Characterization of Two Thin Postion-Sensitive Avalanche Photodiodes on a Single Flex Circuit for Use in 3-D Positioning PET Detectors

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***Abstract*— We are developing 1 mm resolution, 3-D positioning, high sensitivity positron emission tomography imaging systems for small animal and breast-dedicated imaging applications. The system uses detector modules that comprises two adjacent position-sensitive avalanche photodiodes (PSAPDs), each with a segmented lutetium oxyorthosilicate (LSO) scintillation crystal array, mounted on a single flex cable readout circuit. The module is oriented two PSAPDs deep in the depth of interaction direction, which facilitates high photon sensitivity ($\sim$2 cm of LSO). In this study, we are testing two PSAPD chips in a single flex-cable module simultaneously to investigate their performance and access the degree of inter-device cross-talk. The inter-device cross-talk was measured by looking at the signal in an un-irradiated PSAPD chip while the adjacent PSAPD chip was irradiated, both chips under bias. The signal was three orders of magnitude lower in the unirradiated PSAPD versus the irradiated PSAPD . Individual crystal energy resolution for an array coupled to a PSAPD was measured to be 10.03 $\pm$ 4.45% for the 1mm x 1mm x 3mm array. All crystals were resolved in a flood histogram, with an average peak-to valley ratio of $\sim$11, with the lowest PVR being 1.8. The average coincidence time resolution was 3.75ns FWHM across the devices. These measurements indicate that degradation due to the close proximity of two PSAPDs on the same readout circuit is small.**

***Index Terms*— PSAPD, LSO, Edge-On, 3D, characterization, flex-cable, RMD, APD**

I. Introduction

THE small size, high quantum efficiency, and high spatial resolution of semiconductor photodetectors when coupled to the high-Z scintillator crystals commonly used in positron emission tomography (PET) have made them good candidates for use in detector systems. A novel position-sensitive avalanche photodiode (PSAPD) [1] has been developed by Radiation Monitoring Devices, Inc. and studied when packaged individually on a flex-cable readout circuit in our previous work [2].

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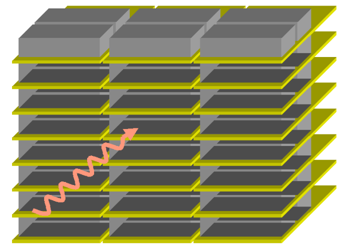


Fig. 1. Shown is a portion of the designed system; 8 modules are stacked and then repeated in three columns. In the figure a red photon is incident, the modules consist of grey LSO crystal sitting atop two dark grey PSAPDs (1cm x 1cm) and yellow flexcable. The top row of crystals are opaque, showing their relative location; and the rest of the levels are transparent, showing the PSAPD underneath. In this geometry, incoming photons see a minimum of 2 cm thick LSO.

In order to increase the stopping efficiency and effective photon sensitivity of a detector system based on this technology, we have designed and tested a module that consists of two thin PSAPDs mounted on a single flex cable readout circuit (see illustration of a portions of the system in Fig. 1).

Previously, we have tested a flex-circuit with a single PSAPD chip mounted on a flex-cable readout circuit [2]. In this study, we are testing two chips mounted on a single flex-cable, and the degree of inter-device cross-talk expected due to their close-proximity. In a single module, the chips are only $\sim$ 50μm apart, both very sensitive to ambient EM fields and require about 1700 Volts of biasing voltage. It is not obvious that the performance characteristics of each of the PSAPDs on this dual-chip version will be same as that achieved by one PSAPD chip mounted on the flex-circuit. Energy, spatial and coincidence time resolution were measured with both devices biased. One of the modules that we have tested is pictured in Fig. 2.

Fig. 2. Picture of two silicon chip PSAPDs (black squares) on one flex cable (yellow material). The module is mounted to glass with tape to rigidly secure the structure during movement and coupling to acquisition electronics.

II. Methods

A high-voltage supply and readout board was constructed to read-out and deliver bias to the two PSAPDs through the single flex-circuit. Positioning for the PSAPD is calculated using signals from the four corner anodes shown in Fig. 3, using the following standard Anger-type logic formula:

$$X = \frac{(A+B)-(C+D)}{A+B+C+D} \tag{1}$$

$$Y = \frac{(A+D)-(B+C)}{A+B+C+D} \tag{2}$$

where A, B, C, and D are the digitized four corner anode signals of the PSAPD; X and Y are the coordinates of the scintillation light centroid on the PSAPD surface. Either A,B,C and D are summed or the common signal is read to obtain the energy of an event.

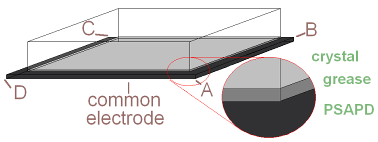


Fig. 3. Illustration of the four corner positioning anodes (A,B,C and D) and the common cathode. The inorganic scintillator (LSO) is optically coupled to the PSAPD with grease and then wrapped with Teflon as a reflector material (not shown).

All measurements were made using a 10 μCi, 500μm diameter, ^{22}Na point source. The same array of 1x1x3 mm^3 lutetium oxyorthosilication (LSO) crystals was optically coupled to both of the PSAPDs on the flex cable for each study performed. The crystals were coupled by one of their 1x3 mm^2 faces, to form a 8x3 crystal array, 8mm x 9mm in area, on the face of the device. The array was wrapped in 12 layers of Teflon to provide a reflective surface, but had no reflective material between the individual crystal elements. For each measurement, both devices were biased together, with the same voltage supply. Parameter optimization experiments have determined optimal device operation is obtained with a bias between 1680 and 1760 V.

Spatial crystal identification was measured for the devices by using flood irradiation and by acquiring the four spatial channels of the irradiated device. Events were triggered by the sum of the four corner channels. Energy resolution was determined by fitting two gaussians to the photopeak - one for 511 keV events, and one for 511 keV - 63 keV events where the 63 keV x-ray produced in the photoelectric interaction escaped the crystal. Being that these crystals are tiny, an x-ray escaping the crystal of interaction happens a measurable amount of the time.

Coincidence time resolution was measured using the same ^{22}Na point source between the PSAPD, in alignment with a 1cm diameter Hamamatsu H3164 photomultiplier tube (PMT), which had a 3mm x 3mm x 8 mm piece of LSO cystal attached as the scintillation material. The events were triggered by a timing seperation of less than 50 nanoseconds between an energy gated common signal of the PSAPD and an energy gated 8th (last) dynode signal of the PMT.

Cross talk was measured in two ways: (1) by acquiring spatial signals for one of the devices on a flex-circuit while irradiating a crystal array coupled to the other PSAPD and (2) by acquiring spatial signals from the irradiated device as well as the common channel of the unirradiated device.

III. Results and Discussion

A. Crosstalk

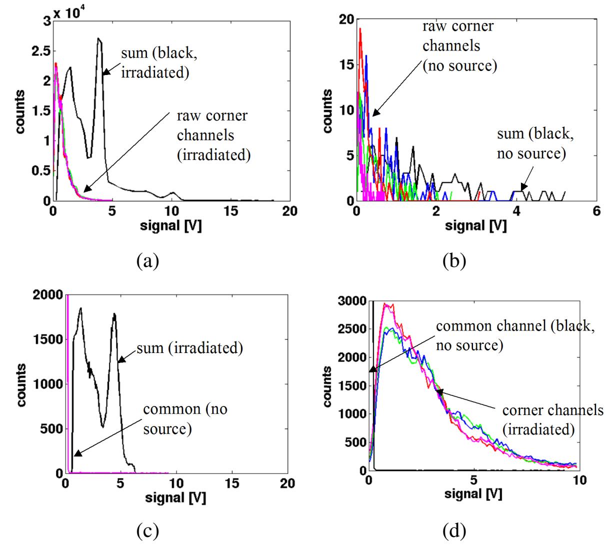


Fig. 4. Top, Left: Signals from the corner anodes for the irradiated device with an LSO array of 2x2x3 mm3 crystals and, Top, Right: adjacent PSAPD chip device with no LSO crystal coupled to it. The black line is the sum of the four corner anodes, which are shown in magenta, red, green and blue. Bottom, Left: The sum of the corner signals (black), compared to the common signal from the un-irradiated device with no crystal coupled (magenta). Bottom, Right: Signals from the 4 corner channels compared to the common channel (black) of the un-irradiated device.

Cross talk between the two devices was measured and is compared in figure 4 with the data acquired in both PSAPDs for the same acquisition time. The number of events recorded in the non-irradiated compared to the irradiated PSAPD was three orders of magnitude lower across all energies, including in the photopeak. This is an indicator that the devices are electrically isolated relatively well from one another, i.e., readout or current generation from one device will not in general trigger a spurious event from the neighboring chip.

B. Crystal Identification

Shown in Fig. 5 are typical results of flood irradiation of segmented LSO arrays optically coupled to one of the PSAPD chips with both chips biased. Figure 5 is an 8x3 array of 1x1x3 mm^3 crystals, with no inter-crystal reflector, coupled to each of the PSAPDs on one dual-chip module. Crystals are identified and results are comparable to previous results achieved with one PSAPD per module. Profiles were taken through the middle row of each array shown on the left hand side of Fig. 5. The average peak to valley ratio for the inner chip was 11.3 and was 10.9 for the outer chip.

For comparison, a segmented crystal array manufactured by Agile Engineering, made of LSO, each crystal having a size

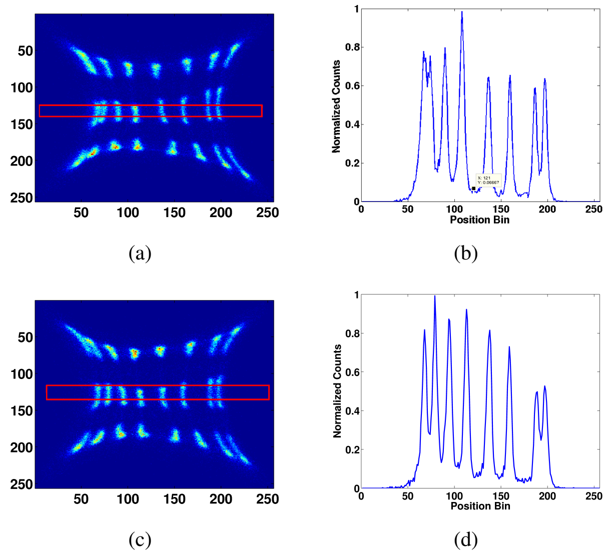


Fig. 5. Array of 1x1x3 mm3 crystals with no inter-crystal reflectors. Left: Histogrammed position from a flood irradiated LSO array coupled to one of the PSAPDs. Right: Profile through the bins bounded in the red box shown in the figure on the left. Top: array irradiated on the PSAPD closest to the signal leads (inner), Bottom: array irradiated on the PSAPD farthest from the signal

of ∼1mm on a side, was coupled to the inner PSAPD on the flex cricuit (Fig. 6). This array has a thin layer of reflective material between the crystals, and the exposed edges of the array that was not coupled to the PSAPD was wrapped in 12 layers of Teflon. The average peak-to-valley ratio was 5.5, with the minimum PVR being 3.

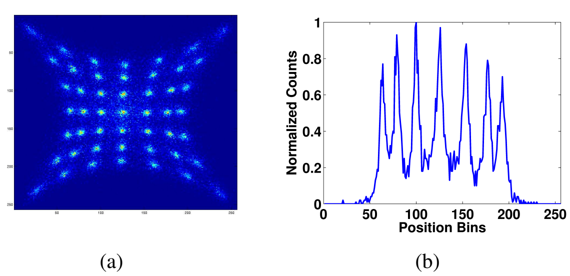


Fig. 6. Flood histogram of the 7x7 array with inter-crystal reflector.

C. Energy Spectra Features per Crystal

Energy spectra were extracted for each crystal in the array coupled to the PSAPD. Figure 7a and 7b show the individual energy spectra for the array coupled to the inner and outer PSAPDs, respectively. Figure 7c shows the energy spectrum of a common crystal in the array after compton edge subtraction. The average counts per crystal were 960±98 for the inner PSAPD and for the outer the counts were 921±104. The average ER at 511keV for the 24 crystals was 10.03±4.45%, very similar to previous measurements.

The photopeaks were very well resolved from the compton edge, and the photopeak-to-valley ratios for the position gated energy spectra were very high: 32 ± 16.5 and (with the smallest being 13) and 31 ± 24 (with the smallest being 8) for the outer and inner PSAPD respectively.

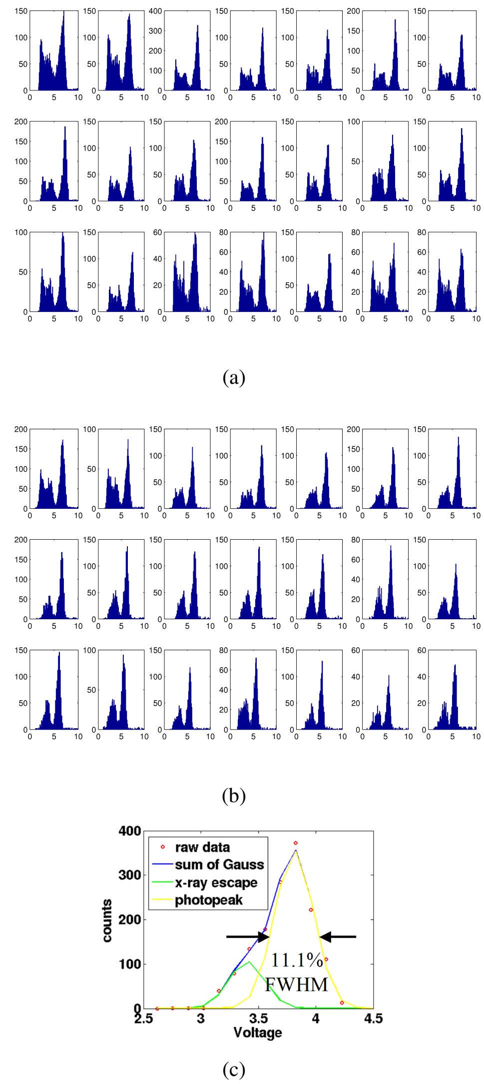
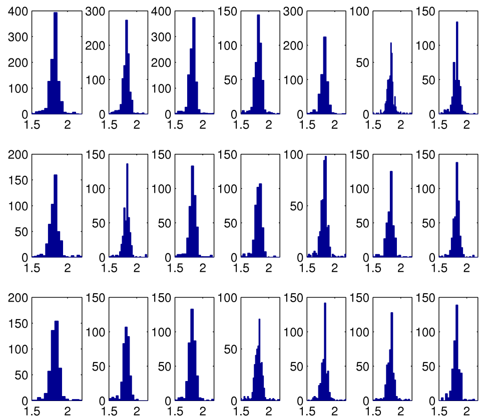


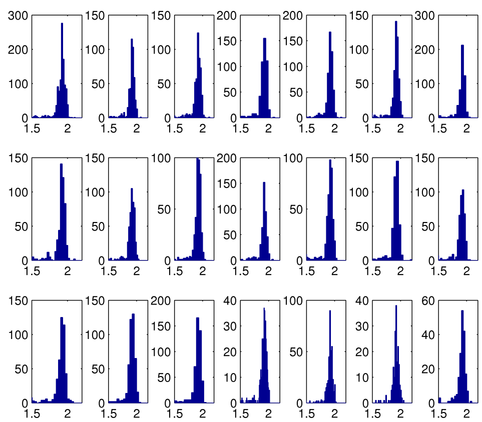
Fig. 7. Individual energy spectra for each crystal on the a) inner and b) outer PSAPD. c) Two Guassian fit to energy spectra data from a typical crystal in the 8x3 array. The yellow gaussian is where all energy from the photoelectric interaction is deposited into the crystal, the green gaussian is the events where the x-ray produced in the PE interaction escaped from the crystal.

D. Coincidence Timing Resolution per Crystal

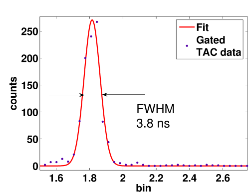
Coincidence timing was measured for both the inner and outer PSAPDs on both modules, for each individual crystal, with the PMT and PSAPD energy gate applied for that particular crystal. The inner PSAPD had an average coincidence time resolution of 3.7ns ± 0.27ns, with a peak position standard deviation of 0.14ns. For the outer PSAPD, the average coincidence time resolution was 3.8ns ± 0.31ns, with a peak position standard deviation of 0.16ns. The peak position varied a small fraction (∼5%) of the full width half maximum for all crystals on both the inner and outer chip, making the coincidence time parameters (resolution and window offset) on the face of the chip nearly independent of position.



(a)



(b)



(c)

Fig. 8. Individual TAC spectra for each crystal on the a) inner and b) outer PSAPD. c) A typical TAC spectrum and its Gaussian fit.

IV. Conclusions and Future Work

In most of the performance parameters measured, the results from the PSAPDs on the dual-chip flex-cable mounted modules tested were comparable to results obtained with only one PSAPD per module, and both chips on one module were comparable to each other. Spatial crystal identification and energy resolution for an 8x3 array of LSO crystals were very similar to one-PSAPD results, with the average energy resolution of ∼10% and peak to valley ratio of 11 across the chips. Coincidence timing resolution measurements showed a higher jitter in the timing spectra compared to single chip flex modules previously tested [2], with an average timing resolution of about 3.75 ns. Improvements in timing acquisition parameters may be possible however, measuring the jitter of the PSAPD on the oscilloscope showed less than 1.8ns time width.

References

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