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A study of timing properties of Silicon Photomultipliers

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ABSTRACT

Silicon Photomultipliers (SiPMs) are solid-state pixelated photodetectors. Lately these sensors have been investigated for Time of Flight Positron Emission Tomography (ToF-PET) applications, where very good coincidence time resolution of the order of hundreds of picoseconds imply spatial resolution of the order of cm in the image reconstruction. The very fast rise time typical of the avalanche discharge improves the time resolution, but can be limited by the readout electronics and the technology used to construct the device. In this work the parameters of the equivalent circuit of the device that directly affect the pulse shape, namely the quenching resistance and capacitance and the diode and parasitic capacitances, were calculated. The mean rise time obtained with different preamplifiers was also measured.

1. Introduction

ToF-PET is a medical diagnostic technique that gives information on the metabolic activity of cells. It requires the use of detectors with a very fast response that in turn determines very good time resolution. Being analogue to the Photomultiplier Tubes (PMTs), traditionally used for PET applications, the Silicon Photomultiplier (SiPM or MPPC) is currently one of the most promising sensors for ToF-PET, in association with very fast scintillating crystals. The main improvements in the use of SiPMs are expected to be compactness of the designs and a superior coincidence time resolution. Moreover, its insensitivity to magnetic fields opens the horizons toward the combination of the ToF-PET with the Nuclear Magnetic Resonance (NMR).

Silicon Photomultipliers are solid-state single-photon sensitive devices made of a matrix of Geiger Mode Avalanche Photodiodes (GM-APD). Each pixel works as a binary device, giving an output to a standard signal. The almost simultaneous firing of multiple pixels preserves the information on the number of photons striking the sensor. However, due to the limited number of pixels in the device, saturation effects can affect the linearity of its response, whenever the one-to-one correspondence between a photon and a pixel is lost; i.e. multiple photons incident on the same pixel at the same time generate the same standard output as a single detected photon [1].

The formation of the signal is generated by the photoelectric effect of visible photons in the Silicon bulk. The detector is reverse biased at a voltage higher than the breakdown voltage, V_{br} and the carriers migrate to a region with a very high electric field of the order of $10^5\,\mathrm{V\,cm^{-1}}$. Once here these carriers have enough energy to create an electron-hole pair by impact ionisation. The daughter carriers in turn are accelerated by the strong electric field and will generate further carriers. An avalanche effect is settled in the very thin depletion region of the sensor of the order of few μm, characterised by a current of the order of μA [2]. This avalanche is passively quenched by the high resistivity of a resistor R_q, in series with each pixel. The presence of R_q contributes to the pulse formation with a very small capacitance in parallel, C_q. The typical pulse shape of a SiPM is then characterised by the build-up time of the avalanche, of the order of tens of ps, and by a mixed contribution from R_q, C_q and the diode capacitance C_d, that affect mainly the decay time of the pulse, of the order of tens of ns. Finally, the readout electronics can play a degrading role on the timing performances of these devices, in particular affecting the pulse rise time.

In this paper, the characterisation of various MPPCs will be discussed and the effects of different readout electronics will be studied.

2. Experimental method

The experiments described in this work were performed using four different Hamamatsu MPPC, S10362-11-025C, S10362-11-50C, S10362-33-025C and S10362-33-050C, with a total area of

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$1 \times 1\ \text{mm}^2$ and $3 \times 3\ \text{mm}^2$ and pixel size of 25 μm and 50 μm (cf. Table 1).

The IV forward and reverse characteristics were measured using a Keithley 487 picoammeter interfaced with a computer through a dedicated LabVIEW DAQ software. The capacitance and conductance of the sensors were instead measured using an Agilent 4284A LCR meter at 1 V AC voltage and at a frequency of 1 MHz as in Refs. [3–5].

The values of R_q and of V_{br} were calculated from the IV-characteristics. A linear fit to the Ohmic part of the forward curve gives the total SiPM resistance, from which it is possible to calculate R_q considering that the pixels are in parallel. A parabolic fit to the region between the proportional and the avalanche part of the reverse curve, gives instead the value of V_{br}, which is needed to correctly operate the device in the Geiger mode. The values found are summarised in Table 1.

For the measurement of the charge released by dark pulses, a Hamamatsu Si $p-i-n$ diode S1223 was used for normalisation purposes, readout by a current amplifier Ortec VT 120. The pulses were acquired and stored by means of a dedicated LabVIEW DAQ software by a Tektronix TDS 7254B digital Phosphor oscilloscope, with a sampling rate of 20 GS/s and 2.5 GHz bandwidth. An Ortec 710 quad 1-kV bias supply was used to bias the $p-i-n$ diode and the MPPCs respectively.

The equivalent circuit of a generic SiPM has been developed recently by Corsi [3]. Fig. 1 shows this circuit along with the bias filter, the load resistor R_L and the coupling capacitor. In this figure the dashed rectangle represents a single-photon event: the current due to the avalanche is reproduced by a current pulse with a maximum value of 20 μA and arbitrary short duration of few ps.

For the calculation of the charge developed by a single avalanche event, the pulse generated by the interaction of an α-particle from the decay of ^{241}Am in the Si bulk of a $p-i-n$ diode was used for normalisation purposes. Considering a distance between the α-particle and the entrance window of the diode of about 3 mm, and the attenuation factor of α-particles in air equal to 8.59×10^{-2} MeV/mm [7], an uncertainty of 0.1 MeV was attributed to the energy of the source, $E_\alpha = 5.3 \pm 0.1$ MeV. Taking into account the energy needed to create an electron-hole pair in Si, $\epsilon_i = 3.62$ eV, the contribution of e-h pairs to the total charge is $Q_{pin} = 240 \pm 30$ fC. The charge released by a dark pulse was then obtained from the relation $Q_{SiPM} = Q_{pin} \cdot x_c^{SiPM}/x_c^{pin}$, where x_c^{pin} and x_c^{SiPM} represent the centroid of the distribution of the integral over the same number of pulses for the $p-i-n$ diode and the SiPM respectively. The slope of the curve of single-photon charge versus the bias voltage gives the value of the pixel capacitance C_{pixel} (see Table 1). From the calculation of the total admittance of the circuit, and using the values of the capacitance C_{meas} and conductance G_{meas} measured with the LCR meter, the values of the diode, quenching and parasitic capacitance of the circuit in Fig. 1 are found solving the system [8]

$$C_d = \sqrt{G_{meas} \cdot \frac{1+\omega^2 R_q^2 C_{pixel}^2}{N_{pixel}\omega^2 R_q^2}}, \quad (1)$$

$$C_q = C_{pixel} - C_d, \quad (2)$$

$$C_g = C_{meas} - N_{pixel} C_d + \frac{\omega^2 N_{pixel} R_q^2 C_d^2 C_{pixel}}{1+\omega^2 R_q^2 C_{pixel}^2}. \quad (3)$$

For the study of the effects of different readout electronics on the pulse shape, the MPPCs were illuminated by a Ti:Sapphire Coherent™ ultra fast laser system giving an output of about 100 fs pulses centred at 800 nm with a repetition rate of 250 kHz.

Table 1
Table of the measured Hamamatsu MPPC parameters.

Parameters	11-25C	33-25C	11-50C	33-50C
Total area (mm^2)	1×1	3×3	1×1	3×3
Pixel size (μm)	25	25	50	50
N_{pixel}	1600	14 400	400	3600
V_{br} (V)	68.31 ± 0.06	69.25 ± 0.08	68.138 ± 0.006	69.567 ± 0.004
R_q (kΩ)	218.0 ± 0.5	358.1 ± 0.7	131 ± 4	163.1 ± 0.4
G_{meas} (μS)	3.064 ± 0.008	46.84 ± 0.08	10.40 ± 0.08	139.9 ± 0.4
C_{meas} (pF)	32.82 ± 0.04	272.0 ± 0.3	36.72 ± 0.06	304.1 ± 0.6
C_q (fF)	2.9 ± 0.9	2.5 ± 0.6	7 ± 6	7 ± 8
C_d (fF)	14.92 ± 0.02	15.20 ± 0.02	71 ± 1	78.0 ± 0.2
C_g (pF)	8.97 ± 0.06	53.4 ± 0.4	8 ± 2	25.3 ± 0.9
C_{pixel} (fF)	17.8 ± 0.9	16.7 ± 0.6	78 ± 6	85 ± 8

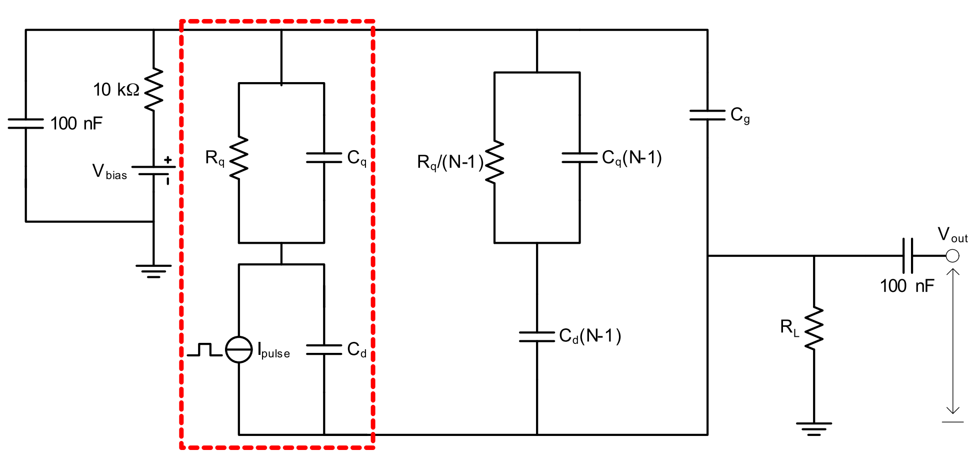

Fig. 1. SiPM equivalent circuit with bias circuit suggested by Hamamatsu [6]. The portion in the red dashed square indicates one pixel firing. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)