number of APD cells; $N_{tpd}$ is the total number of events (photons, optical cross-talk photons, and electrons causing after-pulses) having the potential to be detected as described by:

$$N_{tpd} = N_{photon} \times \mathrm{PDE} \times (1+P) \quad (2)$$

where $N_{photon}$ is the number of incident photons; PDE is the photon detection efficiency; $P$ is the probability of a false pulse caused by phenomena such as cross-talk and after-pulses. This probability becomes higher with an increase of bias voltage and depends on the type and production technology of the SiPM used. For constant bias voltage this probability is constant and independent of the number of incident photons. The primary dark count is neglected.

### 1.1. Aim of the study

In most SiPMs (except digital SiPMs), each APD cell have an effective recovery time that last from few to tens of nanoseconds after the detection of a single photon (this value depends on the SiPM production technology). The finite effective recovery time means that, depending on the duration of the light pulse or the decay time of the scintillator light pulse, each APD cell can fire more than one time during one light pulse.

The main aim of this work was to provide experimental proof of Eq. (1), by illuminating a SiPM with a short light pulse of a few ns in

* Corresponding author.
*E-mail address:* m.grodzicka@ncbj.gov.pl (M. Grodzicka).

10.1016/j.nima.2015.01.074
0168-9002/

Please cite this article as: M. Grodzicka, et al., Nuclear Instruments & Methods in Physics Research A (2015), 10.1016/j.nima.2015.01.074

duration and then supplement Eq. (1) with parameters such as effective recovery time and duration (or decay time) of the light pulse. First the experimental conditions simulated a situation where each APD cell could fire only one time during the light pulse and then the duration of the incident pulse was extended in order to allow multiple responses of single cells. Determination of the effective recovery time of a SiPM was done on the basis of the measured linearity of the response of the SiPM to the light pulses of different durations, which was also larger than the effective recovery time. Closer analysis of the measured characteristics showed the possibility of estimating the number of fired APD cells in the case when a well-defined single photoelectron spectrum was not observed.

Tests of the presented method were carried out with SiPMs manufactured by two companies: Hamamatsu and SensL. Since this work does not have a comparative nature, just the exemplary SiPMs from the old generation were used during the tests.

### *1.2. Motivation*

This paper was triggered by our previous studies presented in Refs. [2,6], which described SiPMs in gamma-ray spectrometry with different scintillators. The data showed an improvement of the linearity range of SiPMs with an increase in the decay time of a scintillator. Earlier studies also showed a problem with the measurement of a single photoelectron spectrum for SiPMs with an active area larger than $2\times2$ mm. Such a spectrum could not be obtained at room temperature using analog electronics, even with the minimum possible shaping time of 0.125 μs in the spectroscopy amplifier. Hence the need arose to look for a new method of determination of a single photoelectron spectrum.

## 2. Experimental details

### *2.1. SiPMs and light sources*

Measurements of the effective recovery time of APD cells were done with Hamamatsu Multi Pixel Photon Counters (MPPCs) because of their well-pronounced single photoelectron spectrum. This allowed for precise measurement of the number of photoelectron (phe) or fired APD cells. The next step of this experiment was to estimate the single photoelectron peak using the new method. These tests were done for SiPMs manufactured by SensL. The main parameters of all of the measured SiPMs are shown in Table 1. Please note that most of the SiPMs tested were from their first production run.

In the measurements with light pulses, a picosecond laser, a blue–violet light emitting diode (LED) and a plastic scintillator were used. Their main parameters are presented in Table 2.

### *2.2. Experimental methods*

All of the measurements were done in an air-conditioned laboratory at a temperature of 21 °C. The experimental proof of Eq. (1) was done using the set-up presented in Fig. 1a. This experiment requires three basic conditions:

– Uniform illumination of the tested SiPM and PMT is extremely important. SiPM is made up of multiple avalanche photodiode (APD) cells, and non-uniform illumination of the SIPM active area can cause a reduction in the total number of firing APD cells, consequently limiting the linear response of the device.
– Very short pulse duration of the used light source. The pulse duration must be shorter than the effective recovery time of the tested SiPM.
– Excellent linearity of the PMT response, which is used for monitoring the light intensity and evaluation of the SiPM response.

As shown in Fig. 1(a and b), the laser or LED light pulses enter the BC 408 plastic scintillator and cause the excitation of the plastic scintillator and isotropic emission of the light. Uniform light output at both ends of the excited scintillator assures uniform illumination of the tested SiPM and PMT. XP2020Q PMT was used for monitoring the light intensity because of its excellent linearity.

Fig. 1b presents a block diagram of the set-up used for measurements of the effective recovery time of APD cells. In this experiment an LED with variable pulse duration was used. The LED pulse duration was controlled by observing the PMT signal from the last dynode on an oscilloscope (see Fig. 1b). The illumination intensity of MPPC and PMT was controlled by moving the light source, mounted on an electronic cart, along the "movement path" marked in Fig. 1b. This method assured much higher accuracy and stability than the variation of the light intensity by the pulse height of the laser trigger.

## 3. Results

### *3.1. Saturation behavior with very short laser pulses*

The basis for all considerations presented in this work is the experimental verification of Eq. (1). An S10985-025C MPPC array was used for this purpose. Measurements of one channel and the entire array structure were performed in an experimental set-up as presented in Fig. 1a. The conditions of the experiment are described in Section 2.2.

The amplitude spectra of light pulses 2.5 ns in duration detected in the MPPC and PMT were simultaneously recorded in a large dynamic range of light intensity. In the first step the responses of the SiPM and PMT were expressed by light pulse peak positions ($PP_{SiPM}$, $PP_{PMT}$) in the recorded pulse amplitude spectra. Next, knowing the previously recorded single photoelectron peak positions of MPPC and PMT ($1PHE_{SiPM}$, $1PHE_{PMT}$), and using the Bertolaccini method [13,14], the light pulse peak positions were expressed in the number of photoelectrons and fired APD cells as $N_{PMT}=PP_{PMT}/1PHE_{PMT}$ and $N_{®red}=$ PP-$_{SiPM/1PHESiPM}$, respectively.

The light intensity on SiPM was monitored using XP2020Q PMT, so the number of total events having potential to be detected in SiPM ($N_{tpd}$) in the full range of measurements is proportional to the number of photoelectrons detected in PMT ($N_{PMT}$): $N_{tpd}=\alpha\times N_{PMT}$.

In the linear range of the SiPM operation, the number of fired APD cells ($N_{fired}$) is equal to the number of total events having the potential to be detected: $N_{fired}=N_{tpd}=\alpha\times N_{PMT}$. This allows the evaluation of the normalization coefficient $\alpha$ using linear range data as: $\alpha=N_{fired}/N_{PMT}$.

The results obtained in the measurements of the Hamamatsu MPPC array with the laser light pulses are presented in Fig. 2 (points), together with the curves calculated using Eq. (1) (solid lines). The measurements were done for 1 ch (14400 APD cells) of the MPPC array (circles) and for all $2\times2$ channels (57600 APD cells) of the entire MPPC array (squares). The measurement points for one channel and the entire SiPM array fit the calculated curves corresponding to the number of APD cells in the tested array channels very well.

### *3.2. Measurement of the effective recovery time of APD cells*

In the previous section we showed that for very short light pulses (2.5 ns), the response of a SiPM is correctly described by Eq.