Solid-State Photomultiplier in CMOS Technology for Gamma-Ray Detection and Imaging Applications

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***Abstract* -A CMOS solid-state photomultiplier (SSPM) coupled to a scintillation crystal uses an array of CMOS Geiger-mode avalanche photodiode (GPD) pixels to collect light and produce a signal proportional to the energy of the radiation. Each pixel acts as a binary photon detector, but the summed output is an analog representation of the total photon intensity. We have successfully fabricated arrays of GPD pixels in a CMOS environment, which makes possible the production of miniaturized arrays integrated with the detector electronics in a small silicon chip.**

In this work, we compare designs for the SSPM detector and present preliminary results in constructing a position-sensitive solid-state photomultiplier (PS-SSPM) using a commercially available CMOS process. The prototype arrays utilize a resistor network to provide a position-sensitive readout of the array. One pixel design achieves maximum detection efficiency for 632-nm photons approaching 20% with a room temperature dark count rate of less then 1 kHz for a 30-µm-diameter pixel. Pair-wise cross talk was measured to be less than 2% for 150 µm pixel spacing.

I. INTRODUCTION

Although scintillating materials are ideal for detecting and measuring high-energy radiation, the limitations of existing optical detectors drastically reduces their functionality. Replacing the photomultiplier tube (PMT) with an appropriate CMOS technology would provide a fully integrated, low-cost solution to optimize the functionality of scintillation materials, which is essential for applications such as the development of deployable digital dosimeters and medical imaging modalities.

A solid-state photomultiplier (SSPM), or an array of avalanche photodiodes operating in Geiger mode (GPDs), produces a device that can achieve the low noise of a PMT at a lower cost, but retain the high quantum efficiency of a silicon device without the deterioration of signal from thermal noise. The SSPM provides a basis for radiation spectrometers with a wide range of applications. Since the light produced in the scintillator is proportional to the energy of the absorbed event, the number of pixels that fire will provide the energy of the incident photon when the SSPM is uniformly illuminated. Fig. 1 illustrates the principle of operation of the SSPM.

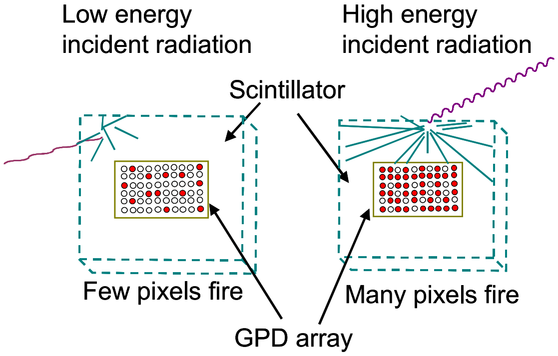

Fig. 1. SSPM principal of operation. Nuclear photons strike the scintillation crystal and produce visible light proportional to their energy. The number of pixels that fire in the GPD array is thus a function of the incident energy.

P. Buzhan *et al.* have shown that this method approaches and exceeds the performance of a standard PMT for detection of the scintillator optical photons in certain applications.[1,2] Implementing this approach in a CMOS compatible process will allow high precision, low-cost, sensors with the additional benefit of integration of signal processing electronics right on the chip. We have fabricated several CMOS-based test arrays of these pixel sensors and characterized their performance as individual detectors, and as arrays.

Borrowing a technique used in large area, position sensitive APD’s, the SSPM can be used as a position sensitive detector, (PS-SSPM). The position sensitive SSPM pixels are coupled together in a resistive network to produce four signal outputs at the corners of the device to provide signals that determine the position of the event in the scintillation crystal, as demonstrated in Fig. 2. The PS-SSPM provides a fast, simple approach to reading out solid or even segmented scintillator devices [3]. In addition, the

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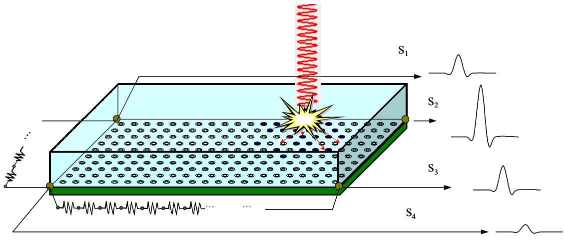

Fig. 2. Schematic showing position readout principle of a PS-SSPM.

use of CMOS facilitates the integration of ancillary circuit components.

Accurate position information depends on a sufficiently thin crystal that the light spread is minimal. Even in a thin crystal, however, interaction depths close to the array will lead to higher photon densities at the pixel, and in extreme cases, can lead to a non-linearity in the energy information. Empirical measurements should be able to resolve first order effect due to this issue as a calibration correction. The maximum energy resolution is obtained with uniform illumination. However, uniform illumination provides no position information. In the PS-SSPM, there is a compromise between spatial and energy resolution.

II. EXPERIMENTAL METHODS

A. Radiometeric performance

The pixels are operated in Geiger mode, operated a few volts above the reverse bias breakdown potential. Radiometric performance of test pixels was measured with an integrated 80 kΩ resistor to quench the Geiger avalanche; this method is refered to as passive quenching. The test diode outputs were connected to Cremat preamplifiers; a low level discriminator was used to filter the noise and create constant pulses for the frequency counter. Standard NIM amplifier and logic modules were used for these measurements. Detection efficiency measurements were made with flood field illumination from an LED array operated in CW mode.

B. Time measurements

We performed a Bollinger-Thomas experiment to measure the decay time of an LSO:Ce crystal using a single GPD. Two scintillation crystals were placed opposite a ^{22}Na positron source. The optical pulse from one crystal was read out by a standard PMT, the other by a single CMOS photodiode pixel. Each signal was fed into a constant fraction discriminator to pick off the leading edge, and then into the start and stop channels of a time to amplitude converter (TAC) with 50 ns of delay inserted before the stop channel. The ungated output from the TAC was read by an Amptec pocket MCA.

C. Interaction strength

A prototype chip containing three 3x3 element arrays was used to measure pair-wise cross talk. The arrays were designed with seven connected elements and two independent elements.

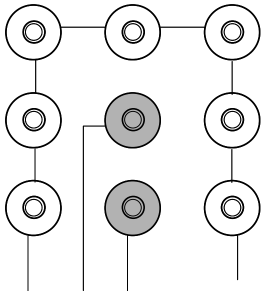

Fig. 3. Schematic of 3 x 3 array, illustrating the pixels used to determine the pair-wise interaction strength.

The interaction strength represents the probability that a neighboring pixel will fire as a result of an avalanche in the original pixel. For pixels A and pixel B, the interaction strength is defined in equation 1. The quantity combines the effect of A on B with B on A, to provided a normalized result that is independent of the actual rate in either pixel. $A_{b\ on}$ is the rate measured in pixel A while its neighbor B is on, $A_{b\ off}$ is the actual isolated count rate of pixel A, and so on.

$$I = \frac{\left(A_{B\,on} + B_{A\,on}\right) - \left(A_{B\,off} + B_{A\,ff}\right)}{A_{B\,on} + B_{A\,on}} \qquad (1)$$

D. Light detection

A pulsed 632-nm laser was used to measure the SSPM sensitivity to vary the light illuminating seven pixels connected as shown in Fig. 3. The output was fed into an MCA that was gated on the light pulse.

E. Position readout

The external circuit shown in Fig. 4 was used to read out the position information from the array.

Three diodes spaced approximately 1 mm and 5 mm apart were connected using an external resistive scheme similar to the conceptual PS SSPM described above. The electrical connections are shown in Fig. 4. A fiber emitting 632-nm light from a pulsed laser was positioned above the pixels and translated along the length of chip containing the pixels. The average pulse height recorded by an oscilloscope was recorded over 100 micron steps.

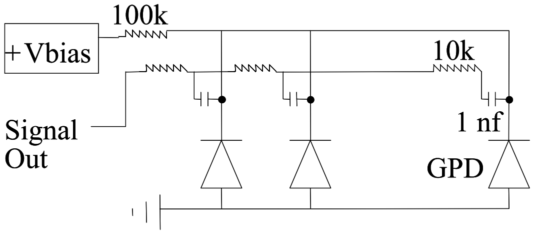

Fig. 4. Schematic of position sensitive readout. The bias voltage was 28.0 V, the output was average in an external oscilloscope.

3. RESULTS

A. Radiometric performance

The basic radiometric properties of the CMOS avalanche photodiodes have been measured for test pixels on each prototype chip. Typical results for a single 30-micron pixel show a detection efficiency of better than 20% at 470 nm, after correcting for afterpulsing. The room temperature dark count rate for our best pixels is 0.5 kHz; the average is approximately 3 kHz. For 150 micron pixel spacing, the pair-wise cross talk is less that 2% over the whole range of operating biases. Actively quenched cells have achieved quenching times of as low as 25 ns in duration, allowing for a maximum count rate of 25 MHz. For scintillation counting experiments, the time must be lengthened to match the crystal light decay time, as in Fig. 5 below.

B. Time measurements

Fig. 5 shows the time difference for signals from a PMT and a GPD viewing two scintillators intercepting coincident photons from annihilation events created in a ^{22}Na source. The curve shows a decay time of approximately 28 ns, which is characteristic of LSO.

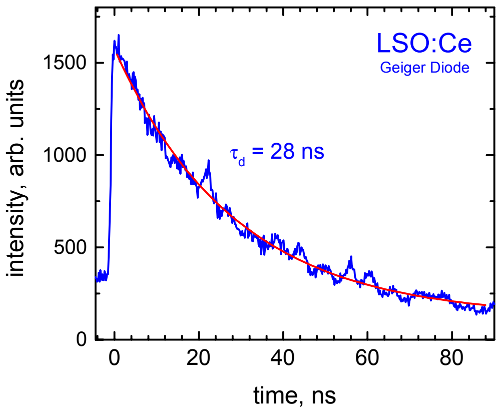

Fig. 5. TAC output for a Bollinger Thomas experiment showing the decay time from a small LSO crystal.

C. Interaction strength

The interaction strength experiment was performed using dark counts and repeated using external illumination, the results are very similar. Fig. 4 shows the results of the illuminated measurements. Two promising trends are apparent. First, the strength increases as a function of excess bias, since the detection efficiency is rising. Second, the spacing of lines is related to the approximately the square of the distance between pixels, as expected.

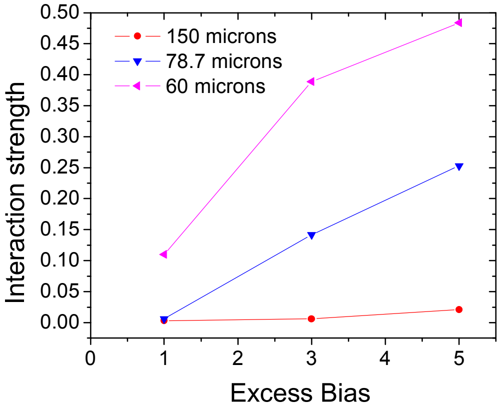

Fig. 6. Pair-wise interaction strength. The strength calculated using equation 1 is shown for three different pixel spacing at three different values of excess bias. This The data is an average of measurements made with several prototype chips. The change in slope for the top line is from saturation due to high numbers of counts.

D. Light detection

Varying the light incident on seven coupled pixels from a pulsed 632-nm laser produced a spectrum that showed from one to seven pixels firing simultaneously, depending on the intensity of the incident light. The result, shown in Fig. 7, indicates that large area SSPM devices will provide signals proportional to the light intensity.

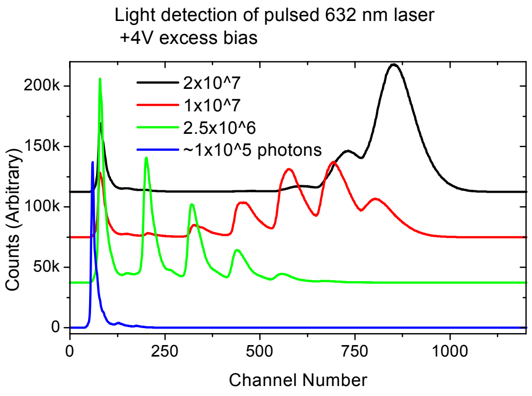

Fig. 7. Light detection by a seven pixel GPD array. The channel number corresponds to a pulse height from a multi-channel analyzer, gated by the input pulse to suppress dark counts. Each peak from left to right in the figure represents an additional pixel firing simultaneously. Seven peaks are visible in the data, the centroid of the distribution shifts based on the light intensity.

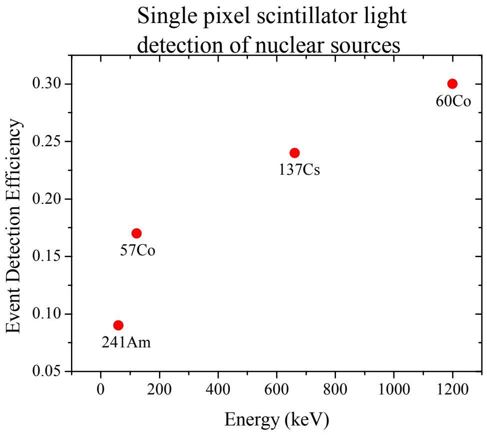

Fig. 8. Single pixel dosimeter function. The data was generated using a single 30 micron GPD pixel viewing a 0.6 mm x 2.0 mm x 4.2 mm LSO pixel. Corrections were made for the intrinsic efficiency of the crystal; no correction was included for the change in photopeak to Compton scattering ratio with increasing energy**.**

E. Preliminary resolution of energy

Using an LSO crystal on a single pixel SSPM to detect radiation, several sources were brought near the detector. The event detection efficiency, shown in Fig. 8 as a function of incident energy, was calculated by dividing the expected incident events on the detector by the actual increase in count rate from the GPD.

Since higher energy photons absorbed by the crystal create more photons, the event is more likely to be seen by a single pixel. For this measurement, the dark count rate in the detector is subtracted from the count rate when a source is actually present. In an actual SSPM, the signal would have a discriminator level set above the height of dark count events so that the output would not be effected by dark counts.

F. Position readout

The results from the position sensitive readout examination are shown in Fig. 9. The measured pulse height is proportional to the position along the array. The laser width is on the order of 300 µm. The results obtained for light shows easy resolution of the pixels; light spread from a scintillator will convolute the position sensitivity.

4. DISCUSSION

Experiments to measure the time response with a single pixel have shown promising results. Increasing the number of pixels to collect a more substantial percentage of the light will produce a fast nuclear detector for coincidence and high rate applications. For passively quenched pixels, measurements of the interaction strength show that a pixel spacing less that 100 µm will lead to substantial optical cross talk. Numbers as low as 15% pair-wise interaction are significant in an array where each pixel has eight neighbors, each with a 15% chance of interference. Active quenching should reduce this strength by reducing the duration of the avalanche, and thus the number of photons emitted.

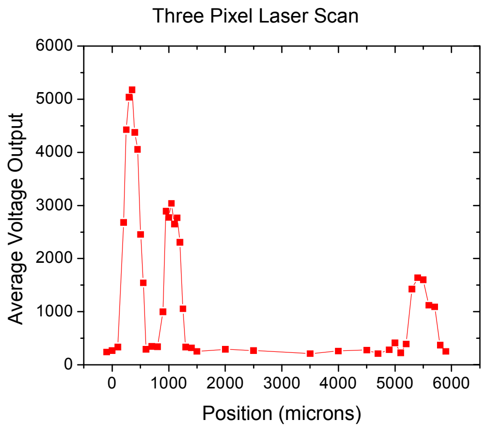

Fig. 9. Position sensitive SSPM operation. The width of the pixels shown in the plot on the right is due to a fairly wide (300 micron) laser spot. The diodes are printed on the CMOS chip; the resistors shown in the diagram on the left are external for this experiment.

The passively quenched pixels have an avalanche duration of several microseconds while actively quenched pixels can be made as short as 25 ns with existing prototype circuits. The interaction strength may be reduced by several orders of magnitude by using actively quenched pixels.

A quantized pulse height spectrum for seven pixels has been observed with one set of prototypes. Suppression of dark counts required us to gate the MCA to see the variance due to the change in light intensity. For SSPM readout of a scintillation crystal, a threshold will provide the same noise suppression. Since the dark counts are randomly correlated in time, it is less likely that multiple events will occur simultaneously, as long as the optical cross talk probability is low. Since a scintillation flash produces many thousands of photons, depending on the scintillator properties, a threshold of several pixels will remove the effect of dark counts from the detector operation.

Experiments coupling the SSPM to a crystal has indicated that it is possible to obtain energy information from an SSPM coupled to a scintillator. To accurately describe the depth of resolution information obtainable will require measurements with multiple pixels; we present model predictions below.

Although the SSPM can be externally connected to provide position information, the results of similar circuits printed directly on the CMOS have proven more difficult to extract position information from. The logic signal from actively quenched pixels will provide a more stable signal for developing the position sensitive readout in future designs.

Model results

The final performance of the device is critically dependant on several variables. The scintillator properties that change the performance include its light output, the aspect ratio, the volume of crystal, and the efficiency of coupling the crystal to the chip surface. The size and corresponding dark count of the pixels in the array, the number of pixels in the array and the space between pixels, the operating bias, and the duration of the active quench process strongly effect the SSPM output and sensitivity. We modeled the response in terms of theoretically obtainable energy resolution for a prototype SSPM.

To interpret the results of the model it is necessary to constrain several variables. Since the concept requires multiple chips to be cut from a single wafer, the area available for pixels must be constrained; the area is also strongly related to total cost. The dark count rate per pixel was fixed at 1 kHz, and a careful 15% detection efficiency was used. In order to determine the proportionality of the response, the dynamic range was set at 2 MeV, based on the light output from CsI(Tl) of about 55,000 photons per MeV. The results from the model shown in Fig. 10 do not include contributions from the intrinsic scintillator resolution. A clear peak at 1.5% resolution is seen at about 100 mm, which is largely a function of the parameters taken from cross talk measurements shown above.

5. CONCLUSIONS

The CMOS-based SSPM forms the foundation for an extremely versatile detector. The pixels that have been fabricated have high sensitivity to a broad range of light. Basic values of the radiometric performance have been presented, along with basic attributes important to SSPM function, such as optical cross talk. Our model predicts that a resolution contribution less that 2% is obtainable with our current technology.

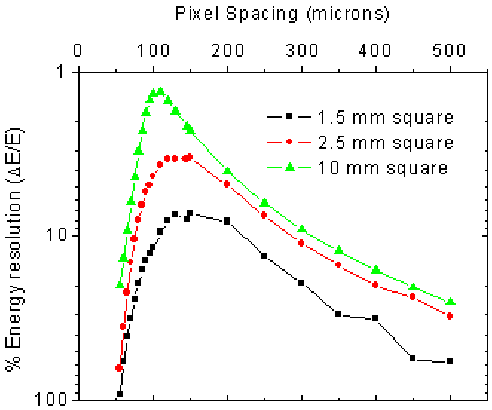

Fig. 10. Model results for fixed area SSPM with varying pixel pitch. The cross talk measurements shown in fig. 6 were used to determine the effect of changing pixel spacing. The loss of resolution for close pixel spacing is a result of cross talk, the loss for large pixel spacing is due to the area constraint.

The SSPM detector can be applied to many imaging and detection applications. PET, SPECT, and direct gamma-camera applications, survey devices and ratemeters, digital dosimeter badges and portal scanning systems. The devices have a fast rise time, utilize inexpensive, high efficiency scintillation material with variable light output for the target application. The low voltage operation simplifies supporting electronics.

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