Performance Study of Silicon Photomultipliers as Photon Detectors for PET

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Abstract

The use of Silicon Photomultipliers (SiPMs) as photon detectors in Positron Emission Tomography (PET) modules offers significant advantages over conventional light sensors, including application in a magnetic field, better resolution and easier operation. Different types of SiPMs have been tested: Photonique, $2.1 \times 2.1 mm^2$, Hamamatsu $3 \times 3 mm^2$ and STMicroelectronics $3.5 \times 3.5 mm^2$. Dark noise, surface sensitivity, photon detection efficiency and linearity at low light intensities have been measured. A LYSO crystal was coupled to a SiPM to test the performance as a photon detector for PET. We will present the results of the measurements for different samples and types.

Key words: Positron emission tomography, Geiger mode APD, Silicon Photo-multiplier, LYSO scintillator

1. Introduction

Positron Emission Tomography (PET) is a non-invasive method for in-depth and in-vivo imaging of tissue. The positron emitted in a β^+-decay of the nucleus slows down in the tissue and subsequently annihilates with a nearby electron. The annihilation gamma-rays of 511 keV are usually detected indirectly, through scintillation in inorganic crystals. Photon detectors, like Photomultiplier Tubes (PMTs), detect the scintillation light. The majority of PET devices use PMTs, but due to their size, relatively poor ratio of active to total surface and high price, which is a significant fraction of the total cost of the device, it is worthwhile to search for alternate detectors of visible and infrared photons. The sensitivity of PMTs to magnetic fields and the increasing requirement to unify different image modalities in one measurement, provides an additional reason to search for new detectors. One would like to incorporate a PET apparatus inside a MRI magnet for simultaneous imaging of tissue function and density. A new type of semiconductor detector, the Silicon Photomultiplier (SiPM) looks very promising [1, 2, 3, 4]. Results for the surface sensitivity, energy resolution and linearity, as well as timing resolution for several SiPM samples are presented.

2. Surface Sensitivity

Surface sensitivity is assessed by exposing each SiPM to a pulsed $\sim 5\ \mu m$ wide laser beam. The SiPM is moved relative to the light source to produce two-dimensional scans (Figure 1) of the count rate over the surface of the silicon photomultiplier. Only SiPM pulses corresponding to the single photon pulse height and coincident with the laser pulse within a $\sim 10\ ns$ time window are selected. Surface sensitivity for different SiPMs (Hamamatsu H100C, CPTA/Photonique S137 and STMicroelectronics) were measured and found that they are fairly uniform accross their surfaces. More detailed surface scans of the SiPMs, Figure 1, reveal the pixelated structure of the SiPMs and reflect the internal structure of quenching resistors and diode cells for every SiPM.

The Hamamatsu H100C and CPTA/Photonique S137 SiPM used for the surface scans were $1 mm \times 1 mm$ sized samples. However, larger sized samples of these companies use the same technology as the small ones so the results should be similar. Also it is important to note that the SiPMs from STMicroelectronics have additional thin trenches filled with oxide and metal surrounding the individual cells. Such a trench serves to reduce the electro-optical coupling between individual microcells. One disadvantage of this trench is the reduction of the fill factor ($\sim$36%) of this SiPM compared to SiPMs from other manufacturers (H100C$\sim$ 75% and S137$\sim$ 60%).

3. Energy Resolution

The energy resolution of the SiPMs has been measured by coupling a LYSO crystal from Sinocera [5] (Figure 2) to the SiPMs and measuring the coincidence annihilation γ's from a ^{22}Na source. The LYSO crystal has a fast decay time (40-44 ns) and a high light yield (75%), an intrinsic energy resolution of 20% and a peak emission wavelength at 428 nm. The crystal was wrapped with teflon and attached to the SiPM using optical grease to ensure a good optical coupling between the crys-

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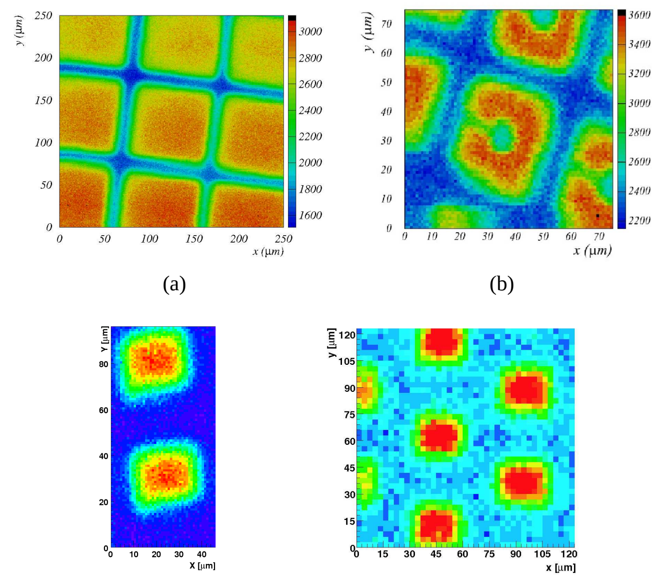

Figure 1: Two-dimensional scans for (a) Hamamatsu H100C, (b) CPTA/Photonique and (c) & (d) STMicroelectronics. Surface scans are valuable to asses the surface sensitivity of SiPM, (a),(b) & (c) were performed with a step size of 1 μm and clearly shows the structure of individual SiPM cells. (d) shows part of a larger surface scan (STMicroelectronics with a step size of 3 μm) to asses to overall uniformity of the SiPM.

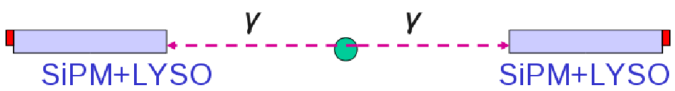

Figure 2: Schematic of the setup used to measure the energy resolution of single SiPMs. A LYSO crystal coupled to a SiPM was used as triggering detector for the coincidence measurement.

tal and the SiPM. Figure 3 shows the results for the 3 SiPMs, showing a ~19% FWHM for CPTA/Photonique and STMicroelectronics and 10% FWHM for Hamamatsu H100C. The energy resolution measurements are limited due to the intrinsic energy resolution of the crystal. Note that the energy resolution for the Hamamatsu H100C was not corrected for the non-linear behaviour due to the finite number of cells.

Photonique and STM offer smaller pitch (~50×50 μm^2) compared to the used Hamamatsu H100C SiPM which has a larger cell size (100×100 μm^2). Hamamatsu also offers SiPMs with a smaller cell size, however a larger cell size, using the same technology, results in a higher geometrical efficiency (higher PDE) and higher gain (better timing). On the other hand it also reduces the number of cells per mm^2 effectively reducing the dynamic range. This also reflects in the non-linear response of the Hamamatsu SiPM due to the total number of scintillation photons from the LYSO crystal exceeding the number of cells as shown in Figure 4a. Energy linearity, Figure 4a, was evaluated for the Hamamatsu H100C (900 cells/3×3 mm^2) by measuring the energy spectrum for 3 different radioactive sources (^{22}Na, ^{137}Cs and the ^{176}Lu background of the LYSO crystal).

For the STMicroelectronics (4900 cells/3.5×3.5 mm^2) a uniform illumination from a laser was used to study the linearity. The laser light intensity was controlled by using neutral density filters.

The comparison of the results for linearity of the Hamamatsu and STMicroelectronics samples (Figures 4a & 4b) clearly shows a better linear response for the STMicroelectronics sample over a wider dynamic range than the Hamamatsu one.

4. Timing Resolution

In PET scanners, the time difference between two back-to-back photons yields information about the position of positron-electron annihilation in the patient's tissue. This information can be used to improve the imaging resolution due to much higher background rejection. Therefore, the accurate determination of the position of an event is dependent on the time resolution.

One of the issues is whether the intrinsic timing resolution of SiPMs limits the coincidence timing. Therefore the intrinsic timing resolution of two Silicon photomultipliers from different producers was measured by exposing the samples to very low light pulses (~10 ps width) from a PILAS [6] laser. The laser light intensity was controlled with neutral density filters and was set to the single photon level.

Although not that fast as for example a micro channel plate PMT, the time resolution of the measured samples amounts to 100-200 ps (Table 1). The measurements of the time resolution at different wavelengths (blue 405 nm and red 635 nm) show that the measured samples give a better time resolution in the blue light region. This makes them good candidates to be used together with the LYSO crystal (peak emission at 428 nm).

First measurements with Hamamatsu 3×3 mm^2 SiPMs of back-to-back γ's resulted in a timing resolution of ~442 ps (Figure 5). This is worse than the expected $\sqrt{2}\times200$ ps obtained from the laser measurements. It can be attributed to the expected slower behaviour of the used larger sample size due to its higher capacitance. This larger capacitance results in longer signals which in turn worsen the timing resolution of the SiPM. The other limiting factor is a relatively high discrimination level at about 10 photo-electrons. Using fast pre-amplifiers with a wide dynamic range would enable the single photo-electron timing discrimination and improve the timing resolution.

1mm^2 SiPM	S137	H100C
σ_{red}(ps)	182	145
σ_{blue}(ps)	151	136

Table 1: The time resolution after time-walk correction for different SiPMs.

5. Conclusions

Silicon photomultipliers seem to be a very promising detector for PET. The main advantages are their insensitivity for magnetic fields and their compactness. Surface sensitivity, energy resolution and timing resolution of several SiPMs have been evaluated. The relatively good energy resolution and fast response might enable to reduce the background in PET imaging and thus improve the resolution. Further studies will be perfomed using SiPMs in a PET module to assess the possibility to use SiPMs as photon detectors in a NMR-PET combination. All three measured SiPM samples show a reasonable performance to be used for PET.

References

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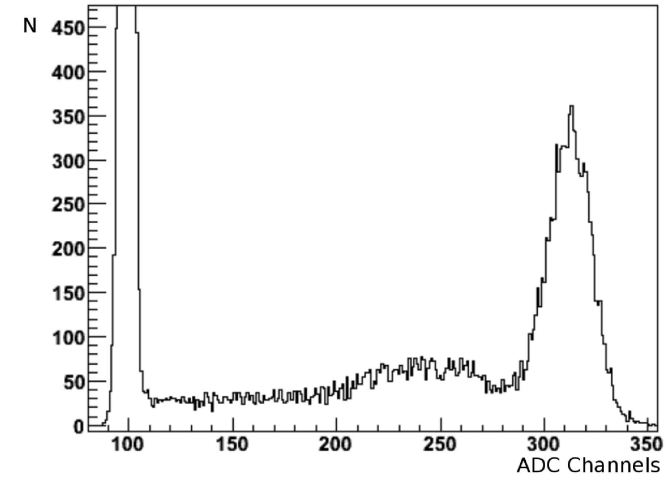
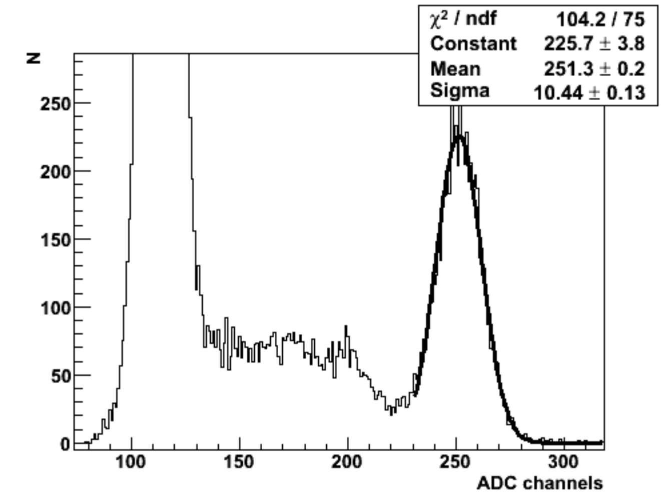
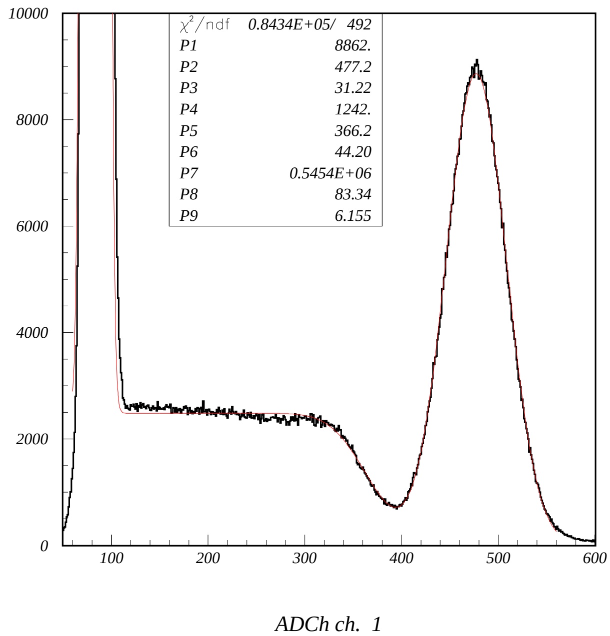


(a)

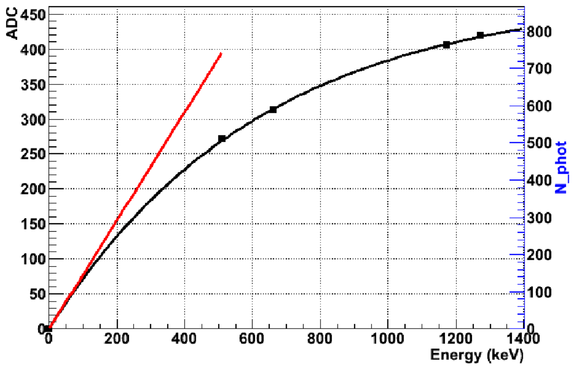


(b)

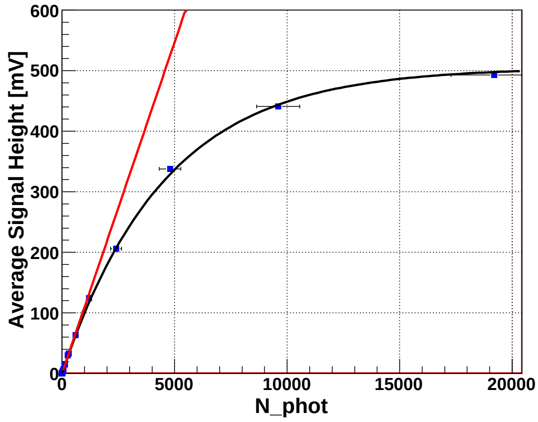


(c)

Figure 3: Energy spectra for 3 different SiPMs: (a) Hamamatsu H100C. (b) CPTA/Photonique S137 and (c) STMicroelectronics.



(a)



(b)

Figure 4: Energy linearity for 2 different SiPMs: (a) Hamamatsu H100C clearly shows a non-linear behaviour. (b) the STMicroelectronics SiPM shows a good linearity up to several thousands of photons.

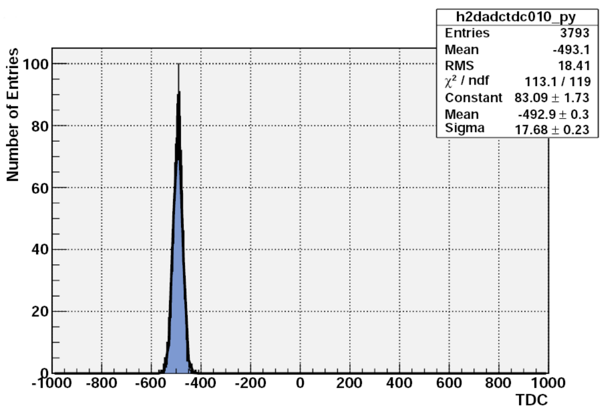


Figure 5: Timing resolution for back-to-back γ's (25 ps/bin $\rightarrow$ $\sigma_t \sim 442$ ps). Hamamatsu 3×3 mm^2 SiPMs were used for this measurement.