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Time and amplitude characterization of STMicroelectronics Silicon Photomultipliers for Time-of-Flight PET scanners

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A study of time and energy resolution of recent Silicon Photomultipliers (SiPMs) by STMicroelectronics was carried out for possible applications in PET tomography. The devices have 60x60 microcells with an active area of 3.5x3.5 mm^2 and were coupled to 3x3x15 mm^3 LYSO crystals to measure the linearity response with different gamma sources. The time resolution was investigated with the two 511 keV photons from a ^{22}Na positron source by means of a digital oscilloscope.

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1. Introduction

LYSO scintillation crystals are usually employed in Positron Emission Tomography (PET) scanners, because of their light yield and efficiency, which result in good energy and time resolution. Time-Of-Flight (TOF) PET, which makes use of the time information to improve the spatial resolution and the signal-to-noise ratio in the localization of the emitting source, requires an optimal time resolution. Due to their small size, insensitivity to magnetic field, high gain and fast response, Silicon Photomultipliers (SiPMs) could be a promising choice as photosensors in PET scanners. Large efforts are being carried out worldwide to improve the design of the devices, the associated electronics and the treatment of the signal, by appropriate hardware and software tools[1], in order to reach a resolution comparable to those of standard photomultipliers which equip most of the existing PET systems, while maintaining the intrinsic advantages of SiPMs. In this contribution we report a preliminary study concerning the study of time and energy resolution properties of recent devices developed by STMicroelectronics, in view of their possible use for PET applications.

2. Experimental setup and working conditions

The experimental setup includes a dark box with a mechanical structure (Fig.1) to handle a radioactive source, and two 3x3x15 mm^3 LYSO crystals each optically coupled to a SiPM mounted on a miniboard. The two LYSO crystals, SiPMs and source centre are all aligned, with mechanical tolerances of the order of 100 μm.

To measure event-by-event the amplitudes of the two signals and their time difference, data acquisition was carried out by a Tektronix DPO7254 digital oscilloscope (2.5GHz, 20 Gs/s, 8 bits ADC) with 50 ps time sampling time, to allow for a digital processing of the individual signals. Measurements were done at several bias voltages at constant room temperature (about 20°). A few thousands events were collected below the photoelectric peak for each run. Fig.2 shows a typical signal from one of these devices.

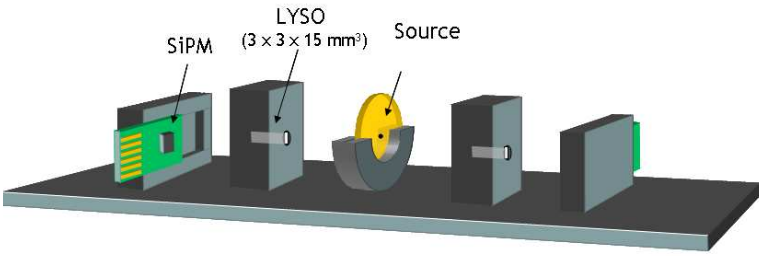

Figure 1: Layout of the experimental set-up.

3. Experimental results

3.1 Device under test

STMicroelectronics is developing four different fabrication processes to improve the Photon

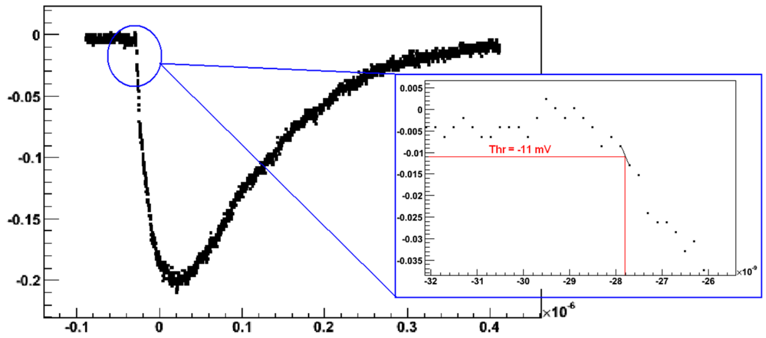

Figure 2: A typical signal from one of the devices under test. The insert shows the beginning of the signal, which is critical for the time resolution.

Parameter	Unit	Value
Package dimensions	mm^2	5.5 x 5.0
Active area	mm^2	3.5 x 3.5
Number of cells		3600
Cell fill factor	%	45
Typical breakdown voltage	V	28
Cell PDE @ 420 nm (0V = 4.5 V)	%	22
Total PDE @ 420 nm (0V = 4.5 V)	%	10
SiPM quenching resistance	Ω	75
SiPM capacitance (C_d) @ 0V = 4.5 V	pF	570
Gain@ 0V = 4.5 V	x 10^6	5.1
Typical pixel dark current @ 0V = 4.5 V	μA	10

Table I: Main parameters of the SiPM device under test

Detection Efficiency (PDE), which is a critical factor affecting the time resolution. Fig.3 shows a comparison between the different devices, where the accuracy was estimated to be around 10%.

The SiPM structure investigated in this work (Mod.SPM35CN) is fabricated on silicon epitaxial p-type wafers and made by planar n+/p microcells. The quenching resistor, made of low-doped polysilicon, is integrated inside the cell. Thin optical trenches filled with oxide and metal surround the microcell active area in order to reduce electro-optical coupling effects (crosstalk) between adjacent pixels. A suitable double-layer antireflective coating is deposited on the surface of the device to enhance its spectral response in the blue and near ultraviolet wavelength ranges. The main parameters of the devices under test (Mod. SPM35CN) are reported in Table I. Further details about the manufacturing method of STMicroelectronics SiPM technology are reported in[2]. Previous electrical measurements of these devices have been already reported[3].

3.2 Energy resolution and non linearity effects

A study of non linearity effects was carried out by different gamma sources (^{54}Mn, ^{137}Cs,

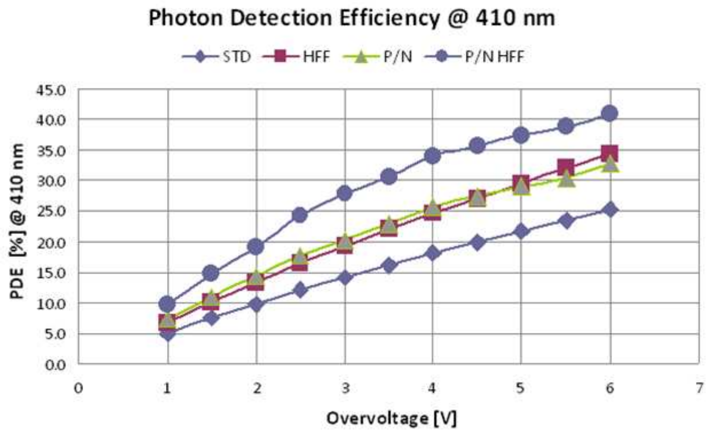

Figure 3: Comparative measurements of Photon Detection Efficiency for different STMicroelectronics devices. STD= Standard Process, HFF=High Fill factor process, P/N= "p on n" Process, P/N HFF="p on n" High-Fill Process, suitable for TOF PET. Accuracy for such measurements is around 10%.

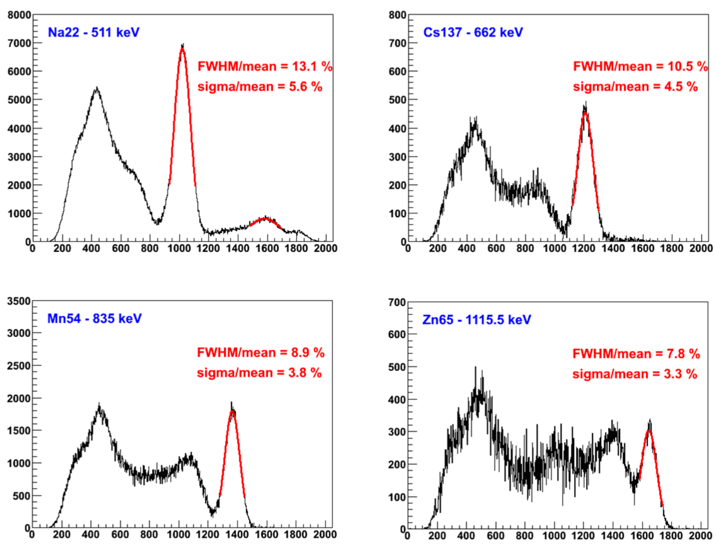

Figure 4: Amplitude spectra of different γ sources from (LYSO+SiPM), measured at an overvoltage of 5.4 V.

^{22}Na, ^{65}Zn), spanning the energy range from 511 keV to 1275 keV. Fig.4 shows typical amplitude spectra for such sources. The photoelectric peak is well separated from the background due to Compton shoulder and LYSO radioactivity. A Gaussian fit of the photoelectric peaks was done to evaluate the mean value and the standard deviation, to study non-linearity effects and the energy resolution of the SiPMs. Fig.5 shows the photopeak positions (top) and the resolution (bottom) as a function of the energy.

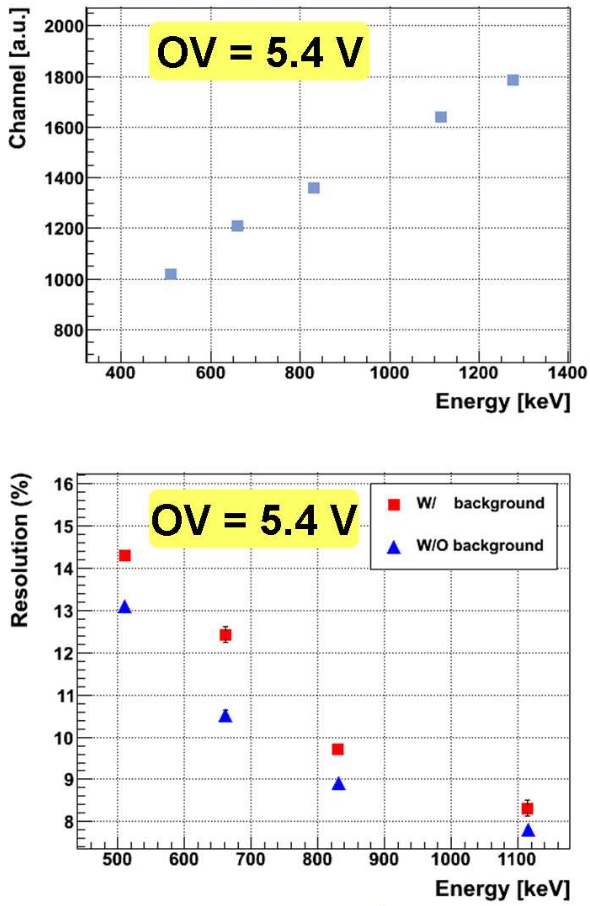

Figure 5: Photopeak positions (top) and resolution - with and without the background - for the various gamma energies, at an overvoltage of 5.4 V

3.3 Unfolded time resolution

To evaluate the time resolution, the two 511 KeV photons emitted by the ^{22}Na source are detected simultaneously in the two crystals and the time difference of the two signals is measured to extract the intrinsic time resolution of the devices, after selection of the photoelectric peak in the two amplitude spectra.

Several algorithms are being tested for the analysis of the digital signals. The results shown in Fig.6 were obtained implementing a leading-edge software procedure with interpolation between successive time steps, after event-by-event subtraction of the baseline.

The dependence of the time resolution (CRT) on the bias voltage was also studied and the results are shown in Fig.6: the CRT decreases with bias voltage and for the device under test reaches its minimum around an overvoltage of 5.4 V. The obtained value of the optimal resolution (unfolded) was about $\sigma/\sqrt{2}$=150 ps.

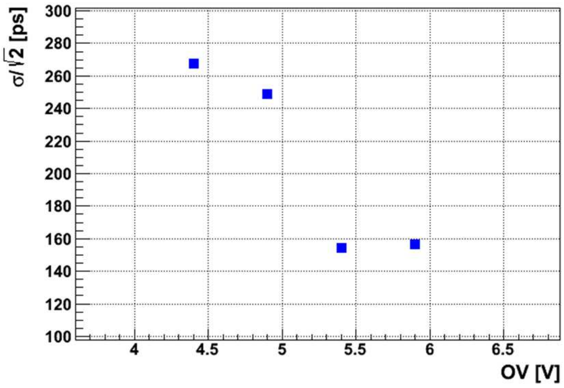

Figure 6: CRT resolution as a function of the overvoltage.

4. Discussion and outlook

The start-up phase of this activity has demonstrated the feasibility of the planned characterization measurements in our lab. A dedicated setup has been successfully installed and tested. A first set of measurements has been undertaken in order to measure gamma spectra with different radioactive sources, investigate non-linearity effects and calibrate the system. Finally, a coincident detection of the two photons originating from a ^{22}Na source has been used to measure the unfolded time resolution of the devices, which turned out to be 150 ps (sigma), for the type-C device, as expected.

The various factors contributing to the ultimate timing resolution in SiPM-based PET systems have been discussed in a recent paper[1] and include the photoelectron statistics, the scintillation photon transit time, the location of the gamma conversion process inside the crystal, the time jitter of the SiPM and the resolution of the electronic chain and data processing. It is seen that the first two are the main factors contributing to the overall time resolution. The near future activity will be concentrated along different directions. Small improvements in the existing setup and data analysis procedures will be explored. The attention will be concentrated also to testing new devices, whose development is in progress, employing basically the same procedure tested so far.

References

[1] F. Powolny, *IEEE Trans. on Nucl.Sci* **58** (2011) 597.

[2] M. Mazzillo et al., *IEEE Trans. on Nucl.Sci* **56**(2009) 243.

[3] M. Mazzillo et al., *IEEE Trans. on Nucl.Sci* **57**(2009) 227.