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NOVEL HYBRID IMAGING DETECTOR

SBIR - PHASE I **Final Report**

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THE PHASE I FINAL REPORT

The research work in the Phase I project covered several areas. This included optimization of design and fabrication of position sensitive avalanche photodiodes, optimization of GaAs photocathodes, fabrication of hybrid PSAPDs, and evaluation of the hybrid devices.

SUMMARY

The goal of the Phase I research program was to investigate a new hybrid position sensitive detector for scintillation spectroscopy and imaging. The Phase I research consisted of work in two general areas: the design and fabrication of the new HPSAPD devices with position sensing capability and the testing of the spectroscopic and imaging properties of these new detectors. Hybrid PSAPDs were fabricated during the Phase I project and extensive evaluation of these devices was carried out. Gain, noise, quantum efficiency, spatial resolution, and sensitivity were characterized. HPSAPDs were then coupled to scintillation crystals and arrays and energy resolution as well as imaging behavior of these sensors under gamma ray exposure were evaluated. Over and above the standard GaAs photocathodes, other potential photocathodes were also explored. Successful demonstration of these devices in the laboratory clearly proved the feasibility of building high performance HPSAPDs that can be used for gamma ray detection and imaging.

Our Phase I research showed that high sensitivity and spatial resolution at low optical exposure levels (which would correspond to scintillation studies with low energy gamma rays) is an important advantage of the hybrid PSAPDs over silicon p-i-n and APD technologies. Minimal electronic readout requirement is also an important aspect of the PSAPD design. Optimization of the promising hybrid devices including fabrication and evaluation of larger HPSAPDs is planned for the Phase II effort.

Figure 39b. Timing resolution measured with HPSAPD-LSO and PMT-LSO detectors operating in a coincidence timing circuit. Each detector was irradiated with coincident 511 keV positron annihilation γ -ray pairs (^{22}Na source).

A. SIMULATION STUDIES OF POSITION SENSITIVE APDS

1. SPICE Simulations of PSAPDs with Four Corner Contact Design

One of the important aspects of the Phase I project was to fabricate the position sensitive avalanche photodiodes. At RMD, we began investigation of the PSAPDs prior to the Phase I effort and we have an active program aimed at optimization of these promising devices. This effort has been very helpful in optimization of PSAPDs for incorporation in the hybrid devices.

As mentioned earlier, PSAPDs are capable of providing high spatial resolution, high gain, and low noise. The imaging response of the PSAPDs (with four corner contacts) exhibits pincushion distortion. Prior to the Phase I research, we have used circuit simulation techniques to understand the distortion effects in the PSAPDs that are mostly due to charge transport processes in the resistive layer on which the corner contacts are fabricated. This circuit simulation is readily achieved with the SPICE (Simulation Program with Integrated Circuit Emphasis). **Figure 10** shows a unit cell design that was used for SPICE simulation of the majority carrier transport through the PSAPD with four corner contacts (shown in **Figure 2**). A square array of 20×20 unit cells were simulated to be connected together with rows being connected by contacts **1** and **2** and columns being connected by contacts **3** and **4** and each of the four outermost contacts in such chains was connected to a load resistance. Contact **5** is connected to a common ground plane. The imaging performance of such a device was simulated by assuming that photocurrent was injected from a point source into one of the unit cells. By varying the position of the point source over the entire device, the imaging performance of the PSAPD was simulated and the results are shown in **Figure 11**. It is important to note that the simulation results are in very good agreement with the experimental results for a device with four corner anodes (shown in **Figure 9**). Both the simulation and the experimental results show pincushion distortion with data-points in middle of each row or column pushed towards the center.

Such pincushion distortion can be explained on basis of charge sharing effects in the device with four corner anodes. In this device design, the charge sharing amongst the four anodes is appropriate for event locations near the corner or the center of the device and the estimated positions are in reasonable agreement with the actual ones. However, for events, which occur near the side of the device (between contacts), significant current flows to all four contacts, which pushes the estimated event location more to the center than the reality. This leads to the pincushion distortion, which is an inherent property of the device with four corner anode design. Since the pincushion distortion is a fixed pattern, a calibration map can be used to correct the data in order to

Figure 10. Unit cell for SPICE simulation of PSAPD with four corner contacts.

Figure 11. Simulation results for imaging performance of PSAPD with four corner contacts when the input test pattern is 8×8 square array (1.85 mm spacing between adjacent points in both directions) covering the entire device area.

determine actual location of event. Furthermore, our simulations also show that an optimal balance is required between the external load resistance and the sheet resistance of the PSAPD surface (on which four corner contacts are fabricated) to minimize the pincushion distortion effects.

2. SPICE Simulations of PSAPDs with Other Anode Designs

Prior to the Phase I research, we have also simulated two other anode designs using SPICE and have found that the spatial distortions are significantly reduced in both cases. In one case, contact strips are placed at the edge of the device (see **Figure 12**, left) and the simulation results show that the response is fairly uniform over much of the device area with small “barrel” type distortion observed near the corners of the device. The other design consists of corner contacts which are connected with linear resistive strips (see **Figure 12**, right) and the simulated response of such a design is very uniform over the entire device area. In order to achieve such excellent spatial response map, it is important that the sheet resistance of the n-type surface be much higher than the resistance of the strips that connect the corner anodes for the devices shown in **Figure 12**. Furthermore, as stipulated in case of device design with simple four corner anodes, the sheet resistance of n-layer should also be more than the external load resistance for the PSAPD designs shown in **Figure 12**.

Figure 12. SPICE simulation results (with similar input pattern as in **Figure 11**) for two anode designs. The design on left has four contact strips (shown in yellow) placed at edges of a square device on a resistive layer. This device has a fairly uniform response over much of its area but shows minor “barrel” distortion at the corners. The design on right combines strip (shown in blue) and corner pad (shown in yellow) contacts and its response is uniform over entire area.

Finally, we have also performed simulations for a device design that is an extension of the design shown on right in **Figure 12**. In the new design, in place of linear resistive strips connecting the corner anodes, resistive strips in arc geometry are used as shown in **Figure 13**. This design is referred to as pincushion anode [Lampton] and can provide distortion free imaging response if the relationship $R_L = \rho/r$ is satisfied, where R_L is the arc resistance, ρ is the resistivity of the substrate on which the anodes are constructed and r is radius of the arc. We have performed SPICE simulations of the pincushion anode design using realistic APD parameters. The results, shown in **Figure 13**, indicate that this device is capable of providing distortion free imaging response. It should be noted that the spatial sampling for this device is only performed for the region inside the arcs as seen in **Figure 13**.

Figure 13. SPICE simulation studies of imaging response of a pincushion anode design for PSAPDs. On left, the anode design is shown and on right, the simulated imaging response is shown, which is excellent.

From these simulation results, we were able to gain a deeper understanding of the imaging performance of various PSAPD designs as well as an appreciation for various parameters that govern their response. For the Phase I research, we selected the simple four corner anode PSAPD design (shown in **Figure 2**) for incorporation in the hybrid structure in view of its simplicity and ease of construction. Even though PSAPDs with this design show pincushion distortion, in most cases it is possible to readily correct such distortion in the image processing step using a previously generated calibration map. We are in process of instituting such a correction with the hybrid devices. PSAPDs with other anode designs, particularly the one with corner contacts connected with resistive arcs (see **Figure 13**) are also promising and are being investigated at RMD [Grazioso]. Such PSAPDs with anode design shown in **Figure 13** will be investigated in the hybrid structure in the Phase II research.

B. PSAPD FABRICATION USING PLANAR PROCESS

During the Phase I project, we fabricated position sensitive avalanche photodiodes using the low cost planar processing approach. This planar process was originally designed for fabrication of large area APDs and monolithic APD arrays [Shah 01], but is also suitable for fabrication of position sensitive APDs. The basic approach employed in fabrication of PSAPDs using the planar process is illustrated in **Figure 14**. In this process, grooves are cut in n-type starting silicon material. The shape of the groove is used to influence the profile of the subsequent p-type diffusions and thereby, the p-n junction profile. The insights gained from the simulations regarding optimal values of surface resistance of the n-layer, anode size and placement, and arc resistance were incorporated in our device fabrication process. The main fabrication steps are as follows:

1. Fabricate grooves into our starting n-type neutron-transmuted doped (NTD) silicon wafers.
2. Carry out standard p-deep diffusion into such Si wafers to define the doping profile.

3. Etch the p-type material from the front and the back for proper termination of the p-n junction.
4. Define device periphery and fabricate front p^+ contact.
5. Create an n-type resistive layer on the back-face and fabricate anodes to produce the PSAPD.

Figure 14. Schematic diagram of the process steps involved in fabrication of a planar PSAPD.

While many of the earlier steps are routinely used in our APD production, the final step that involves creating anode structures to provide position sensitivity, was optimized to fabricate PSAPDs. This involved creating n-type back-surface layer with high resistance ($\sim 2000 \Omega/\text{square}$) and good uniformity. Some fabrication runs with lower resistance for n-type back-surface layer ($\sim 600 \Omega/\text{square}$) were also carried out for comparison.

Photolithography as well as evaporation masks were used for deposition of the anode contact pattern on the resistive n-type layer. We used this approach to build PSAPDs with the standard four corner contact design with sizes of $8 \times 8 \text{ mm}^2$ and $14 \times 14 \text{ mm}^2$.

C. PSAPD EVALUATION

Once the PSAPDs with simple four corner anode design were fabricated, they were characterized. This involved measurement of gain, noise, and uniformity of response of these devices. Their spatial resolution, and distortion effects were also characterized. Results are presented here for both $8 \times 8 \text{ mm}^2$ and $14 \times 14 \text{ mm}^2$ PSAPDs with simple four corner anode design.

1. Gain, Noise and Uniformity

Evaluation of the planar PSAPDs has been conducted (both prior to and during the Phase I research). One of the first tasks was to evaluate the gain and noise behavior of the PSAPDs. A low energy X-ray source (^{55}Fe - 5.9 keV X-rays) was used to calibrate the energy scale for gain and noise measurements and a low noise pulse generator was used to quantify noise.

Figure 15 shows the ^{55}Fe X-ray spectrum recorded with an $8 \times 8 \text{ mm}^2$

Figure 15. ^{55}Fe spectrum recorded with $8 \times 8 \text{ mm}^2$ PSAPD at 20°C .

PSAPD at room temperature. The energy resolution of 5.9 keV X-ray peak was measured to be 1.4 keV (FWHM), while the noise (quantified from pulser broadening) was measured to be 900 eV (FWHM). Similar experiment was also conducted with a $14 \times 14 \text{ mm}^2$ PSAPD and the resolution

of 5.9 keV peak and pulser were measured to be 1.5 keV (FWHM) and 1.2 keV (FWHM), respectively at room temperature.

We have also measured gain and noise as a function of bias for the $8 \times 8 \text{ mm}^2$ PSAPD by recording pulse height spectra of an optical pulse on a calibrated energy scale (as shown in **Figure 16**). As seen in the figure, the optimal gain of the PSAPD (where its effective noise is minimized) is ~ 5000 , while the corresponding noise is 800 eV (FWHM) or 220 electrons (FWHM) at 20°C . A similar experiment was then conducted for a $14 \times 14 \text{ mm}^2$ PSAPDs and the optimal gain value was ~ 1000 , while the corresponding noise was 1 keV (FWHM) or 280 electrons (FWHM) at room temperature. Overall, these noise and gain results are encouraging and are similar to those for standard, planar, non-imaging APDs of similar size.

We have also characterized uniformity of response for the $14 \times 14 \text{ mm}^2$ PSAPD over its entire active area by scanning the surface of the device with a 1 mm optical fiber illuminated with a 550 nm LED. The results are shown in **Figure 17** and indicate that the optical response of the full active area of the device is fairly uniform. The lower response represented by yellow and green periphery around the red section occurs when the fiber is passed over the grooves of the PSAPD. These results are very encouraging.

The timing properties of the PSAPDs have been measured. The risetime of a PSAPD was measured by irradiating its top surface with 5.5 MeV α -particles and recording the resulting signal from the top contact directly (without amplification) on a digital scope. The risetime was found to be $\sim 1 \text{ ns}$, confirming fast operation of PSAPD.

2. Imaging Response

We have characterized imaging response and distortion effects for PSAPDs with the simple, four-corner anode design. Experiments were conducted to demonstrate position sensing capability of the PSAPD. Prior to the Phase I project, we had performed an experiment in which an optical fiber (1 mm diameter) was placed at different locations on a $14 \times 14 \text{ mm}^2$ PSAPD to create a 7×8 rectangular pattern (1.85 mm spacing between adjacent points in both directions). The response of the PSAPD was mapped in this manner and the results were shown earlier in **Figure 9**. Some pincushion distortion was observed (see **Figure 9**), which is expected for the simple four corner

Figure 16. Gain and noise versus bias of $8 \times 8 \text{ mm}^2$ PSAPD at 20°C .

Figure 17. Uniformity of optical response for a $14 \times 14 \text{ mm}^2$ PSAPD at room temperature. The optical response map was generated by scanning a 1 mm diameter optical fiber (illuminated with 550 nm light) across the PSAPD surface. As seen in the figure, the full $14 \times 14 \text{ mm}^2$ area of the device appears in red section of the response map, indicating that the optical response is high and uniform over the full area of the device.

contact geometry (based on our simulations). The imaging response of the device was found to be in excellent agreement with the simulation results shown for this device design in **Figure 11**.

Despite the pincushion distortion, the plot in **Figure 9** confirmed the position sensing capability of the PSAPD, and indicates that the position resolution of the device is much better than 1.85 mm, since all the data points can be readily distinguished in **Figure 9**. We have also performed a similar study in which imaging response of a $14 \times 14 \text{ mm}^2$ PSAPD with simple four corner anode design was mapped over a 12×12 square pattern with 1 mm spacing between adjacent points in both, x- and y-directions using a 0.5 mm diameter optical fiber in a related research effort. The optical intensity at the PSAPD surface was $\sim 30,000$ photons/pulse. The measured response of the PSAPD is shown in **Figure 18**, and indicates that the spatial resolution of the device is better than 1 mm, since all points are readily identified.

Figure 18. Measured optical fiber position map with $14 \times 14 \text{ mm}^2$ PSAPD for fiber placement in a square 12×12 pattern on PSAPD. The spacing between adjacent fiber positions is 1 mm in both directions. Some of the points at corners are missing in the image. The image clearly indicates that the spatial resolution of this PSAPD is $< 1 \text{ mm}$

3. Spatial Resolution Measurements

We have conducted detailed characterization of the intrinsic spatial resolution of PSAPDs with simple four corner anode design. These measurements were conducted for $8 \times 8 \text{ mm}^2$ and $14 \times 14 \text{ mm}^2$ PSAPDs at room temperature.

Figure 19. Images of a laser spot ($\sim 25 \mu\text{m}$ size) recorded using $8 \times 8 \text{ mm}^2$ PSAPD at different optical intensities (4000-60,000 photons/pulse range) at room temperature.

In this experiment, a 635nm laser was focused onto the PSAPD with a spot size of approximately $25 \mu\text{m}$. The laser was pulsed at a high frequency and the output voltages of the four bottom contacts (anodes) were noted directly out of the preamplifiers on a digital oscilloscope. This was repeated until a large number of measurements were taken at the same laser position on the PSAPD. The x- and y-positions were calculated and plotted for all the data points, and the FWHM of the histograms for both co-ordinates provided the estimate of the position resolution of the PSAPD at that location. Similar measurements were then carried out as the laser intensity was varied in order to

study the change in spatial resolution as a function of the incident optical intensity. **Figure 19** shows the images of the incident laser spot recorded at different laser intensities. Histograms of the y-position co-ordinate, recorded at different laser intensities are plotted in **Figure 20**.

Figure 20. Histograms of the y-position coordinate for the laser spot ($\sim 25 \mu\text{m}$ size) imaged with a $8 \times 8 \text{ mm}^2$ PSAPD at different optical intensities.

noise effects of the device and the external electronics start playing a role, which leads to the observed degradation in the resolution. We also measured the spatial resolution of these PSAPDs at different spots on their surface (such as center and corners) and the results were similar to those shown in **Figure 21**.

Similar measurements were also performed with the $14 \times 14 \text{ mm}^2$ PSAPD in a related research effort. The intrinsic spatial resolution in this case was about 0.3 mm (FWHM) at high laser intensity ($\sim 50,000$ photons/pulse). This spatial resolution is slightly worse than that for 8 mm PSAPD due to higher noise for 14 mm devices. Such PSAPDs were then incorporated in a hybrid tube structure as discussed in detail in the following section.

Figure 21. Spatial resolution as a function of laser intensity for an $8 \times 8 \text{ mm}^2$ PSAPD with four corner anode design at 25°C .

D. HYBRID POSITION SENSITIVE APD FABRICATION

Once the PSAPDs were fabricated and evaluated, they were incorporated inside a tube body to build a hybrid device. The device consists of a planar, high gain PSAPD which is placed inside a vacuum tube enclosure with a light sensitive photocathode placed at the optical entrance face of the device (see **Figure 1**). In this device, when the optical photons strike the photocathode, it converts them into electrons, which are accelerated to energy of at least few keV when they reach the surface of the PSAPD. The incident photoelectrons then produce several thousand carriers in the PSAPD, each of which subsequently experiences an avalanche gain of several thousand. The hybrid design that we plan to explore is of the proximity type in which the photocathode and the PSAPD are kept close to each other to preserve spatial information. In this design, the area of the PSAPD

determines the imaging area of the device. The main advantage of the hybrid device over a bare PSAPD is the additional, noise-free gain stage due to acceleration of photoelectrons emitted by the photocathode to energy of few keV. This additional gain would allow the hybrid devices to perform imaging with high spatial resolution at significantly lower optical intensity than the bare PSAPDs, which was indeed observed in the Phase I research.

In our research, we have built the proposed hybrid device that consisted of a $14 \times 14 \text{ mm}^2$ PSAPD (with the four corner contact design) and a GaAs photocathode. The position sensitive APD was built at RMD and was placed inside a vacuum tube structure having a GaAs photocathode at ITT Night Vision. The photocathode-to-PSAPD distance was $\sim 5 \text{ mm}$ in the Phase I design. The tube body design that we used in the Phase I research consisted of several standard components that are integrated into the existing fabrication setup at our subcontractor's site (ITT Night Vision). The tube body consists of a stack of ceramic rings with a metal cup on top and a custom built ceramic plate with electrical feedthrough pins on the bottom. In our hybrid design with position sensitive APD (see **Figure 22**), the ceramic back-plate has four anode contact feedthrough pins and two alignment pins for a retainer piece that keeps the PSAPD aligned with the anode contacts. A tab piece located one ring above the plane of the APD was used to push the APD down against the anode contacts on the back plate. The tab piece was also used to apply a bias to the APD cathode. Indium and conductive polyimide were used to connect the back anodes on the PSAPD to the contact pads on the ceramic substrate of the tube body.

Figure 22. Tube body mount for the Hybrid position sensitive APD. The contact pins are brazed into a ceramic disk, which is brazed onto the back of a stack of ceramic rings and a metal cup. This assembly is compatible with commercial tube manufacturing processes. The picture in the middle shows the tube body mount inside the research-grade vacuum chamber. The diagram on the right shows a detail of the use of conductive material to ensure electrical continuity between the APD and the anode contact feedthroughs.

GaAs photocathode was fabricated on a glass face-plate (18 mm diameter, 2 mm thick with refractive index of 1.48) that was sealed to the cup on the top of the tube assembly using indium. **Figure 23** shows a photograph of a hybrid position sensitive avalanche photodiode fabricated in this manner. GaAs was used as the photocathode material for much of the Phase I research. GaAs has been selected as the photocathode because its quantum efficiency is high compared to that for traditional bialkali photocathodes. In addition to the hybrid devices fabricated using the “standard” GaAs photocathodes, some runs were also performed using the new, “blue-enhanced” GaAs photocathodes as well as GaAsP, AlGaAs and bialkali photocathodes that our ITT collaborators are developing. Such hybrid PSAPDs were then extensively evaluated in the Phase I project at RMD in collaboration with Dr. Cushman at the University of Minnesota.

Figure 23. Photograph of hybrid device with a PSAPD and GaAs photocathode.

E. EVALUATION OF HPSAPDs

During the Phase I project, we initially performed evaluation of the basic HPSAPD properties such as gain, noise, and quantum efficiency.

1. Gain Measurements

The gain of the hybrid device was measured by irradiating the photocathode with a pulsed LED ($\lambda = 575$ nm) and measuring the response of the hybrid device on a digital oscilloscope. Two experiments were performed. In the first experiment the PSAPD bias (V_{APD}) was kept constant and the response of the hybrid tube was recorded as a function of the photocathode bias (V_{PC}) to determine the relationship between the gain of the first-stage and V_{PC} . In second case, the photocathode bias (V_{PC}) was kept constant and the response of the hybrid device was recorded as a function of the PSAPD bias (V_{APD}). This allowed us to determine the PSAPD (or second-stage) gain versus V_{APD} relationship.

a. First-Stage Gain versus V_{PC}

The first stage gain due to acceleration of the photoelectrons emitted by the photocathode upon irradiation with a pulsed LED ($\lambda = 575$ nm) was measured in this study as a function of the photocathode bias (V_{PC}). The PSAPD bias was kept constant ($V_{APD} = 1750$ V) and the response of the hybrid device was recorded as V_{PC} was varied from 0 to 8 kV. The response of the hybrid device at photocathode bias of 0 V was considered to be the unity gain value (for the first-stage). The response at higher photocathode bias values was normalized with respect to this unity gain value to determine the gain (of the first-stage) versus photocathode bias relationship as shown in **Figure 24**. At photocathode bias in range of 1.5 – 2 kV, the first-stage gain is relatively low (< 100). At the photocathode bias of 8 kV, the first-stage gain is ~ 1000 . Similar first-stage gain versus V_{PC} measurements were also performed at other constant V_{APD} value of 1400 V and the results were found to be very similar to those shown in **Figure 24**. It should be noted that the effect of silicon conversion efficiency (E_{pair}) is included in the first-stage gain shown in **Figure 24**.

b. Second-Stage (PSAPD) Gain versus V_{APD}

In order to record the PSAPD gain as a function of the bias applied to it for the hybrid device (see **Figure 25**), the photocathode bias (V_{PC}) was kept constant at 5 kV and the PSAPD bias (V_{APD}) was varied from 200 to 1800 V. The response of the hybrid device

Figure 24. Gain of the first-stage of the hybrid device as a function of the photocathode bias (V_{PC}). Gain of ~ 1000 is achieved at $V_{PC} = 8$ kV.

Figure 25. Second-stage (or PSAPD) gain as a function of the bias (V_{APD}) applied to it.

was recorded upon constant irradiation with a pulsed LED ($\lambda = 575$ nm) on a digital oscilloscope. The response of the PSAPD at low V_{APD} value (≤ 200 V) corresponds to the unity gain value. The response at higher V_{APD} values was normalized with respect to this unity gain value. **Figure 25** shows the PSAPD gain versus PSAPD bias (V_{APD}) relationship, determined in this manner at a constant photocathode bias value ($V_{PC} = 5$ kV). As seen in the figure, the PSAPD gain is relatively small (< 20) at V_{APD} up to 1500 V, and then increases rapidly near the breakdown voltage of 1800 V. At V_{APD} of 1750, the gain is ~ 1000 and increases to about 4300 at 1800 V. PSAPD gain versus V_{APD} curve was also recorded with no bias applied to the photocathode ($V_{PC} = 0$ V) and the results were found to be similar to those shown in **Figure 25**.

Based on these measurement, the overall gain of the hybrid device, which is essentially a multiplication of the first-stage gain (the photoelectron acceleration step) and the second-stage gain (intrinsic APD gain) exceeds 10^6 at $V_{PC} \geq 8$ kV and $V_{APD} \geq 1750$ (see **Figures 24 & 25**). A 3-D representation of this overall gain as a function of V_{PC} and V_{APD} is shown in **Figure 26**.

Figure 26. A 3-D plot showing overall gain of the hybrid device as a function of the bias applied to the photocathode (V_{PC}) and the PSAPD (V_{APD}).

2. Noise Measurements

The noise of the hybrid device was measured during the Phase I project upon operation at photocathode bias (V_{PC}) of 8 kV and PSAPD bias (V_{APD}) of 1750 V. The dark current of the tube was measured to be $0.5 \mu\text{A}$ under these conditions. The PSAPD was irradiated directly with ^{109}Cd photons (22 keV) through the glass face-plate of the hybrid tube and the resulting energy spectrum was acquired along with a test pulse spectrum as shown in **Figure 27**.

Shaping time of $0.25 \mu\text{s}$ was used in this experiment. From the calibration of the energy scale for PSAPD provided by the ^{109}Cd spectrum, the broadening of the test pulse spectrum was estimated to be ~ 2.8 keV (FWHM). It should be noted that this noise measurement does not include the effect of the first stage gain (of ~ 1000 at V_{PC} of 8 kV) arising from the acceleration of the photoelectrons emitted by the photocathode. As a result, the effective noise of the hybrid device is 2.8 eV (FWHM) or 0.3 electrons (rms), which is impressive. This noise is ~ 900 times lower than the noise of the PSAPD without the first-stage gain. Such low noise of the hybrid device should allow detection and imaging of low intensity optical exposures at room temperature.

Figure 27. Noise estimation for the PSAPD in the hybrid device using direct interaction of 22 keV photons (^{109}Cs source) with PSAPD for calibration. Using a test pulse, the noise was estimated to be 2.8 keV for the PSAPD placed in the hybrid device at $V_{\text{APD}} = 1750$ V and $V_{\text{PC}} = 8$ kV. The overall noise of the hybrid device can be estimated to be ~ 0.3 electrons (rms) by taking into account the first-stage gain of 1000 at $V_{\text{PC}} = 8$ kV.

3. Quantum Efficiency

The quantum efficiency of the HPSAPDs with a standard GaAs photocathode was measured by recording the photocurrent produced in response to light from a grating monochromator. The current was calibrated to compute absolute quantum efficiency using a standard visible light reference photodiode calibrated for responsivity in A/W. The photo-response from the hybrid device was recorded with $V_{\text{PC}} = 0$ kV and $V_{\text{APD}} = 200$ V where the gain of both stages is close to unity. The resulting quantum efficiency curve for the hybrid device is shown in **Figure 28** and the quantum efficiency was estimated to be $> 30\%$ in the 500-800 nm region. While the quantum efficiency of this device is quite good at wavelength > 500 nm, its blue response is low. Alternative photocathodes were explored in the Phase I research for improving the blue response of the hybrid devices, as discussed in detail in a later section.

Figure 28. Quantum efficiency versus wavelength for a hybrid PSAPD with ITT's standard GaAs photocathode.

4. Timing Resolution

The timing resolution of the hybrid PSAPD was also measured in the Phase I project. During the experiment, an optical fiber illuminated with a pulsed LED provided the input signal ($\sim 30\text{k}$ photons/pulse) for the hybrid PSAPD and a PMT placed in a coincidence timing circuit. The PMT channel served as the “start” channel of the timing circuit while HPSAPD served as the “stop” channel. The signal from each detector (with fixed delay between them) was processed with a

timing filter amplifier and timing SCA, and then fed to a time-to-amplitude converter (TAC). The output of the TAC was recorded on a multichannel analyzer placed in a personal computer to generate a timing spectrum that is shown in **Figure 29**. The timing resolution of the system was recorded to be ~ 3 ns (FWHM) at room temperature, which is promising. Further improvement in the timing resolution should be possible upon optimization of the electronic setup.

5. Single Photoelectron Detection

When a single photoelectron released by the photocathode hits the APD surface, the generated charge can produce a single photoelectron peak in the energy spectrum. In order to successfully detect such single photoelectrons, the noise of the device needs to be sufficiently low.

During the Phase I project, we have performed an experiment to detect single photoelectrons with the hybrid PSAPD. The device was cooled to about 0°C in order to reduce the noise. Such cooling reduces the dark current of the PSAPD as well as the thermal generation of photoelectrons from the GaAs photocathode. The photocathode of the hybrid tube was biased at 5.6 kV in this study while the PSAPD was biased at 1600 V. The PSAPD gain at this bias was ~ 300 . For calibration of the energy scale, direct interaction of 22 keV photons (^{109}Cd) source with PSAPD through the glass face-plate was utilized as shown in the energy spectrum in **Figure 30**. The

photocathode of the PSAPD was then illuminated with a weak light source and the resulting pulse height spectrum is also shown in **Figure 30**. As seen in the spectrum, a peak appears at energy of ~ 6 keV which corresponds to detection of single photoelectrons in view of the photocathode bias of 5.6 kV. Additional features corresponding to detection of 2 and 3 photoelectrons are also visible in spectrum.

Figure 29. Coincidence timing spectrum recorded with a hybrid PSAPD and a PMT operating in timing circuit. Both detectors were irradiated with an LED optical pulse.

Figure 30. Energy spectrum showing single photoelectron peak with HPSAPD.

F. SPATIAL RESOLUTION MEASUREMENTS

We have conducted detailed characterization of the intrinsic spatial resolution of the hybrid PSAPDs during the Phase I project. In this experiment, a 635nm laser was focused onto the photocathode of the hybrid PSAPD with a spot size of approximately 25 μm . The laser was pulsed at a high frequency and the output voltages of the four bottom contacts of the PSAPD inside the hybrid device were noted directly out of the preamplifiers on a digital oscilloscope. This was repeated until a large number of measurements were taken at the same laser position on the photocathode. The x- and y-positions were calculated and plotted for all the data points, and the FWHM of the histograms for both co-ordinates provided the estimate of the position resolution of the hybrid PSAPD at that location. Similar measurements were then carried out as the laser intensity was varied in order to study the change in spatial resolution as a function of the incident optical intensity. **Figure 31** shows the images of the optical

Figure 31. Images of a 25 μm laser spot recorded with a hybrid device at different incident intensities.

spot recorded at different laser intensities. Histograms of the x-position co-ordinate, recorded at different laser intensities are plotted in **Figure 32**. From the data shown in **Figure 32**, the spatial resolution as a function of incident optical intensity was estimated and the results are shown in **Figure 33**. As seen in the figure, even at low laser intensity (~ 5 photons/pulse), the spatial resolution of the device is ~ 0.3 mm-FWHM and it remained relatively unchanged as small variations were made in the laser intensity. At high optical intensity ($>50\text{k}$ photons/pulse), the spatial resolution was <0.2 mm (FWHM), which is similar to the intrinsic spatial resolution of the PSAPD. As seen in **Figure 33**, the main advantage of the hybrid device is its high resolution at low intensities, which is possible due to its

Figure 32. Histograms of the x-position co-ordinate for the laser spot images recorded with the hybrid device at different intensities.

Figure 33. Spatial resolution versus intensity of the optical pulse for a hybrid PSAPD.

much higher gain compared to a PSAPD.

The imaging performance of the hybrid PSAPD at low optical intensity has also been evaluated in our research. Initially, a dark count image was acquired at room temperature with a photocathode bias of 8 kV and PSAPD bias of 1750 V. Next an image of a 200 micron spot from a 632 nm LED scanned at 2 mm intervals over a 5x5 grid near the middle of the device with a photocathode bias of 4 kV was acquired. Each LED

pulse contained approximately 10 photons. Both the dark count image and the LED spot image are shown in **Figure 34**. As seen in the figure, even at such low optical exposure, excellent spatial resolution (<0.5 mm) is observed, which is due to very high signal to noise ratio of the hybrid device. This results in good agreement with the data shown in **Figure 33**. Some pincushion distortion is observed, which is an inherent property of the position sensitive device with four corner anode design (as discussed earlier). Such distortion can be corrected in software using a previously generated calibration map.

Figure 34. Images acquired with the hybrid device. On left is the dark count image acquired at photocathode bias of 8 kV. On right is an image of a 200 μm LED spot in 5 x 5 format with 2 mm spacing between spots and 10 optical photons/pulse recorded at photocathode bias of 4 kV.

Overall, the data shown in **Figure 34** illustrate that the hybrid device is capable of detecting low intensity signal, and it can provide high spatial resolution. These results are very encouraging.

G. GAMMA RAY SPECTROSCOPY WITH HYBRID PSAPDS

During the Phase I project, we have performed gamma ray detection studies using the hybrid PSAPDs. The hybrid PSAPD was coupled to a CsI(Tl) crystal ($1 \times 1 \times 1 \text{ cm}^3$) and irradiated with isotopic sources such as ^{241}Am (60 keV photons) and ^{137}Cs (662 keV photons). The photocathode bias was adjusted to be in 5-8 kV range while the PSAPD bias was kept at 1750 V. The signal from the top contact of the PSAPD was processed with a preamplifier (Cremat #102B), spectroscopy amplifier (Canberra #2022) and then fed to a multi-channel analyzer residing in a personal computer. The shaping time of the spectroscopy amplifier was kept at 4 μs in view of decay time constant of $\sim 1 \mu\text{s}$ for CsI(Tl) scintillator. It should be noted that the peak emission wavelength of CsI(Tl) is 540 nm, which is a good match for the spectral response of the hybrid PSAPD with GaAs photocathode. **Figure 35** shows ^{241}Am and ^{137}Cs gamma ray spectra collected with the hybrid device coupled to a CsI(Tl) scintillator. The energy resolution of the 662 keV peak is $\sim 9\%$ (FWHM) and that of 60 keV peak is 16% (FWHM) at room temperature. For both isotopes, best results were obtained at high photocathode bias (> 5 kV) as expected due to increased gain of the hybrid device. These results clearly demonstrate possibility of room temperature gamma ray spectroscopy with the hybrid devices coupled to inorganic scintillators. Further improvement in the gamma ray energy resolution of the hybrid devices (coupled to CsI(Tl) and other inorganic scintillators) should be possible in the Phase II project upon optimization of the uniformity and spectral response of the hybrid device as well as the scintillator coupling issues.

H. GAMMA RAY IMAGING STUDIES WITH HYBRID PSAPDS

During the Phase I project, we performed imaging studies by coupling the HPSAPDs to segmented CsI(Tl) arrays with varying pixel sizes. The purpose of this study was to characterize gamma ray imaging performance of the hybrid PSAPDs. Since the signal to noise ratio of the hybrid PSAPDs is excellent, these imaging studies were conducted with low energy gamma rays such as 60 keV photons from ^{241}Am source.

For such imaging studies with hybrid PSAPDs, we have available a readout system with 5 separate channels. Each channel consists of a pre-amplification stage (Cremat #102B), a shaping stage (Canberra #2020), and a sample-and-hold stage. The static detector signals are sampled by a 12-bit A/D conversion card from Keithley. Upon a lower-level-discriminator trigger on the 5th input (top contact of the PSAPD), the digitizer simultaneously captures and converts all 5 signals from the hybrid PSAPD readout sample-and-hold circuitry. Four of the signals are used to generate position and the fifth, the trigger signal, is used for pulse-height analysis. The digitizer is installed in a laboratory computer running Microsoft (MS) Windows 98. MS Visual BASIC and DriverLINX are used to control the I/O card, and to manipulate, display and store the results.

Figure 35. ^{241}Am and ^{137}Cs spectra recorded with the hybrid PSAPD coupled to a 1 cm³ CsI(Tl) scintillator at room temperature. The energy resolution of 60 keV and 662 keV photopeaks is 16% (FWHM) and 9% (FWHM), respectively.

1. Histograms with 4 x 4 CsI(Tl) Array (2 mm Pixels)

First, we conducted an experiment to acquire a flood histogram with a 4 x 4 array of segmented CsI(Tl) crystals placed on a hybrid PSAPD. The pixel size of the CsI(Tl) array was 2 mm (with 5 mm thickness) and a ^{241}Am (60 keV γ -rays) source was used to excite the scintillation segments. The resulting flood histogram is shown in **Figure 36** (in both 2-D and 3-D formats), where all the scintillation segments are well separated.

This imaging study, performed at room temperature, clearly demonstrates that the hybrid PSAPD can provide unambiguous identification of crystal of interaction. As expected, minor pincushion distortion is observed in the flood image, which can be corrected in using a prior calibration map of the device. As seen in the 3-D view of the flood histogram, excellent peak to valley ratio ($\sim 7:1$) is observed in the flood image.

2. Histograms with 4 x 4 CsI(Tl) Array (1 mm Pixels)

Encouraged by the excellent imaging results obtained with the hybrid PSAPD coupled to CsI(Tl) arrays with 2 mm pixels, we continued the studies with a higher resolution CsI(Tl) array. The format of the new CsI(Tl) array was 4 x 4 elements with pixel size of 1 mm and thickness of 5 mm. This array was coupled to the hybrid PSAPD and the scintillation segments were irradiated with ^{241}Am source (60 keV photons) at room temperature. A flood image acquired in this manner is shown in **Figure 37**. Excellent separation between CsI(Tl) pixels is observed indicating that the hybrid device is capable of providing very high spatial resolution (< 1 mm) for scintillator imaging at room temperature.

Figure 36. Flood histogram images in 2-D (left) and 3-D (right) format acquired upon coupling the hybrid PSAPD to a 4 x 4 element CsI(Tl) array (2 mm pixels, 5 mm tall). ^{241}Am source (60 keV photons) irradiated the CsI(Tl) pixels in this study conducted at room temperature. As seen in the figure, all 16 elements of CsI(Tl) are clearly visible in the images.

This study confirms that the hybrid device can play an important role in high resolution gamma-ray imaging studies using segmented scintillators at room temperature. The ability of identifying 1 mm scintillation pixels upon exposure to low energy photons such as 60 keV γ -rays (^{241}Am) source is particularly impressive. It should be noted that when position sensitive APDs are directly coupled to the CsI(Tl) arrays (1-2 mm pixels) and irradiated with 60 keV photons, identification of individual scintillation segments is not possible at room temperature due to poorer signal to noise ratio of the PSAPD compared to the hybrid device. Thus, the additional gain provided by the photocathode stage is important for high resolution imaging studies at low exposure levels.

Figure 37. Flood histogram images in 2-D (left) and 3-D (right) format acquired upon coupling the hybrid PSAPD to a 4 x 4 element CsI(Tl) array (1 mm pixels, 5 mm tall). ^{241}Am source (60 keV photons) irradiated the CsI(Tl) pixels in this study conducted at room temperature. As seen in the figure, all 16 elements of CsI(Tl) are clearly visible in the images.

I. ALTERNATIVE PHOTOCATHODES

In addition to the standard GaAs photocathodes, our ITT collaborators have also evaluated alternative photocathodes with higher quantum efficiency in the blue region. This included thin GaAs photocathodes that exhibit higher blue response than the standard GaAs ones. In addition, bialkali, GaAsP, and AlGaAs photocathodes have also been investigated by our ITT collaborators. **Figure 38** shows quantum efficiency versus wavelength relationship for these alternative photocathodes, measured at ITT. Comparison of the results shown in **Figure 38** and **Figure 28** indicates that the quantum efficiency in the blue region is substantially higher for these alternative photocathodes compared to that for the standard GaAs ones. We used the thin GaAs photocathode for construction of a hybrid PSAPD with high blue response during the Phase I project. This photocathode was selected due to its high quantum efficiency in 350-450 nm region (where a number of scintillators such as LSO, NaI(Tl) and LaBr₃:Ce emit) compared to the other photocathodes. Our ITT collaborators fabricated a hybrid device with such a photocathode and RMD's standard 14 x 14 mm² position sensitive APD. These hybrid devices were then tested with NaI(Tl) and LSO scintillators that emit in the blue region ($\lambda_{\text{max}} = 415$ nm for NaI(Tl) and $\lambda_{\text{max}} = 420$ nm for LSO).

Figure 38. Quantum efficiency versus wavelength for bialkali, GaAsP, AlGaAs, and thin GaAs photocathodes fabricated at ITT.

For energy resolution measurements a NaI(Tl) crystal was coupled to the input glass window of the hybrid device and was irradiated with 662 keV gamma rays (¹³⁷Cs source). The photocathode bias was set at 5 KV and the PSAPD bias was set at 1750 V in this study and the resulting gamma-ray spectrum is shown in **Figure 39a**. The energy resolution of the 662 keV photopeak was estimated to be ~9% (FWHM) at room temperature in this study. This result confirms successful fabrication and operation of a blue enhanced HPSAPD.

Figure 39a. ¹³⁷Cs spectrum (662 keV γ -rays) recorded with a HPSAPD (having a thin, blue enhanced GaAs photocathode) coupled to a NaI(Tl) scintillator at room temperature.

For timing resolution measurements with HPSAPD we used LSO scintillators in view of their fast response. The timing resolution of the new hybrid PSAPD coupled to LSO crystal was measured in coincidence with another LSO scintillator coupled to a PMT. The LSO-PMT detector operated as a “start” detector in a timing setup while the hybrid PSAPD-LSO detector operated as a “stop” detector in the timing setup. Both detectors were irradiated with 511 keV gamma-ray pairs emitted by a ²²Na source. The signal from each detector (with a fixed delay between them) was fed to a timing filter amplifier (TFA), a timing SCA and then to a time-to-amplitude converter (TAC). The TAC output was fed to a multichannel analyzer to collect a

coincidence timing spectrum (as shown in **Figure 39b**). The timing resolution was measured to be 3.5 ns (FWHM) at room temperature. Further optimization of the blue enhanced hybrid devices will be carried out in the Phase II project.

J. LITERATURE CITED

Aeibi, V.W., G.A. Davis, *A GaAsP Photocathode with 40% QE at 550 nm*, J.P. Edgecumbe, Society of Photo-Optical and Instrumentation Engineers, Vol 1655, Electron Tubes and Image Intensifiers, (1992).

P. Burger, M. Keters, L. Van Buul, J. Verplancke, *New Generation of Position Sensitive Silicon Detectors*, Presented at the Fall MRS Meeting, Boston, December (1997).

P. Cushman, A. Heering, and A. Ronzhin, *Custom HPD readout for the CMS HCAL*, Nuc. Inst. and Meth. in Phys. Res., A442, p. 289, (2000).

Farrell, R. *et al.*, *Large Area Silicon Avalanche Photodiodes for Scintillation Detectors*, Nucl. Inst. and Meth., **A288**, p. 137, (1990).

Farrell, R., K. Vanderpuye, G. Entine, and M.R. Squillante, *High Resolution, Low Energy Avalanche Photodiode X-ray Detectors*, IEEE Trans. Nuc. Sci., **NS-38**, p. 144, (1991).

Farrell, R., K. Vanderpuye, L. Cirignano, M.R. Squillante, *Radiation Detection Performance of Very High Gain Avalanche Photodiodes*, Nucl. Inst. and Meth., **A353**, p. 176 (1994).

R. Grazioso, R. Farrell, K.S. Shah, J. Glodo, *A Novel Distortion-Free Position Sensitive APD for Nuclear Imaging*, Presented at IEEE Nucl. Sci. Symp., Norfolk, VA, Nov., 2002.

Huth, G.C., IEEE Trans. Nucl. Sci NS-13 (1966) 36.

N. Kanaya, *HPD for linear colliders*, Nuc. Inst. and Meth. in Phys. Res., A442, p. 295, (2000).

K. Kleinknecht, **Detectors for Particle Radiation**, 2nd Edition, Cambridge University Press, Cambridge, U.K. (1998).

G.F. Knoll, **Radiation Detection and Measurement**, 3rd Edition, John Wiley & Sons, NY, (1999).

M. Lampton and C.W. Carlson, *Low-distortion, resistive anodes for two-dimensional position sensitive MCP systems*, Rev. Sci. Instrum. 50(9) Sept. (1979).

C. Martin, P. Jelinsky, M. Lampton, R.F. Malina, and H.O. Anger, *Wedge and strip anodes for centroid-finding position sensitive photon and particle detectors*, Rev. Sci. Instrum. 52(7) 1981.

Radeka, V., *Low-Noise Techniques in Detectors*, Ann. Rev. Nucl. Part. Sci., **38**, p. 217, (1988).

Redus, R. and Farrell, R. *Gain and Noise in Very High Avalanche Photodiodes: Theory and Experiment*. SPIE Vol.2859, p.288, (1996).

D.G. Sarantites et al., Nucl. Inst. Meth. Phys. Res. A381 (1996) 418

K.S. Shah, J. Glodo, W.W. Moses, S.E. Derenzo, M.J. Weber, *LaBr₃:Ce Scintillators for γ -Ray Spectroscopy*, Presented at IEEE Nucl. Sci. Symp., Norfolk, VA, Nov., 2002b.

K.S. Shah, R. Farrell, R. Grazioso, E. Harmon, and E. Karplus, *Position-Sensitive Avalanche Photodiodes for Gamma-Ray Imaging*, IEEE Transactions on Nucl. Sci., Vol. **49**, August 2002.

K.S. Shah, R. Farrell et al., *Large Area APDs and Monolithic APD Arrays*, IEEE Trans. Nuc. Sci., V. 48(6), p. 2352 (2001).

K.S. Shah, Gothoskar, P., Farrell, R and Gordon, J. *High Efficiency Detection of Tritium Using Silicon Avalanche Photodiodes*. IEEE Trans. Nuc. Sci., 44, No. 3, 885-889, June (1997).

JA Sorenson, ME Phelps, **Physics in Nuclear Medicine**, W.B. Saunders Company, Philadelphia, (1987).

Sze, S.M., **Physics of Semiconductor Devices**, Wiley, New York, (1981).

E.V.D. van Loef, P. Dorenbos, C.W.E. van Ejik, K. Kramer, and H.U. Gudel, *High Energy Resolution Scintillator: Ce^{3+} Activated $LaBr_3$* , Appl. Phys. Lett., 79(10), p.1573, (2001a).