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Spectral Characterisation of a Blue-enhanced Silicon Photodetector [1]

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Abstract

In this work we report on spectral response data and gamma ray spectroscopy measurements using two newly developed silicon photodetectors that are designed to have enhanced sensitivity in the blue spectral region. The enhanced sensitivity is a result of our newly developed ion implantation profile used to create the active area of the photodetector. The quantum efficiency of the new photodetectors (without any optimised antireflective coating) has been measured to be ~40% at a wavelength of 420nm. Gamma ray spectroscopy experiments have been performed using a CsI(Tl) and a LSO crystal excited by a ^{137}Cs or ^{22}Na source and read out by the new photodetectors. We have measured an energy resolution of 7.7% and 22.7% FWHM for the 662 keV gamma rays from a ^{137}Cs for the CsI(Tl) and LSO scintillator crystal respectively. We intend to use the photodetectors, in the form of a detector array optically coupled to CsI(Tl) or LSO, in the development of a new scintillator detector module for use in positron emission tomography.

I. INTRODUCTION

The ultimate aim of this research is to produce a new detector module suitable for use in positron emission tomography. The design of the detector module will not include photomultiplier tubes, instead an array of silicon photodiodes (PDs) will be used to readout the scintillation crystals. In this case the necessary timing signal and energy signal must be generated solely from the PDs. The present article centres on the development of such PDs. We use a unique ion implantation technique to create the active region optically coupled to the scintillator crystals. The technique gives rise to enhanced sensitivity in the blue spectral region, where many common scintillation crystal emission spectra peak, while still maintaining good charge collection properties, ensuring a fast rise time of the detector signal for timing purposes.

In designing the new detector module we have performed extensive Monte Carlo simulations based on using the new PD as part of an 8x8 silicon pixel array coupled to a 25x25x3 mm^3 LSO or CsI(Tl) scintillator crystal. The simulations predicted that for any position of a gamma ray interaction in the scintillator crystal, the spatial resolution and signal-to-noise ratio (S/N) obtained by the new detector arrangement would be satisfactory in order to obtain the gamma ray interaction position in the plane of the silicon photodetector.

The detector arrangement can then be configured to form a PET detector module with total dimensions 4x25x80 mm^3, which includes associated readout electronics. In our module the pixel photodetectors (with an effective active area of 25x25 mm^2) are placed on the side of the scintillator crystal with matched surface dimensions. More details on the PET module design will be discussed elsewhere.

The new detectors, designed by the Centre for Medical Radiation Physics at the University of Wollongong in collaboration with the High Energy Physics Department, University of Melbourne, were produced by SPA "Detector", Ukraine. This work concentrates on the spectral performance of the new photodetector using optical excitation spectroscopy and gamma ray spectroscopy.

II. METHODS

A. Spectral Response

The spectral response of the photodetectors was determined by using standard modulation techniques. The light from a quartz-halogen lamp, operated at a constant current, was chopped and focussed on the entrance slit of a one-metre spectrometer (SPEX model 1704). The light exiting the spectrometer passed through a 1mm iris before being incident on the photodetector. The photodetectors were positioned accurately at a constant distance from the iris and the incident beam was carefully centred on the photodetector. The lamp power was monitored and fluctuations in the lamp power of order 1% could be observed in the response of the photodetectors. The linearity and modulation frequency independence of the measured response was checked.

Under the same experimental conditions the spectral response of a Hamamatsu (model S3590-08) photodiode was measured. Using this data and the specification data sheets provided by Hamamatsu, the absolute responsivity and corresponding quantum efficiency of the photodiodes could then be deduced. More details are given in section IV-B.

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B. Gamma Ray Spectroscopy

Room temperature spectroscopy experiments were performed on the isolated photodetector elements. The photodetectors were optically coupled to a 4x4x10 mm^3 LSO crystal (purchased from CTI™) or a 3x3x3 mm^3 CsI(Tl) crystal (purchased from AMCRYS-H™) using BICRON™ optical grease. All the LSO crystal surfaces were highly polished. All of the CsI(Tl) crystal surfaces were smooth but not polished. Crystal surfaces not in contact with the photodetector were covered with several layers of Teflon™ tape.

The scintillators were excited using a ^{137}Cs and a ^{22}Na source. The spectroscopy readout arrangement comprised of an ORTEC™ 142A preamplifier and an ORTEC™ 671, spectroscopy amplifier. A PC, using software supplied with the MCA, collected the data via an AMPTEK™ 8000A MCA.

III. NEW DETECTOR DESIGN

The ultimate aim of the present work is to develop a detector module for use in positron emission tomography, which is completely independent of photomultiplier tubes. The new detector module will utilise 8x8 arrays of silicon photodiodes (each with a 3x3 mm^2 active area) to readout the scintillator crystal of interest. We have chosen silicon photodiodes as they are very robust and relatively cheap to manufacture. The main drawback in using photodiodes is that there is no internal amplification process involved in the conversion of the optical signal to an electrical signal. In this case careful design considerations must be taken into account to ensure a satisfactory signal to noise ratio is obtained.

We intend to use LSO or CsI(Tl) scintillator crystals in our module that have emission spectra which peak at 420 nm and 540 nm respectively. The absorption length of light with a wavelength of 420 nm is 0.1-0.2 μm[1]. In order to improve the sensitivity of the new photodiodes to the shorter of the two wavelengths (traditional silicon photodiodes are sufficiently sensitive to wavelengths around 540 nm) we are using a special (boron) ion implantation technique[2] to produce the p^--layer optically which is coupled to the scintillator crystal. The new technique allows the resulting electric field to extend very close to the p^- active surface, which has the dimensions of 3x3mm^2 for each pixel element in our array, when the PD is under bias while still maintaining the potential across the p^- surface. In effect we are able to improve the sensitivity of the PD in the blue spectral region, by reducing the effect of Auger recombination, while maintaining good charge collection properties to ensure fast timing signals for coincident detection techniques. We have optimised the trade-off between good spectral sensitivity (near 420 nm) and fast charge collection of the photodetectors by performing charge collection modelling of the new ion implantation profile using Integrated Systems Engineering (ISE) TCAD simulation software including (DESSIS, LIGAMENT, PROSIT, TE2DIOS)," Release 4.0 ed. Zurich.

Using this technique we have produced two new silicon photodiodes which should have an improved sensitivity in the blue spectral region as a result of the enhanced electric field at the surface of the PD. Schematic views of the two new detector designs are shown in Fig. 1. The two designs differ in that one has a uniform p^- layer at the surface and the other has p^+ strips embedded in the p^- layer. They are here-on in referred to as SPAD1 and SPAD2 respectively.

The two approaches in detector design were undertaken to investigate the effect of the p^+ strips in the uniform p^- layer on both the spectral response of the PD, especially in the region of 400 nm, and the timing properties of the PDs.

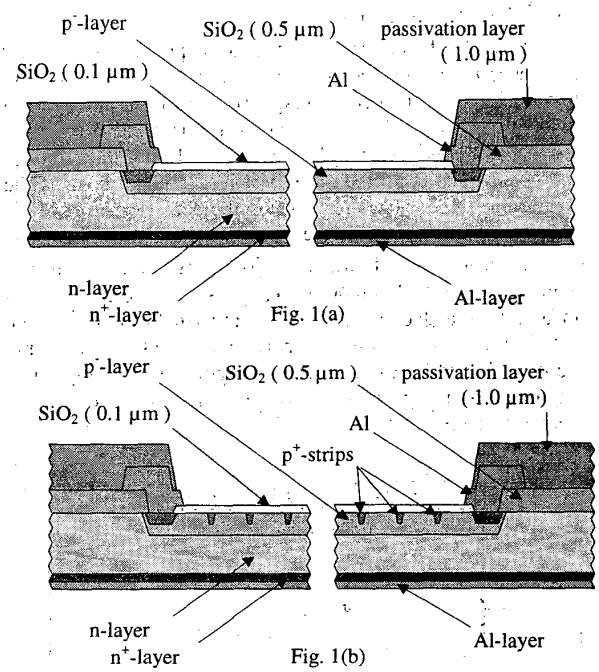

Fig. 1 Schematic diagram of the two detector designs under investigation. The main difference in the two designs is the introduction of a series of p^+ strips (as indicated in Fig 1b) in the uniform p^- layer which makes up the active region of the detectors. Fig. 1a is SPAD1 and Fig. 1b is SPAD2.

It should be noted that it is fairly common practice in the design of modern photodetectors to incorporate an optically transparent antireflective coating (ARC) that covers the active layer of the photodetector [1], in our case the p^- layer. The ARC acts as a quarter-wave plate to minimize reflections from the detector surface at a particular wavelength of interest, effectively improving the quantum efficiency of the PD. The wavelength of interest is determined by the thickness and the refractive index of the ARC. In the case of our detectors we have deliberately chosen not to use an ARC thickness which improves the measured quantum efficiency around 400 nm in an attempt to isolate the blue spectral sensitivity enhancement of the detector that results from our unique ion implantation technique.

The SPAD1 and SPAD2 photodetectors are operated at 40V and have a room temperature dark current of ~1.4 $nAcm^{-2}$ at this voltage. The results from experiments described within this paper arise from 5x5 mm^2 photodetectors individually mounted, but manufactured from the same wafer as the detector arrays. The photodiodes are

of a planar design consisting of a 3x3 mm^2 active area and are 300 μm thick. The active area is surrounded by a p^+ guard ring and all encircled by an n^+ ring. The detectors were produced by SPA "Detector" on high resistivity n-Si (Waker, resistivity 5kΩcm).

IV. RESULTS

A. Spectral Response

The ratio of the absolute spectral response between 380 nm and 700 nm for the two new photodetectors is shown in Fig. 2. The loss in spectral response due to the introduction of the p^+ strips in SPAD2 is evident in the relative response for wavelengths below 440 nm. Above 440 nm the effect of the p^+ strips is expected to be much less significant as the light on average travels further into the detector before being detected and the p^+ stirps are at a very shallow implantation depth. For $\lambda = 380$ nm there is a loss in spectral response of approximately 30% which corresponds to the effective loss in active area due to the finite width (in the plane of the detector surface) of the p^+ strips. For wavelengths around 700 nm the slight loss in spectral response is possibly due a slight difference in thickness of the silicon dioxide coating between the two detectors.

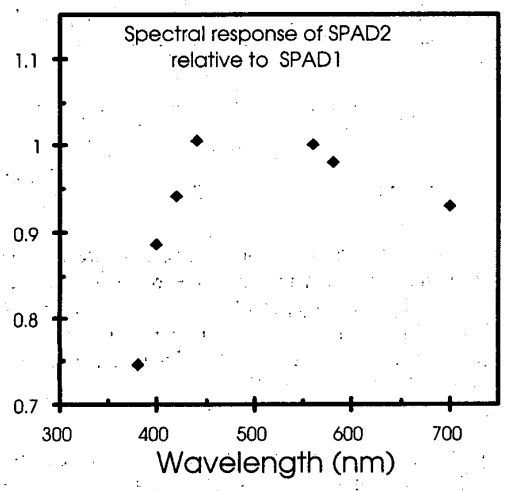

Fig. 2 Spectral response of SPAD2 relative to SPAD1. The significant loss in spectral response measured at 380 nm is due to the p+ layers embedded into the shallow p-layer that forms the active area of the photodiode.

Fig. 3 shows the spectral response of SPAD1 relative to the Hamamatsu S3590-08 over the wavelength range of 380 nm to 700 nm. The spectral response of the SPAD1 PD is less than that of the Hamamatu PD over most of the measured wavelength range. At 700 nm the spectral response of the SPAD1 PD is slightly greater than that of the Hamamatsu PD. These results can be explained in terms of the existing silicon dioxide coating acting as an antireflective coating for longer wavelengths in the case of the SPAD1 PD design. The current version of the photodetector was produced with a coating of silicon dioxide of thickness approximately 0.1 μm (in the plane perpendicular to the detector surface), which is not optimised for the blue spectral region. The Hamamatsu S3590-08 is optimised for detection of light in the blue spectral region and may account for the observed difference. Such optimisation has been shown[1] to have a significant tail which extends to longer wavelengths.

In Fig. 3 there is no measured effect of the ARC used in conjunction with SPAD1 in the wavelength region near 700 nm. It is not unreasonable to expect that the effect of the ARC for the SPAD1 PD will only be observed in the relative spectral response data near the peak of the SPAD1 PD spectral enhancement. Such a result is due to the increased absorption length (in the photodetector) of light with increasing wavelength combined with the tailing nature of the blue enhancement of the S3590-08 PD mentioned above.

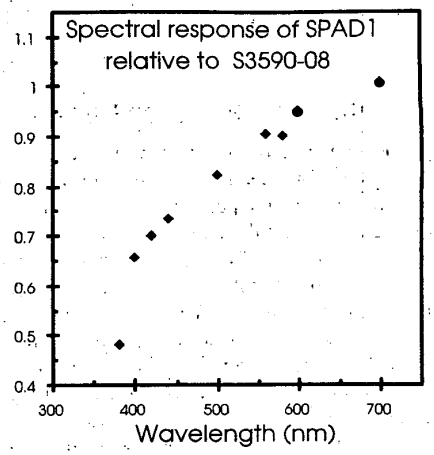

Fig. 3 Spectral response of SPAD1 relative to the Hamamatsu S3590-08, blue enhanced, photodiode.

B. Quantum Efficiency

The quantum efficiency, Q_e, of the SPAD1 photodetector was deduced using the Hamamatsu photodiode as a reference. The measured relative responsivity curve of the S3590-08 photodiode (corrected for the lamp output power dependence on the wavelength, which was independently determined using a photomultiplier tube) was in good agreement with the absolute responsivity, R, curve in the data sheets supplied by Hamamatsu. The quantum efficiency was then deduced using the relationship

$$Q_e = R(A/W) \times hf(eV) \qquad (1)$$

The values of were independently deduced using a second photodetector and found to be in good agreement. Fig. 4 shows the quantum efficiency of the SPAD1 photodiode over the wavelength range of 380 nm to 700 nm. The deduced quantum efficiency at 420 nm is ~40%. Holland et al.[1] used a different approach to design a photodiode array for PET by reducing the polysilicon layer associated with the n^+ contact layer to improve the quantum efficiency near 420 nm. In our diode we produce the n^+ rear contact via the classical ion implanted detector method using evaporated aluminium to produce the uniform potential across the rear surface of the 25x25 mm^2 array. Our deduced quantum efficiency indicates that the SPAD1 PD is

equivalent to a backside illuminated PD as produced by Holland et al. with a 20 nm polysilicon layer. According to the work of Holland et al.[1] we can expect the quantum efficiency to increase by a factor of ~1.7 when we incorporate an antireflective coating optimized for the collection of 420 nm light. This would mean we could expect the quantum efficiency to increase to nearly 70%.

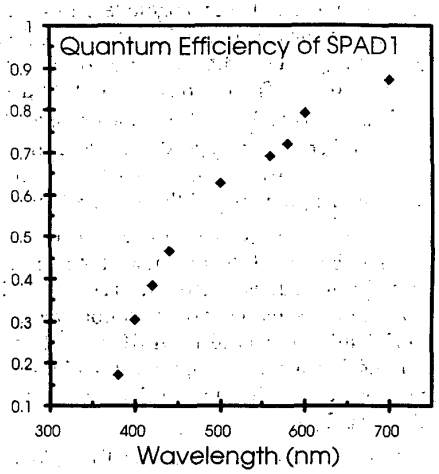

Fig. 4 Deduced quantum efficiency as a function of wavelength for the new photodiode, SPAD1.

C. Gamma Ray Spectroscopy

The SPAD1 PD was optically coupled, in separate experiments, to a 3x3x3 mm^3 CsI(Tl) scintillator crystal and a 4x4x10mm^3 LSO crystal. The results are shown in Fig. 5 and 7 respectively.

Fig. 5 shows the room temperature (298 K) pulse height spectrum resulting from a CsI(Tl) crystal excited by a ^{22}Na (spectrum I) and ^{137}Cs (spectrum II) source as measured by the SPAD1 PD. In these experiments a 3μs shaping time was used. Overlayed is the X-ray spectrum from a ^{137}Cs source (spectrum III) measured directly by the photodetector. The X-ray spectrum serves as a convenient benchmark for a calculation of the light collection efficiency. The observed feature in spectrum III results from the detection of the 32 and 36 keV X-ray emission (just unresolved).

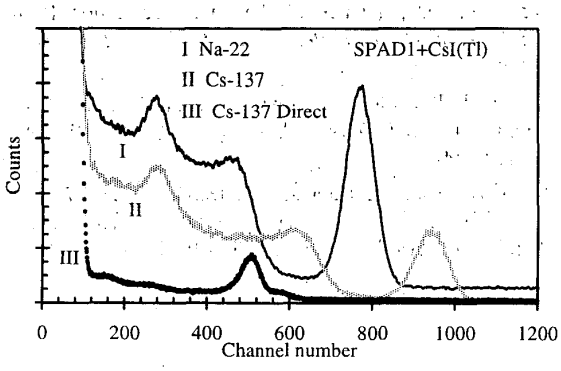

Fig. 5 Room temperature, pulse height spectrum of a 3x3x3 mm^3 CsI(Tl) crystal excited by I ^{22}Na and II ^{137}Cs read out by the SPAD1 PD. Spectrum III is the 32 and 36 keV X-ray spectrum of ^{137}Cs directly detected by the PD.

Fig. 6 shows the corresponding pulse height spectrum from a 4x4x10 mm^3 LSO crystal excited by a ^{22}Na (spectrum I) and ^{137}Cs (spectrum II) source and read out by the SPAD1 PD. In these experiments a 1μs shaping time was used. Again the X-ray spectrum from a ^{137}Cs source (spectrum III) is overlayed. Spectra III in Fig.7 has been scaled by a factor of ten above channel 275 for clarity.

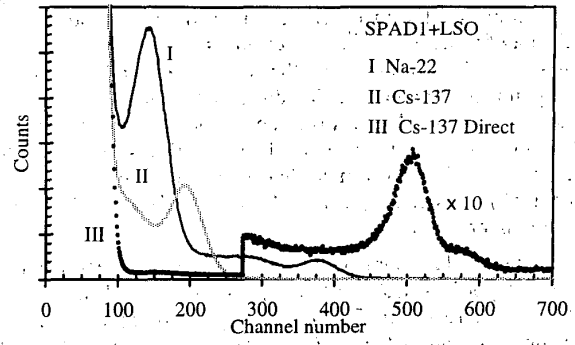

Fig. 6 Room temperature, pulse height spectrum of a LSO crystal excited by I ^{22}Na and II ^{137}Cs. The LSO crystal was read out by the SPAD1 PD. Spectrum III is the 32 and 36 keV X-ray spectrum of ^{137}Cs directly detected by the PD and is scaled by a factor of 10 beyond channel number 275 for clarity.

1) Energy resolution

Using the 3x3x3 mm^3 CsI(Tl) crystal optically coupled to the SPAD1 PD we measured an energy resolution of 7.7% FWHM when excited with 662 keV gamma rays from a ^{137}Cs source and 9.5% FWHM when excited with 511 keV gamma rays from a ^{22}Na source. These values compare very well with some of the best values quoted in the literature for silicon photodiodes. Varying the spectroscopy amplifier shaping time between 1 and 3 μs had no significant effect on the measured energy resolution. Operation outside these shaping times saw a measured degradation of the energy resolution.

The 4x4x10 mm^3 LSO crystal read out by the SPAD1 PD, had a measured energy resolution of 22.7% FWHM when excited with 662 keV gamma rays from a ^{137}Cs source. Excitation using the 511 keV and the 1275 keV gamma rays from a ^{22}Na source led to a measured energy resolution of 28.8% and 16% FWHM respectively. The measured energy resolution results LSO are also within the range of those quoted in the literature for readout schemes of scintillator crystals using silicon PDs.

It is not unreasonable to expect that the measured relative energy resolution for LSO should improve once we incorporate an antireflective coating optimised for wavelengths in region of 420 nm.

2) Light detection efficiency

The light detection efficiency refers to the calculated number of photons detected by the PD as a fraction (or percentage) of the absolute number of photons emitted by the scintillator crystal when excited by a photon of given energy.

The general method to maximise the light detection efficiency is to use several layers of Tefon™ tape. However, various scintillator crystal surface finishes ranging from chemical etching [3] to covering with millepore filter paper [4], for example, can have a significant effect on the overall light collection efficiency. Also, the effect of poor scintillator crystal coupling to detectors has been shown to be significant [4].

An estimate of the light detection efficiency can be easily and conveniently made by comparison of the photopeak channel for the direct ^{137}Cs spectrum (spectrum III in figure 6 and 7) in comparison with other photopeaks under the same experimental conditions. The direct detection of the ^{137}Cs X-rays of energy 34 keV (average of the 32 and 36 keV X-rays) gives rise to the peak at channel 500 in spectrum III in Figs. 6 and 7. We estimate that on average there are ~9400 photoelectrons created within the silicon PD for each 34keV X-ray interaction.

The absolute light output of LSO has been estimated at 27,000 photons/MeV (13,500 photons per 511 keV) [5]. From spectrum I in Fig. 6 and the X-ray data above we estimate we are detect ~4,000 photoelectrons in the SPAD1 PD for each 511 keV gamma ray interaction in the LSO crystal. The corresponding light detection efficiency is then 30%.

The high light loss is most likely due to the relative mismatch between active area of the photodetector in optical contact with the face of the scintillator crystal. The LSO crystal face is 4x4 mm^2 and is optically coupled to the photodetector with an active area of 3x3 mm^2. Therefore there is a reduction of ~44% between the crystal face area and the active area of the photodetector.

We have ignored any light losses resulting from any meniscus associated with the optical contact. Such factors have been shown to have an impact in determining the measured light output of the photodetector using gamma ray spectroscopy methods [4]. It was shown that even perfect coupling (no meniscus) of a 6x6 mm^2 crystal face to a photodetector with an active area of 6x6 mm^2 led to a reduction in the measured light output of ~20%. The reduction is due to the significance of edge losses at the crystal/photodetector interface, and becomes more significant as the crystal/photodetector area decreases.

V. CONCLUSION

An investigation has been performed into the spectral response of a new photodiode designed for improved sensitivity in the blue spectral region. The improved sensitivity is a result of a special ion implantation process used to produce an enhanced electric field, which extends very close to the detector surface when under bias.

Two photodiodes were designed and manufactured based on the new ion implantation technique. The two designs differ in that one (SPAD1) has a uniform p^- layer at the surface and the other (SPAD2) has p^+ strips embedded in the p^- layer. The silicon dioxide coating incorporated in both photodetectors was designed not to enhance the spectral response at wavelength less than 600 nm. Such a design allowed us to isolate the spectral enhancement due to the new ion implantation technique. The spectral response data of the two photodetectors showed that they both have an enhanced sensitivity to wavelengths in the blue region. The quantum efficiency of SPAD1 was deduced to be 40% at 420 nm. The response of SPAD2 degraded at short wavelengths (λ<400 nm) due to the embedded p^+ strips as expected. Further work will need to be done to ensure that the blue enhanced sensitivity does not have a detrimental effect on the timing properties of the new photodiodes.

Gamma ray spectroscopy results using scintillator crystals readout by one of the two new photodiodes indicate that the new photodiode is suitable for use with either LSO or CsI(Tl). The measured energy resolution was 7.7% for a 3x3x3 mm3 CsI(Tl) produced by AMCRYS-H and excited by the 662 keV gamma rays from a Cs-137 source. The equivalent for a 4x4x10 mm^3 LSO scintillator crystal produced by was 24%.

We intend to design an antireflective (AR) coating, optimsed for the detection of light with a wavelength of 420 nm, into the photodiode design. As a result we expect the quantum efficiency to improve to ~70% at 420 nm. Similar improvements in the LSO gamma ray spectroscopy results are also expected as a result of the AR coating.

The new photodiodes will be incorporated, in the form of an 8x8 silicon pixel array coupled to a 25x25x3 mm^3 LSO or CsI(Tl) scintillator crystal, into the design of a new PET detector module.

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