PROCEEDINGS OF SCIENCE

Method to improve SSPM Timing Resolution : Pulse Shape

Chang L. Kim[1]
GE Global Research Center
One Research Circle, Niskayuna NY, USA
E-mail: chang.kim@research.ge.com

Pulse shape, dark counts, photon-detection efficiency, cross talks were identified as critical factors affecting timing resolution after an extensive measurement of solid-state photomultipliers (SSPM) for time-of-flight PET. Among those factors, pulse shape has been investigated through a SPICE simulation, and the measurement of single photoelectron and 511keV gamma ray pulses. First, we showed that, due to the long recovery tail in a single photon pulse, the risetime of 511keV gamma ray pulse from LYSO/MPPC is much slower than the one of PMT. Second, we showed that the parasitic quenching capacitance of the quenching resistor could play an important role in supplying a quick charge in the avalanche process and improve the single photon pulse shape. Third, by changing the parasitic quenching capacitance, we showed that it could be used to improve the risetime of 511keV gamma ray pulse that is directly related to the timing performance of SSPM.

International Workshop on New Photon Detectors (PD09)
Shinshu University Matsumoto Japan
24-26 June 20

[1] Speaker

PoS(PD09)010

1.Introduction

The detector development for time-of-flight (TOF) Positron Emission Tomography (PET) has been recently intensified due to new advances on both scintillators and photosensors. Faster or higher light output scintillators provide more photons per unit time in the rising edge of the signal pulse[1]. Also, higher quantum efficiency photosensors produce more photoelectrons from a given number of incident photons[2,3]. The increased number of photoelectrons reduces statistical fluctuation and improve the coincidence timing resolution in a PET detector.

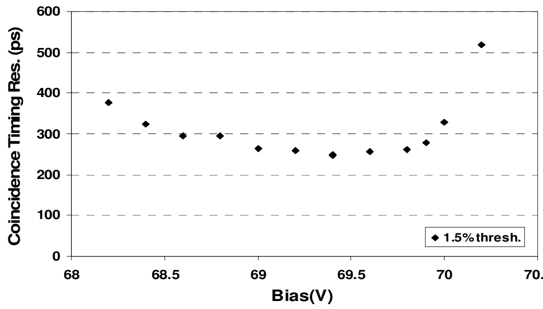


Fig. 1 Coincidence Timing Resolutions of two detectors (each made of a $3x3x10mm^3$ LYSO crystal on a $3x3mm^2$ area, 50micron pitch MPPC) shown as a function of bias voltage. A leading edge discriminator was used for the timing pick-off with the threshold set to 1.5% of 511 keV pulse height.

We have been investigating, as a photosensor for TOF PET, the recently available Geiger-mode multi-pixel avalanche photodiode, also known as Solid State Photomultipliers (SSPM). Their advantages are high gain and high photon detection efficiency (PDE) as well as compactness and magnetic field immunity. While the internal gain is similar to vacuum photomultipliers (PMT), the higher PDE is expected to improve the timing resolution compared to a PMT by a relative factor of

$$\propto \frac{1}{\sqrt{PDE_{SSPM} / PDE_{PMT}}}$$

where PDE_{SSPM} and PDE_{PMT} are the PDE for SSPM and PMT respectively. However, we found that the best coincidence timing resolution of 240ps (FWHM) measured with a $3x3x10mm^3$ LYSO crystal on a Multi-Pixel Photon Counter (MPPC) with an area of $3x3mm^2$ and 50 micron pitch was not better than 220ps (FWHM) timing resolution measured on a fast timing PMT (Hamamatsu H6533) even though PDE_{MPPC} and PDE_{PMT} were 40% and 25% respectively. Fig. 1 shows the measured timing resolution as a function of MPPC bias voltage and more details were reported in reference [4]. Possible factors causing this discrepancy are: a higher rate of dark counts in MPPC, difference in pulse shape between PMT and MPPC, cross-talks among MPPC micro-cells and higher electrical noise from the larger capacitance of the MPPC were identified as the possible causes.

In this paper, we investigate the pulse shape of single photons in MPPC using SPICE models and show its relationship to the rise time of multi-photon signals, especially, 511keV gamma energy deposition in a LYSO scintillation crystal. The timing accuracy ΔT is known to be sensitive to electrical noise by a proportionality factor given by

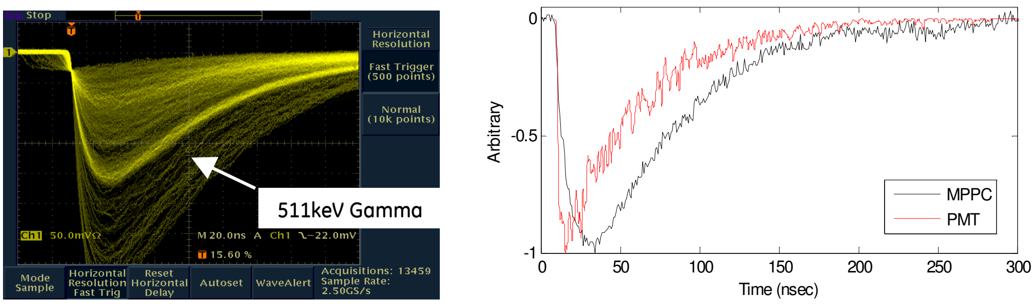
$$\Delta T \propto \frac{\sigma_n}{\left(dV/dt\right)}$$

where dV/dt represents the slope of the rising edge of a pulse and σ_n for electrical noise. Accordingly, faster rise time results in better the timing resolution. So, using the device model, we also investigate the effect of the parasitic quenching capacitance on the shape of a single photon pulse and demonstarate the improvement of the rise time of 511 keV LYSO pulse by adjusting the parasitic quenching capacitance in the device model.

2.Pulse Shape Analysis

2.1Pulse Shape for 511 keV Gamma ray

A single LYSO crystal of 3x3x10mm^3 dimension was wrapped with many layers of Teflon tape except for the bottom surface that was optically coupled to a 3x3mm^2 MPPC having 3600 micro-cells of 50x50µm^2 size. Using a ^{22}Na isotope of 511keV gamma rays, the output pulses were captured on a digital oscilloscope as shown in Fig. 2(a). The intense band in the middle represents signals from full 511keV gamma ray energy deposited in the LYSO crystal. Using the same crystal coupled to a Hamamatsu H6533 PMT, the output signal was also captured and is shown for the comparison in Fig. 2(b) after pulse height normalization. The risetime of MPPC signal is around 10-15ns that is much longer than 5ns for the PMT. This is due to different single photon pulse shapes between MPPC and PMT, as explained below.

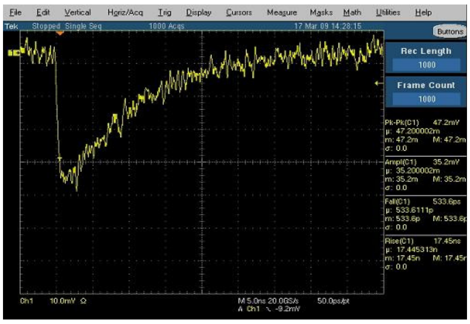


(a) (b)

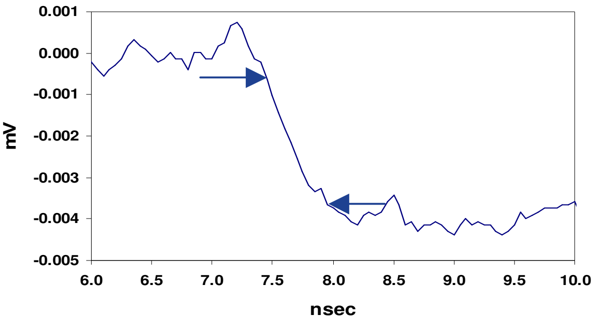
Fig. 2 511keV gamma ray pulses from LYSO/MPPC detector recorded with a digital scope (a) in 20ns time bin and the comparison to a PMT output signal using the same LYSO crystal (b).

2.2Single Photon Pulse Shape

For the study of single photon pulse, the dark count signal from a 3x3mm^2 MPPC device was amplified by various high gain and high bandwidth amplifiers. The output was digitized by Tektronix TDS7404 oscilloscope with 4GHz and 20Giga sample/sec. Fig. 3(a) shows the single photon pulse signal at the output of Hamamatsu C5594 amplifier with 1.5GHz bandwidth and x36 gain. A long tail of about 20ns is very noticeable and is due to the recovery of the avalanched micro-cell. In the case of PMT, the single photon pulse shape is close to a Gaussian with approximately equal rise and fall-times [5]. Opposite to the PMT symmetric response, the MPPC showed a long falltime and a very fast risetime of about 0.5ns. The rising edge of a single photon pulse using Mini-circuit ZX60_4016E amplifier with 4GHz bandwidth and x10 gain is shown in Fig. 3(b). The small risetime is better than that of typical PMT's, which indicates that MPPC can have better timing resolutions than PMTs in case of single photoelectron events. This was expected due to the fast avalanche process in the depletion region. This fast risetime, however, was not transferred to the one of 511keV LYSO pulses as discussed below.



(a)



(b)

Fig. 3 Single photon pulses from 3x3mm^2 MPPC with 50micron micro-cells for C5594 (a) and ZS60_4016E (b) high bandwidth amplifiers. Both amplifiers showed close to 0.5ns risetime.

2.3Simulation of 511keV Pulse Shape

The pulse shape of a multi-photon signal from the full energy deposition of 511 keV gamma ray can be simulated by the convolution of the single photon response pulse and the intrinsic light emission decay curve of the scintillator. The single photon pulses for both PMT and MPPC were generated following using Gaussian and tail pulse shapes, respectively. Fig. 4(a) shows Gaussian pulses for PMT with 0.5, 1, 1.5 and 2.5 ns rise-time. Since the single photon pulses are symmetrical for PMTs, the falltimes are equal the risetimes used. Fig. 4(b) shows the tail pulses for MPPC with the 0.5, 1, 1.5 and 2.5ns risetimes combined with a fixed 20ns falltime. If PMT and SSPM have the same gain, SSPM will have much smaller pulse height since the total area is corresponding to the gain. In other words, the long tail pulse will have much smaller pulse height that can be an important factor for timing. In this simulation, it is not considered and the y-axis is arbitrary. Also, one more set of tail pulses were generated with a fixed 1ns rise-time combined with 10, 15, 20, 25, 30ns falltimes as shown in Fig. 4(c). Multi-photon signals like 511 keV gamma rays were obtained by convolving these single photon pulses with an exponential simulating the intrinsic scintillation decay time of 45ns from LYSO. Fig. 4(d-f) shows the convoluted pulses of Fig. 4(a-c), respectively. For Fig. 4(d), the risetime of all pulses were less than 5ns. The small difference in the risetime was due to the different risetime and falltime in the input Gaussian shapes. Fig. 4(e) shows the simulated pulse shapes for MPPC with single photon pulses from Fig. 4(b). Again, the difference in the risetime of single photon pulses does not make noticeable changes in 511keV pulses since the tail is much longer than the risetime. This indicates that the length of single photon pulse tail is a key factor for the long risetime of 511keV pulse for MPPC and is confirmed in Fig. 4(f). Here, we need to remember that the numbers of photons corresponding to the pulse height of the 511keV signals are very different between PMT and SSPM due to the difference in the tail length. Since a better risetime generally yields a better timing resolution, we could conclude that any method that reduces the duration of the single photon pulse tail would be very helpful to improve timing performance of SSPM.

3.Electrical Model for MPPC

3.1Typical Electrical model

The electrical model of SSPM was well established by S. Cova and F. Corsi et. al. in the reference [6] and [7]. The analytical model has been further expanded and confirmed by measurements on various SSPMs[8-11]. The electrical model suggested and optimized for SSPM consisted of a capacitor representing the cell diode C_d, a quenching resistor R_q, a parasitic quenching capacitance C_q of R_q, and a stray capacitance of all electrical traces C_g. In order to simulate Geiger-mode avalanche, a current source was added for a single cell on the left of the diagram shown in Fig. 5(a). Since an SSPM consists of N micro-cells in parallel, the rest of (N-1) cells are shown in the middle of the diagram with their respective contribution to resistance and capacitance. For completeness, the external load resistance R_s is added to the diagram because it is a significant factor for the overall pulse shape when the total capacitance of the device is large.

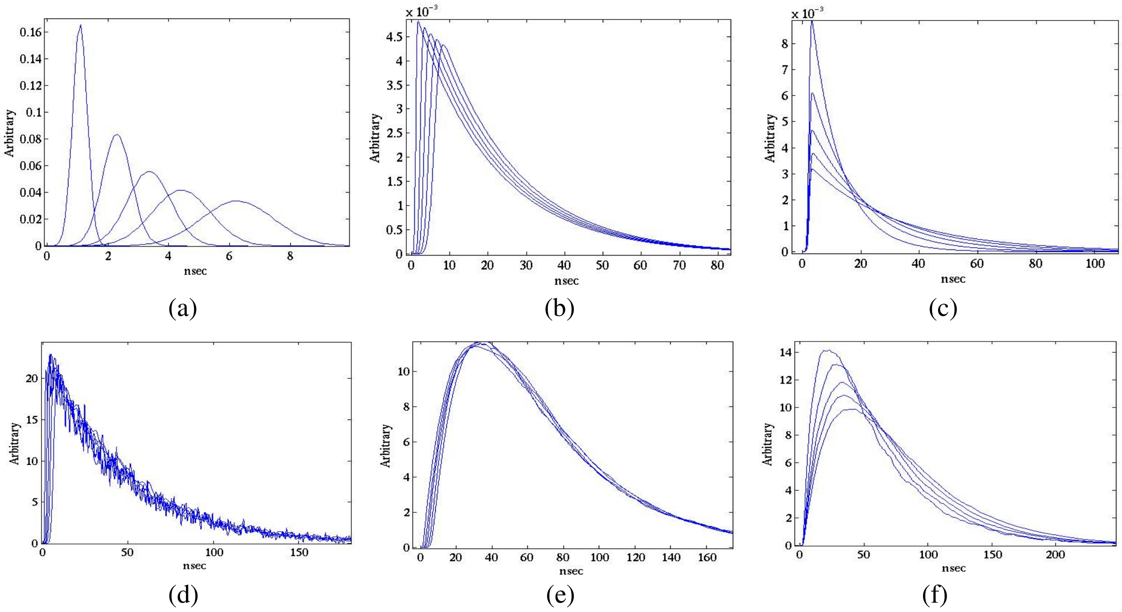


Fig. 4 (a)(b)(c) are for single photon pulse shapes and (d)(e)(f) are for 511keV pulse shapes from the convolution of (a)(b)(c) and LYSO intrinsic decay of 45ns. (a) and (d) represents PMT case and the rest for SSPM.

When an avalanche occurs in a cell, the current start flowing through C_d and R_q. This drops the voltage across the cell diode and increases the voltage across the resistor. When the former drops below the breakdown voltage, the current flow stops and the diode recovers following R_qC_d time constant. R_q can be measured with an I-V curve setup applying the forward bias. C_d can be estimated by measuring gains for single photons with Q_{charge} =Gain*e = $C_d(V_{bias} - V_{breakdown})$. Using these measured parameters, several groups explained their observed pulse shapes [8-11].

3.2Role of Quenching Capacitance

In order to show the role of the quenching capacitance, the single cell models were utilized as shown in Fig. 5(b) and (c) without and with C_q. The SPICE simulation result with R_q=100 kOhm, C_d= 22fF and R_s =10 Ohm is presented in Fig. 6(a). Without C_q, the pulse recovery follows an exponential decay with time constant R_qC_d, as mentioned above, in a single cell model. When C_q was added, a fast component appears in the beginning followed by R_qC_d recovery. This shows that C_q is a fast current supply path in the beginning of avalanche.

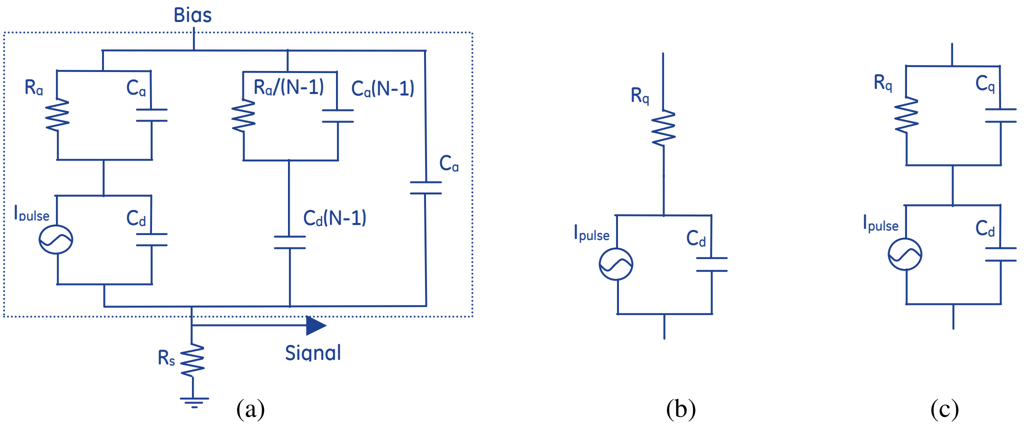


Fig. 5 (a) Electrical model used for SSPM. The dotted line contains only SSPM model and, R_s and bias are external components. (b) and (c) shows a single cell model without and with C_q, respectively.

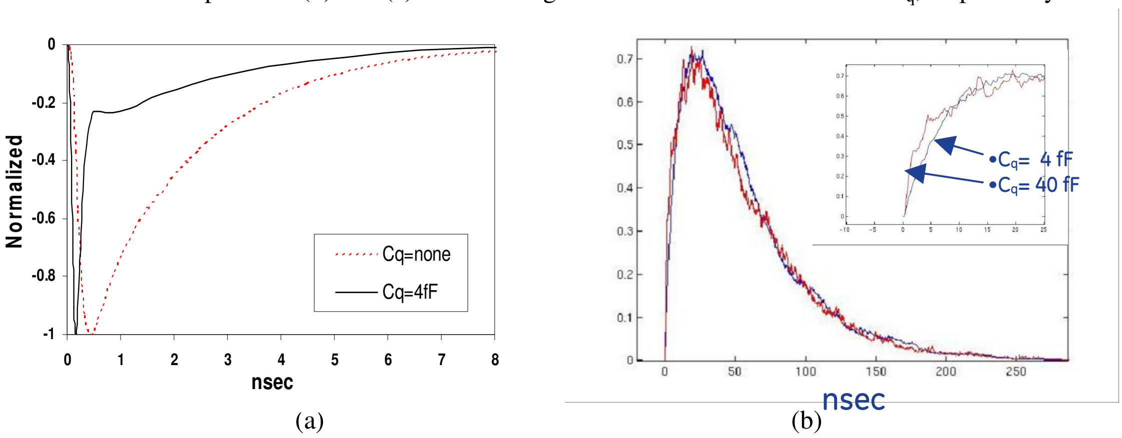


Fig. 6 SPICE simulation of single photon pulse shape with and without C_q included in the model (a). Simulated LYSO pulse shape in case of larger C_q (b). The insert represents the zoom of the rising edge.

C_q can be estimated by fitting the pulse shape using an analytical model or by a calculation based on the size of the resistor and physical layout of the device. Both methods carry large errors. For example, the fitting with a simplified model does not include any other parasitic capacitance or inductance of wire bonding or traces that are not negligible compared to the small C_q and can change the shape of the fast pulse. Also, since the physical layout is not well known due to the proprietary manufacturing process, the later method can lead to large error too. For the demonstration purpose, 4 fF from [12] was used as a baseline.

From the SPICE model, we found that the larger C_q is, the higher the initial peak is. With C_q values of 4 fF and 40 fF, the single cell pulse was generated using Fig. 5(a) model and was convoluted with LYSO intrinsic decay to generated 511keV pulse shape as shown in Fig. 6(b). The risetime with C_q= 40 fF is reduce by half and showed 210ps timing resolution compared to 250ps with C_q= 4 fF in a MATLAB based simulation.

4.Discussions

We have shown that the slow risetime of 511keV gamma ray pulse from LYSO coupled to MPPC is due to the long tail of single photon response pulse shape even though it has a very fast risetime. Based on this observation and using an electrical model for SSPM, we showed that it is possible to improve the risetime of 511keV gamma ray pulse by changing the single photon pulse shape. Especially, the role of the parasitic quenching capacitance was modeled to show that C_q plays a key role to supply the initial fast charge supply. We also demonstrated using the MATLAB simulation that a larger quenching capacitance can be used to speed up the risetime of 511keV pulse and improve the timing performance.

References

[1] A. Iltis, M.R. Mayhugh, P. Menge, C.M. Rozsa, O. Selles, V. Solovyev, "*Lanthanum halide scintillators: Properties and applications*," Nucl. Instrum. Methods Phys. Res. A, vol. 563 pp. 359-363, 2006.

[2] F. Bauer, M. Aykac, M. Loope, C. W. Williams, L. Eriksson, M. Schmand, "*Performance Study of the new Hamamatsu R9779 & Photonis XP20D0 fast 2" Photomultipliers*", IEEE Trans. Nucl. Sci., vol. 54, no. 3, pp. 422-426, Jun. 2007.

[3] S. Gomi, et al., *"Development of Multi-Pixel Photon Counter"*, Nucl. Instrum. Methods Phys. Res. A, vol. 581 pp. 427-432, 2007.

[4] C. Kim, G. Wang, S. Dolinsky, "*Multi-Pixel Photon Counters for TOF PET Detector and its Challenges*", IEEE NSS/MIC Symposium Conference Record, Dresden, Germany 2009.

[5] Photonis reference book, "Photomultiplier tubes: Principles and applications", 2002, Brive, France

[6] S. Cova, et. al., "Avalanche photodiodes and quenching curcuits for single-photon detection", Appl. Opt. V35, No. 12, pp.1956-1976, 1996

[7] F. Corsi, et. al., "Electrical Characterization of Silicon Photo-Multiplier Detectors for Optimal Front-End Design", IEEE NSS/MIC Symposium Conference Record, 2006

[8] F. Corsi, et. al., "Modeling a silicon photomultiplier as a signal source for optimum front-end design", Nucl. Instrum. Methods Phys. Res. A 572 pp. 416-418, 2007

[9] C. Piemonte et. al. "Characterization of the First Prototypes of Silicon Photomuliplier Fabricated at ITC-irst", *IEEE Transaction on Nuclear Science*, Vol.54, No.1:236–244, 2007.

[10] H. Otono et al. "Study of MPPC at liquid nitrogen temperature", *Proceedings of International Workshop on new Photon-Detectors PD07*, PoS(PD07)007.

[11] H. Otono et al., "On the basic mechanism of Pixelized Photon Detectors", New Development in Photodetecction Conference, Aix-les-Bains France, June 2008.

[12] S. Seifert et al., "A High Bandwidth Preamplifiers for SiPM-Based TOF PET Scintillation Detectors", IEEE NSS/MIC Symposium Conference Record, 2008.