Performance of Fast Timing Silicon Photomultipliers for Scintillation Detectors

Jung-Yeol Yeom, Ruud Vinke, Nikolai Pavlov, Stephen Bellis, Kevin O'Neill, Carl Jackson and Craig S. Levin

Abstract— **A new silicon photomultiplier has been fabricated for fast timing applications. This new silicon photomultiplier, called 'fast SPM', is fabricated with a third terminal that has a much lower output capacitance. An N-on-P type ('MicroFM') and a prototype P-on-N type ('B-proto') have been tested for their energy and timing performance. Energy resolutions of the 511 keV full energy peak were 13.7 % and 13.1 % for the MicroFM and B-Proto, respectively, at 4 V overvoltage. The coincidence resolving times (CRTs) for 2 x 2 x 3 mm^3 LSO crystals were 184 ± 5 ps and 157 ± 3 ps for the MicroFM and B-proto, respectively. For longer crystals (3 x 3 x 20 mm^3), more relevant for positron emission tomography (PET) scanners, the CRT was 298 ± 9 ps and 234 ± 6 ps for the two SPM types, respectively. A moderate improvement in timing resolution was observed with bare SPMs (MicroFM), without a hermetic epoxy seal, implying that a non-negligible amount of light is lost for silicon photomultipliers with an epoxy layer.**

Index Terms— **Silicon photomultipliers, timing resolution, scintillators, PET.**

I. INTRODUCTION

Since it was first reported that applying a high electric field across a uniform p-n junction can cause an avalanche multiplication of carriers created by an incoming photon[1], semiconductor photon-counting technologies have developed into the silicon photomultiplier as known today.

The silicon photomultiplier has a fast response time, high gain, high quantum efficiency, single photon detection capability and is an attractive alternative to PMTs for its compact and rugged size, insensitivity to magnetic fields and can potentially be manufactured at low costs [2].

Recently, a novel silicon photomultiplier (fast SPM) architecture with an additional electrode ('Fast terminal') has been developed that has a very fast single photon electron response [2]. The fast terminal is a third electrode in addition to the two electrodes in standard silicon photomultipliers. This capacitively coupled third terminal output, with a capacitance of about one-twentieth of the standard device, is less affected by RC signal shaping compared to the standard device [3] and may thus have a faster signal rise time for improved timing performance without the need for custom designed readout electronics with a low input impedance. In this study, we assessed the timing performance of these new fast SPM devices for Positron Emission Tomography (PET) applications.

II. DETECTOR MODULE AND SETUP

Two types of these new fast SPM were fabricated - an N-on-P device (MicroFM-30035-SMT) with a photon detection efficiency (PDE) at long wavelengths and a prototype P-on-N device (referenced here as B-Proto) with a high PDE at low wavelengths [4]. The specifications and typical performance parameters of the tested devices are summarized in Table 1.

Table 1. Typical parameters of the fast SPM used in this study

Parameters	MicroFM (N-on-p)	B-Proto (P-on-N)
Active area	3 x 3 mm^2	3 x 3 mm^2
Microcell size	35 μm	35 μm
Pixel fill factor	64 %	64 %
Rec. Operating voltage (V_{op})	30 V	27.5 V
Peak wavelength (λ_p)	500 nm	420 nm
PDE at λ_p	20 %	37 %
Standard mode Gain (V_{op}, 20 °C)	2.5x10^6	5.5x10^6
Fast mode Gain (V_{op}, 20 °C)	5.1x10^4	~10^5
Dark count rate (V_{op}, 20°C)	6 MHz	6 MHz
Fast terminal: Signal rise time (10% - 90%)	< 1 ns	< 1 ns

The energy resolution and timing resolution (coincidence resolving time, CRT) of fast scintillators placed head-on has been assessed with the setup shown in Fig. 1. Each SPM was read out with an RF amplifier (Minicircuits RAMP-33LN+) and digitized with a high-speed waveform digitizer (Agilent

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DSO90254A) for offline processing.

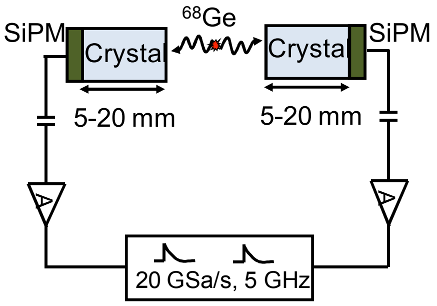

Fig. 1. Setup for the timing measurements.

III. EXPERIMENTAL RESULTS

A. *Energy Resolution*

The energy resolution was calculated by integrating digitized signals of the 3 x 3 x 5 mm^3 LYSO crystals (polished, Teflon reflector) coupled to the fast SPMs and irradiated with a Na-22 source. For this measurement, the background from the Lu-176 radioactivity and from Compton scattered gamma photons was taken into account and subtracted during the Gaussian fit of the 511 keV full energy photopeaks. The uncorrected and corrected (for SiPM saturation) energy resolutions for both types of SPMs are shown in Fig. 2. The saturation correction was performed using Ba-133 (81 keV, 356 keV), Ge-68 (511 keV), and Cs-137 (662 keV) sources at a fixed bias voltage with an exponential function.

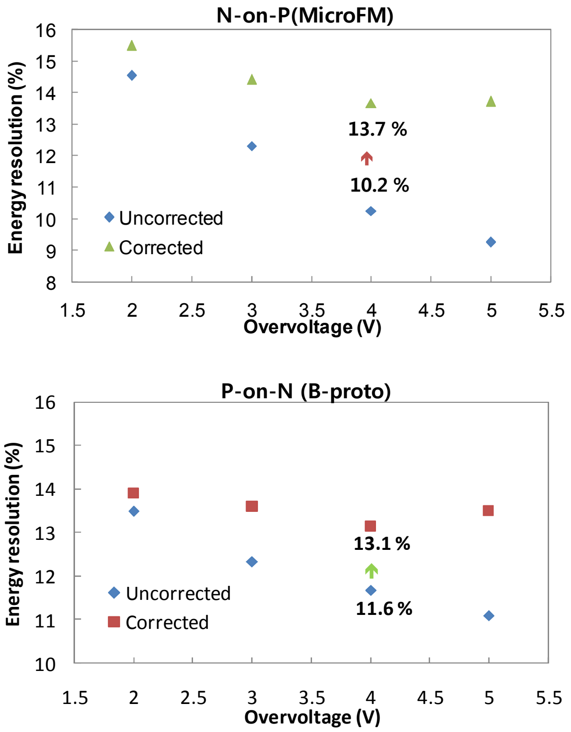

Fig. 2. Energy resolutions (FWHM) of the 511 keV full energy photopeak with N-on-P MicroFM (top) and P-on-N B-Proto (bottom) fast SPMs before and after saturation corrections. The scintillator crystal is a 3 x 3 x 5 mm^3 LYSO.

A. *Timing Resolution*

The timing measurement was performed for coincidence events with energies greater than 450 keV. Leading edge time pickoff was performed on the raw waveforms for the three crystal types (Table 2). The resulting CRT values are summarized in Fig. 3. The CRT obtained with the P-on-N device (B-Proto), which has a good spectral match with the L(Y)SO:Ce scintillator peak emission wavelength, was better than that of the N-on-P device for all measurements.

TABLE 2. Specifications of the scintillation crystals tested.

Crystal	LYSO:Ce	LYSO:Ce	LSO:Ce
Size (mm^3)	3 x 3 x 5	3 x 3 x 20	2 x 2 x 3
Surface treatment	All sides polished	All sides polished	5 sides polished
reflector	Teflon	3M ESR+ Teflon top	Teflon

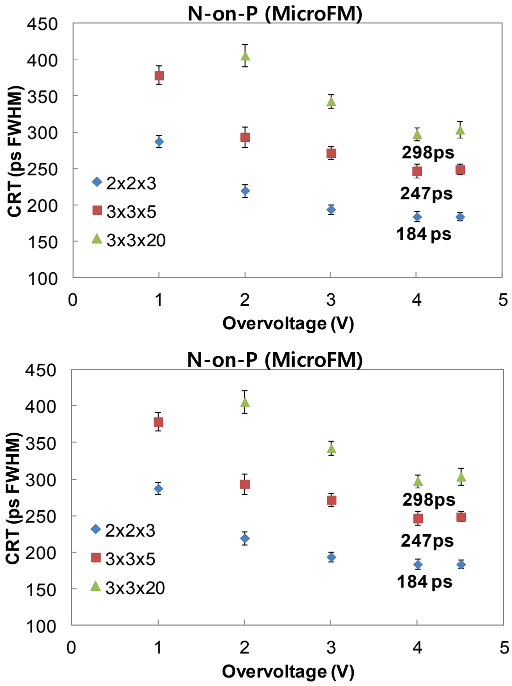

Fig. 3. Timing performance of N-on-P MicroFM fast SPM (top) and P-on-N devices B-Proto (bottom) for different crystal dimensions (in units of mm^3). Error bars indicate the 95% confidence intervals.

Silicon photomultipliers are hermetically sealed with an epoxy to protect the sensor and bond wire connections. The thickness of this layer can range from ~ 200 µm - 400 µm and is not a perfect light transmission medium from the scintillator to the active area of the silicon photomultipliers. To assess the effect of the hermetic seal on the timing resolution, we measured the timing resolution of N-on-P fast SPMs (MicroFM) without the epoxy seal and results are compared with previously obtained values, as shown in Fig. 4. The 2 x 2 x 3 mm^3 crystals have a cross-sectional area smaller than the SPM active area (3 x 3 mm^2), thus leading to a smaller loss of photons through the epoxy. Because of this, a modest improvement in CRT from 184 ± 5 ps to 173 ± 5 ps was observed. A larger improvement in

CRT was observed for the larger 3 x 3 x 5 mm^3 crystals (247 ± 10 ps to 226 ± 4 ps).

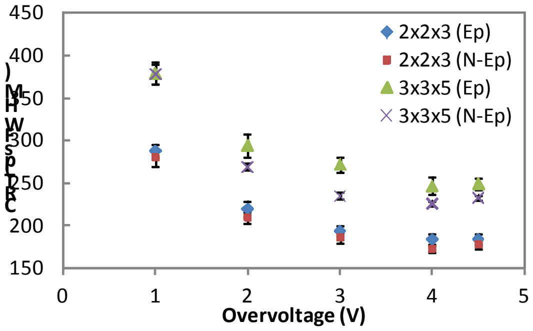

Fig. 4. Timing performance of N-on-P fast SPM with (Ep) and without (N-Ep) epoxy hermetic seal for different crystal dimensions (in units of mm^3). Error bars indicate the 95% confidence intervals.

B. *Summary and Conclusion*

New SiPMs for fast timing applications (fast SPMs) have been fabricated and performance results are summarized in Table 3. These new fast SPMs show significantly improved timing performance over existing standard products [5], making them suitable for use in applications requiring fast timing such as time-of-flight PET.

TABLE 3. Specifications of the scintillation crystals tested.

Crystal size (mm^3)		2 x 2 x 3	3 x 3 x 5	3 x 3 x 20
ER (% FWHM)	N-on-P	-	13.7	-
	P-on-N	-	13.1	-
CRT (ps FWHM)	N-on-P	184 ± 5 [173 ± 5]*	247 ± 10 [226 ± 4]*	298 ± 9
	P-on-N	157 ± 3	183 ± 4	234 ± 6

*N-on-P device without epoxy seal

In addition to the improvement in timing performance, there are several advantages associated with these new fast SPMs: 1) The fast rise/decay times significantly decrease the duration of dark counts, thereby reducing dark count-induced signal pileup, thus improving timing resolution due to the more stable signal background . 2) As the microcell size of the tested devices are 35 µm, they are less susceptible to non-linear behavior due to saturation compared to commonly used silicon photomultipliers with 50 µm microcells. 3) Due to the lower output capacitance (capacitive loading effect), these fast SPMs would be more stable when read out with high-speed electronics. 4) Standard CMOS-compatible manufacturing processes, which avoid proprietary process steps, enable cost-competitive manufacture at standard silicon foundries.

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