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Imaging and Timing Performance of 1cm × 1cm Position-sensitive Solid-state Photomultiplier

P. Dokhale^a, J. Schmall^b, C. Stapels^a, J. Christian^a, S. Cherry^b, M. R. Squillante^a, and K. Shah^a

P. Dokhale: pdokhale@RMDInc.com

^aRadiation Monitoring Devices, Inc. 44 Hunt Street, Watertown, MA 02472, USA

^bDepartment of Biomedical Engineering, University of California-Davis, Davis, CA 95616, USA

Abstract

We have designed and built a large-area 1cm × 1cm position-sensitive solid-state photomultiplier (PS-SSPM) for use in detector design for medical imaging applications. Our new large-area PS-SSPM concept implements resistive network between the micro-pixels, which are photodiodes operated in Geiger mode, called Geiger Photodiodes (GPDs), to provide continuous position sensitivity. Here we present imaging and timing performance of the large-area PS-SSPM for different temperatures and operating biases to find the optimum operating parameters for the device in imaging applications. A detector module was built by coupling a polished 8×8 LYSO array, with 1×1×20 mm³ elements, to a 1×1 cm² PS-SSPM. Flood images recorded at room temperature show good crystal separation as all 64 elements were separated from each other. Cooling the device at 10 °C showed significant improvement. The device optimum bias voltage was ~4.5V over breakdown voltage. The coincidence timing resolution was improved significantly by increasing the operating bias, as well as by lowering the temperature to 0 °C. Results show excellent imaging performance and good timing response with a large-area PS-SSPM device.

Keywords

SSPM; Positron Emission Tomography; position sensitive SSPM

1. Background

A solid-state photomultiplier (SSPM) is an array of avalanche photodiode (APD) elements operated in Geiger mode, *i.e.*, above the reverse-bias avalanche breakdown voltage [1, 2]. Each SSPM element is a Geiger detector for optical photons, and can provide proportional information because the number of photons detected is proportional to the number of triggered GPD elements when the array is uniformly illuminated.

Single GPD elements were introduced by McIntyre [3], and developed by Cova *et al.* [4], Vasile *et al.* introduced arrays of GPDs [5, 6], and Buzhan *et al.* [7], who refers to SSPM as SiPMs, introduced a process where arrays of GPD elements with an integrated quenching

resistor could be fabricated and read out as analog sensors. Jackson *et al.* [8] also developed analogous sensors, which is the foundation for devices manufactured by SensL. Radiation Monitoring Devices, Inc. (RMD) [9] and Rochas *et al.* [10] developed SSPMs using commercial CMOS foundry processes. The devices are called SSPMs to generalize the concept of an array of GPD elements to materials other than silicon. Christian *et al.* [11–15] at Radiation Monitoring Devices, Inc. has designed CMOS SSPM devices that range in size from $1.5\text{ mm} \times 1.5\text{ mm}$ to $1\text{ cm} \times 1\text{ cm}$. Hamamatsu has introduced the multi-pixel photon-counter (MPPC), which is an equivalent device as an SSPM. The following companies offer SSPM, or equivalent, devices: Hamamatsu [Japan], Philips [Netherlands], RMD [Watertown, MA], SensL [Ireland], FBK [Italy], Photonique SA [Switzerland], and Excelitas [New York].

Position sensing is made possible on RMD's large-area $1\text{ cm} \times 1\text{ cm}$ PS-SSPM by implementing a resistive network between the micro-pixels (or GPDs). This provides continuous position sensitivity, as shown in Figure 1 (left) [16]. Comparison of signal collected at each of the four electrodes (A, B, C, & D) provides position information [17], while the sum of all four signals provides energy and timing information.

These devices are being tested for use in high-resolution nuclear medicine imaging. Such system will have many thousands of channels. The use of a position sensitive device permits a substantial reduction in the number of electronic channels without adversely affecting the image resolution.

2. Experimental Results & Discussion

Figure 2 shows a flood histogram recorded at room temperature with a 1-mm polished 8×8 LYSO array coupled to a $10 \times 10\text{ mm}^2$ PS-SSPM for events with $E > 340\text{ keV}$. LYSO is a scintillator used on positron emission tomography (PET). The energy resolution for all crystals in the array ranged from 12% to 16% (FWHM), as seen in the pulse-height distributions shown in Figure 2 (right). Each crystal illuminates an area of approximately 25×25 (625) GPD elements. The position of the event is the centroid associated with this illuminated area, in the absence of noise fluctuations, such as shot noise associated with the distribution of triggered elements and dark noise associated with the fluctuation of signals at the 4 readout contacts due to dark current. At room temperature, thermal excitations trigger approximately 20 GPD elements in a 100 ns integration time at each of the 4 contacts. The typical “pin cushion” effect due to the resistive readout technique is corrected by calibrating the centroids of the flood field spots to the known positions of the physical pixels on the array.

Figure 3 shows the effect of temperature on the position resolution. Flood histograms recorded with a $1 \times 1\text{ cm}^2$ PS-SSPM were obtained at three temperatures with the position resolution optimized at each temperature by adjusting the bias. As can be seen in the figure, spot size sharpens as the position resolution improves. The width of the spot resolution decreases from 0.3 mm to 0.2 mm (FWHM) for the minimally distorted spots in the center, where the pitch of the scintillation element provides the scale for the distance between the spots.

The timing performance of the devices was investigated using a polished LYSO crystal of $2 \times 2 \times 15 \text{ mm}^3$, wrapped with Teflon tape and coupled with optical grease at the center of the $1 \times 1 \text{ cm}^2$ PS-SSPM. Coincidence timing measurements were carried out against another LYSO crystal coupled to a fast PMT. Coincidence timing spectra were optimized and recorded at several different temperatures and at different over bias voltages. Results are shown in Figure 4. Reducing the temperature from 22°C to 0°C improves the timing resolution by about 30% from about 13.5ns at 22°C to 9ns at 0°C . Increasing the over bias voltage improves this further by about another 25%, but at the cost of higher dark counts. For example, the dark count rate at 29V and 22°C is $\sim 700 \text{ MHz}$ while the dark count rate at the same temperature at 34V is $\sim 2.8 \text{ GHz}$. The timing resolution is also limited by the noise from the dark current, relative to the signal amplitude. Therefore, the timing resolution improves as the temperature decreases, which decreases the dark current, and it improves with larger operating bias, which increases the signal relative to the noise.

3. Summary and Conclusions

Large-area solid-state photomultiplier fabricated using standard CMOS processing is an exciting photodetector for scaling up the detector size at low cost. Excellent performance can be achieved with the PET detector modules based on a large area up to $1 \text{ cm} \times 1 \text{ cm}$ PS-SSPMs, reading out LYSO crystal arrays. Good energy, timing and spatial resolution have been achieved with these detectors. The dark current in the $1 \text{ cm} \times 1 \text{ cm}$ PS-SSPM limits both the timing and spatial resolution at room temperature.

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Active area	10mm x 10mm
Total Number of micropixels	40000
Micro-pixel area	30 μ m x 30 μ m
Micro-pixel pitch	44.3 μ m x 44.3 μ m
Geometrical Fill Factor	36%
Quench Resistors O	144k
Network resistors O	90
PDE @ 420 nm	7 - 10%
Dark Count Rate MHz	700 ($V_x = 2V$)
Capacitance fF/pixel	220
Operating voltage	27.5V to 32V

Figure 1.

(left) Position-Sensitive SSPM Resistor network and photograph of the device. The right shows the specification table for the 1 cm $\times$ 1 cm PS-SSPM devices.

Figure 2.
Flood field response of a position-sensitive SSPM coupled to an LYSO scintillator crystal irradiated with ^{22}Na at 22 °C.

Figure 3.
Position resolution at varying temperature.

Figure 4.

Timing resolution measured at the center of the $1\text{cm} \times 1\text{cm}$ PS-SSPM with varying bias voltage at two different temperatures (left). Timing resolution with varying temperature (right).