A study of timing properties of Silicon Photomultipliers

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Abstract

Silicon Photomultipliers (SiPM) 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.

Keywords: ToF-PET, SiPM, MPPC, pulse shape, SiPM parameters

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 in output 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. the 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 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 μ m, characterised by a current of the order of μ A [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 1x1 mm² and 3x3 mm² and pixel size of 25 μ m and 50 μ m (cfr. Tab.1).

The IV forward and reverse characteristics were measured using a Keithley 487 picoammeter interfaced with a computer

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Figure 1: SiPM equivalent circuit with bias circuit suggested by Hamamatsu [6]. The portion in the red dashed square indicates one pixel firing.

through a dedicated LabVIEW DAQ software. The capacitance, and conductance of the sensors were instead measured using an Agilent 4284A LCR meter at 1V AC voltage and at a frequency of 1MHz as in [3][4][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 summarized in Tab.1.

For the measurement of the charge released by dark pulses, an 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 $20 \mu A$ 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 normalization 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 $8.59 \times 10^{-2} \text{ MeV/mm}$ [7], an uncertainty of 0.1 MeV was attributed to the energy of the source, $E_\alpha = 5.3 \pm 0.1 \text{ MeV}$. Taking into account the energy needed to create an electron-hole pair in Si, $\epsilon_i = 3.62 \text{ eV}$, the contribution of e-h pairs to the total charge is $Q_{pin} = 240 \pm 30 \text{ fC}$. 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 Tab.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^{TM} ultra fast laser system giving in output about 100 fs pulses centered at 800 nm with a repetition rate of 250 kHz. The experimental setup is shown in Fig.2. A mirror chain was used to direct the light beam on the sensor and a beam splitter was used to further reduce the intensity of the light. Thorlabs reflective neutral density filters with various optical densities were used to modulate the light intensity. An aperture was used to reduce the number of photons hitting the devices and the detector was housed in an Al box with a collimator entrance window to further reduce background light contamination. The multiple-photon signal (typically containing less than 50 photons) was readout by three commercial current preamplifiers, Ortec VT 120, GSI DBA IV/R and Mini-Circuits ZFL-1000 LN, with same 50Ω input impedance, but different bandwidth, gain and noise performances (cfr. Tab.2).

3. Results and Discussion

3.1. The MPPC characterisation

The method described in Section 2 allows the calculation of the values of the electric parameters of the device, namely

Figure 2: Setup for the test of the readout electronics.

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	14400	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

Table 1: Table of the measured Hamamatsu MPPC parameters.

Preamplifier	Bandwidth (MHz)	Gain (dB)	Rise time MPPC 11-25C (ns)	Rise time MPPC 33-25C (ns)
Ortec VT 120	10 - 350	46	1.714 ± 0.001	3.513 ± 0.001
Mini-Circuits ZFL	0.1 - 1000	20	1.916 ± 0.002	3.732 ± 0.001
GSI DBA IV/R	0.003 - 2000	23 - 45	1.988 ± 0.001	3.399 ± 0.002
No preamp	-	-	2.223 ± 0.002	4.148 ± 0.004

Table 2: Table of the used current amplifiers and the measured rise times.

C_{pixel} , C_d and C_q . These values are summarized in Tab.1. It is found that for devices with the same pixel size, the values of C_d are of the same order of magnitude, consistent with the values reported in [4] and [5]. However, the small discrepancy found for devices with same pixel size, but different total area, can be explained by a strong dependency of the gain and R_q , primarily, on the temperature. Small variations in room temperature are not included in the quoted uncertainties in Tab.1. In the case of C_q , the values are consistent for devices with the same pixel size. Finally, it results that for devices with same total area, the value of C_g is smaller in the case of the MPPCs with a bigger pixel size. In fact, the parasitic capacitance is associated to the grid that connects the pixels in parallel, and this grid is more dense in the case of 25 μm pixel MPPCs. The results obtained are in agreement with this.

3.2. The effects of the readout electronics

The knowledge of the sensor parameters allows a SPICE (Simulation Program with Integrated Circuit Emphasis) simulation of the device. Fig.3 shows the voltage pulses obtained from the simulation of the MPPC under study, taking into account only R_L and the coupling capacitance and ignoring any additional external amplification circuit. The 10% to 90% total amplitude rise times are below 30 ps for all the devices. However, the simulated results for the MPPCs 3325C and 3350C give an overall slower signal. This is due to a combined effect of C_q , C_g and R_L on the rise time and C_d and R_q on the decay time [3]. These results are far from the rise time values obtained with three different current preamplifiers measured using the setup in Fig.2. Fig.4 shows the histogram of the rise time for the MPPC 11-25C. This discrepancy between the simulated and the measured rise time could well be due to the fact that in the simulated case a single photon pulse, while in the experimental

Figure 3: SiPM pulses from a SPICE simulation using the parameters calculated in Tab.1.

results multiple-photon pulses were considered. The results are summarised in Tab.2 for both 25 μm sensors.

The rise time, signal to noise ratio (SNR) and time jitter of multiple-photon pulses were studied using the femto-laser setup. Fig.5 shows that the rise time deteriorates when the bias voltage is increased in the case of the 11-25C MPPC.

This trend corresponds to an increase of dark noise, i.e. to an increase in the number of afterpulses and hot carriers with bias voltage, over the signal level. Fig.5 shows that the time jitter, defined as $\sigma_j = t_r / SNR$, where $SNR = V_{pulse}^{rms} / \sigma_{noise}^{rms}$, improves with overvoltage. In fact, the increase in the bias voltage improves the SNR of the sensor at fixed light intensity. The high frequency noise that affects the signal and is significant at lower bias voltage, becomes less significant due to the higher influ-

Figure 4: Histogram of the rise time obtained using the Hamamatsu MPPC 11-25C and the femto-laser.

Figure 5: Measured rise time and time jitter for the Hamamatsu MPPC 11-25C at fixed light intensity and readout without any preamplifier.

design of a custom-made bias circuit. From the measurement of the rise time it is also found that the time jitter improves with increasing bias voltage due to the corresponding increase in the SiPM gain and a resulting improvement of the SNR. Then these devices do not need to be readout with very fast amplifiers. However, current amplifiers with good noise performances are required to achieve good performances in timing applications. Then, with the knowledge of the terminal capacitance of these devices it is possible to construct custom made preamplifiers with the right value of matching impedance and a good compromise between amplification and SNR.

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ence of the pulse amplitude on the SNR and subsequently on the time jitter.

4. Conclusions

In this paper the parameters of different MPPCs were calculated. A good agreement with the results obtained in previous characterisation [4][5] was obtained. A SPICE simulation of the equivalent circuit showed a very fast pulse, meaning that the effective rise time of the output signal of these sensors is deteriorated mainly by the readout electronics. For this reason, measurements of the rise time using several commercial current preamplifiers with different bandwidth, gain and noise figure were performed. It resulted that the use of a poor quality circuitry (i.e. coaxial components and standard plain PCB) deteriorates the rise time. This is due to parasitic inductances and impedances mismatch. Future developments will be the upgrade of the circuitry to high quality components as well as the