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Over saturation behavior of SiPMs at high photon exposure

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ABSTRACT

Several types of Silicon Photomultipliers were exposed to short pulsed laser light (~ 30 ps FWHM) with its intensity varying from single photon to well above the number of microcells of the device. We observed a significant deviation of the output of SiPMs from the expected behavior although such response curve is considered to be rather trivial. We also noticed that the output exceeds the maximum expected pulse height, which should be defined as the total number of pixels times the single photon pulse height. At the highest light intensity (~ 500 times the number of pixels) that we tested, the signal output reached up to twice the maximum theoretical pulse height, and still did not fully saturate.

1. Introduction

The Silicon Photomultiplier (SiPM) is a semiconductor photo detector which consists of multiple pixels (typically a few 100) of Avalanche Photodiodes working in Geiger-mode. Because of its characteristics such as compact size, low cost, insensitivity to magnetic fields, high photon detection efficiency (PDE) and high gain, the SiPM can be used in many different fields ranging from astrophysics, particle physics to medical imaging, as an alternative to vacuum Photomultiplier Tubes.

Due to its design, the SiPM dynamic range should be limited to an order of the total number of pixels. This effect is reflected in a saturation behavior of the SiPM response. The relation between the number of incident photons on the detector surface (N_{photon}) and the number of fired pixels (N_{fired}) can be described by the following model:

$$N_{fired} = N_{total} \times \left[1 - \exp\left(-\frac{N_{photon} \times \mathrm{PDE}}{N_{total}}\right)\right] \tag{1}$$

with N_{total}, the total number of pixels of the SiPM. With increasing N_{photon}, the SiPM response curve, i.e. the relation between light input and SiPM output (N_{fired}), deviates from linearity, dependent on the PDE, and saturates at $N_{fired} = N_{total}$. Eq. (1) is valid for an ideal photosensor and an infinitely short light pulse. In a real SiPM, however, the response to incident light is influenced by several effects, such as after-pulsing, cross-talk, dark-noise and the pixel recovery. Therefore, the SiPM output is expected to deviate from the response curve as given by Eq. (1).

As presented in the following sections, we came across to observe a deviation between the SiPM output and the expected response, which cannot be explained only by the above effects. We measured the response curve for various SiPMs, all with 1 mm^2 sensitive area but different number of pixels and from different vendors. The models tested are the Hamamatsu MPPC S10362-11-100U with 100 pixels and S10362-11-050U with 400 pixels, the SSPM-0611B1MM-TO18 from Photonique[1] with 556 pixels and a Zecotek MAPD-1 with 560 pixels. The main parameters of all tested devices are summarized in Table 1.

2. Setup and method

To measure the response curve, the SiPMs were exposed to short light pulses with intensities ranging from single photon up to several ten thousand. The measurement setup is shown schematically in Fig. 1. All tests were done at room temperature (~25 °C). As light source we used a pulsed laser with 32 ps pulse width (FWHM) from Advanced Laser Diode Systems. The emission wavelength of the laser head (PIL040) is $\lambda = 404$ nm. The repetition frequency was set to a level of 20 kHz, to have a time interval between two laser pulses well above the SiPM cell recovery time. After passing a variable optical attenuator, the laser pulses were split using a beam splitter with a splitting ratio of 45:55 (45% reflectivity, 55% transmission). One path of the beam is targeted at a Hamamatsu S5971 PIN photodiode for monitoring the light intensity. The current of the PIN photodiode was measured using a Keithley 6517 electrometer. After passing another variable optical

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[1] Photonique SA has suspended its operations. Product information can be found here: http://www.photonique.ch/LEGACY.

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Table 1
Main SiPM parameters. The breakdown voltage, V_{bd}, has been measured. The operating voltage V_{bias} is typically set ~1 V above V_{bd}. The exact values and the corresponding gain are given. Other parameters are taken from the data sheets [1–3]. The PDE given by Hamamatsu includes effects from cross-talk and after-pulsing. There are several other measurements of the PDE available, but the results are also known to strongly depend on the operating conditions, e.g. over-voltage and temperature, and the measurement procedure. Therefore, we refer to the values given by the companies.

Parameter	Hamamatsu MPPC		Photonique SSPM	Zecotek MAPD
	S10362-11-100U	S10362-11-050U	0611B1MM-TO18	MAPD-1
Active area (mm^2)	1 × 1	1 × 1	1 × 1	1 × 1
Number of pixels	100	400	556	560
Pixel size (μm^2)	100 × 100	50 × 50	–	–
Fill factor (%)	78.5	61.5	> 70	–
PDE (% @ 400 nm)	72	47	18	15
Capacitance (pF)	35	35	40	75.6
Breakdown voltage (V)	69.45	68.65	27.80	34.00
Operating voltage V_{bias} (V)	69.95	69.85	29.00	34.70
Gain @ V_{bias}	1.1×10^6	6.6×10^5	5.4×10^5	5.9×10^5

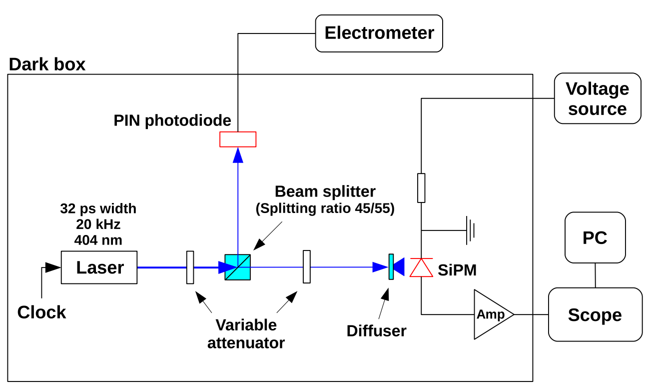

Fig. 1. Schematic of the measurement setup.

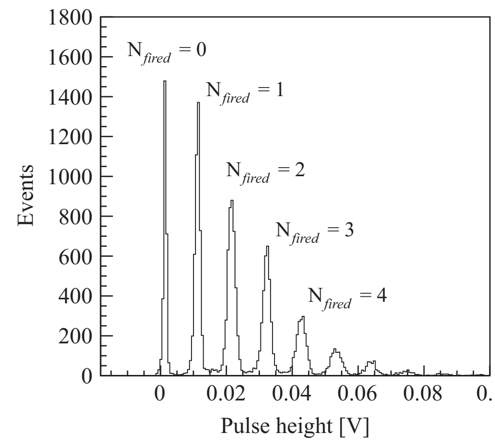

Fig. 2. Single photon spectrum of the Hamamatsu MPPC with 100 pixels operated at $V_{over} = 1$ V. The peaks correspond to a certain number of fired pixels.

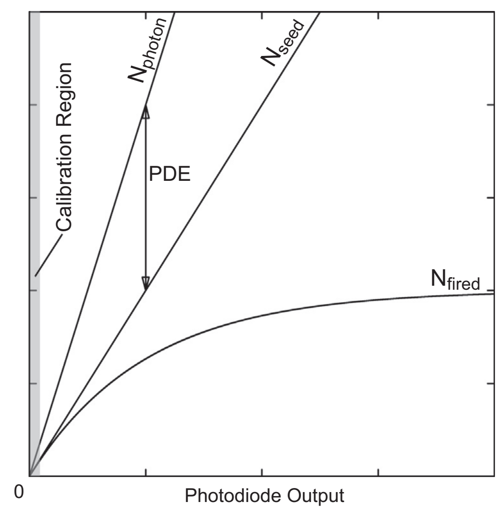

Fig. 3. Schematic of the calibration method.

attenuator, the second beam was directed to a diffuser in order to homogeneously distribute the light on the SiPM active area. The second attenuator in between beam splitter and SiPM is needed to deal with the different sensitivities of the SiPM and the photodiode.

The SiPM signal was amplified by using a Photonique AMP-0611 preamplifier [2]. The DC voltage supply was set to 5 V. The linearity of the preamplifier was confirmed by measuring the preamplifier response to defined input pulses. Within the whole input range we tested, a linear behavior of both, the output pulse height as well as the output charge, was found. The measurement resulted in a gain of about 23. The operating voltage of the sensor, V_{bias}, was typically set to $V_{over} \sim 1$ V above the breakdown voltage, V_{bd}, which had been determined in a separate measurement. The values are given in Table 1. The corresponding gain of the SiPM, G, can be estimated by $G = C_{pix} \cdot V_{over}/q_e = C_{pix} \cdot (V_{bias} - V_{bd})/q_e$, with C_{pix} being the pixel capacitance and q_e the elementary charge. The operating voltages given in Table 1 were selected in order to operate the SiPMs at low to moderate gain and therefore low noise (dark-noise, after-pulsing, cross-talk).

The SiPM response, i.e. the number of fired pixels, N_{fired}, was determined by measuring the average output pulse height with the LeCroy WavePro 735Zi digital oscilloscope. In order to estimate N_{fired} from the measured pulse height, the output signal of a single fired pixel must be determined. This is done at low light intensity by filling the pulse height values into a histogram, as shown in Fig. 2. Each peak corresponds to a certain number of fired pixels (N_{fired}). By fitting the spectrum and extracting the distance between adjacent peaks, the pulse height corresponding to a single fired pixel can be determined several times.

The PIN photodiode was calibrated at very low light intensities ($N_{fired} < 10$, in case of Hamamatsu 100U, $N_{fired} < 20$, for the others), where one can expect a linear behavior of the response, due to the homogeneous distribution of input photons on the sensor surface. The calibration procedure is illustrated schematically in Fig. 3. For interpretation of the data, we introduce the average number of "seeds", N_{seed}, which is the average number of photons arriving at the sensitive area of the SiPM, that could trigger an avalanche unless the cells had been fired already. The number of fired pixels, N_{fired}, is the main observable of the measurement. N_{fired} can be determined by measuring the signal pulse height, as described before. In the calibration region $N_{seed} = N_{fired}$, thus N_{seed} and the linear relation between the photodiode output current and the number of "seeds" can be determined and in the following extrapolated to higher light intensities. The relation between N_{seed} and the number of incident photons, N_{photon}, is given by $N_{photon} = N_{seed}/\mathrm{PDE}$. In order to avoid the use of a PDE, which depends on the temperature, the operation voltage and the way it is measured, we plot N_{fired} as a function of N_{seed} and compare