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Performance Evaluation of novel SiPM for Medical Imaging Applications

Bjoern Seitz, Andrew G. Stewart, Kevin O'Neill, Liam Wall, and Carl Jackson

***Abstract*—Silicon Photomultiplier (SiPM) detectors are investigated world-wide as a suitable replacement for the conventional vacuum based PhotoMultiplier Tube (PMT) and are enabling applications otherwise not possible with PMT detectors. Progress in recent years has been substantial with SiPM detectors pushing the boundaries in energy and time resolution as well as photon detection efficiency and active surface area. In this paper we report on the performance of a gamma detector comprising latest generation SiPM detectors from SensL coupled to novel Cerium doped $Gd_3Al_2Ga_3O_{12}$ (GAGG) scintillators from Furukawa, Japan. Both 3mm×3mm N-on-P and P-on-N SiPM detectors have been optically coupled to 3mm×3mm×30mm crystals. An energy resolution (662 keV Cs-137) of 9.4% has been measured for GAGG crystal coupled to a 3mm×3mm N-on-P SiPM detector.**

***Index Terms*—Silicon Photomultiplier, Ce:GAGG, gamma spectroscopy, positron emission tomography, PET, SPECT, LYSO, scintillators, geiger mode photodiodes, scintillation detection, silicon.**

I. INTRODUCTION

SILICON Photomultiplier detectors provide a compact, single-photon sensitive, scalable photon detection platform and have received considerable interest for application in medical imaging modalities such as Positron Emission Tomography (PET) and Single Photon Emission Computed Tomography (SPECT) [1], [2], [3], [4]. While the present generation of scintillator crystals, cerium doped lutetium oxyorthosilate (LSO) and lutetium-yttrium oxyorthosilicate (LYSO), currently used in commercial PET imaging systems have an emission spectrum well matched to the absorption spectrum of bialkali based photo-cathodes of photomultiplier tubes, the emission spectrum of these scintillators is a poor match to the spectral response of SiPM detectors with a N-on-P structure. This spectral mismatch has pushed the development of SiPM detectors with a P-on-N structure as this results in a shift of the peak efficiency to shorter wavelengths [5], [6].

More recently a new fast, high-luminosity single-crystal cerium doped scintillator, $Gd_3Al_2Ga_2O_{12}$ (Ce:GAGG), has been grown that has a peak emission wavelength well matched to the peak sensitivity of N-on-P structure SiPM detectors.

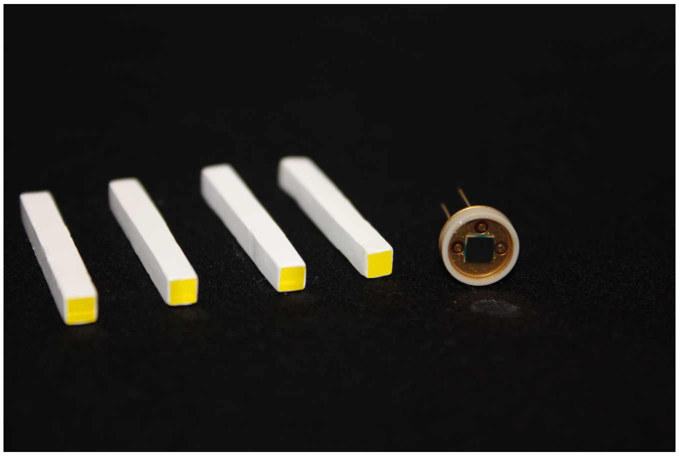

Fig. 1. 3mm × 3mm × 30mm Ce:GAGG scintillating crystals from Furukawa Co. Ltd. Japan. The crystals were polished on all faces and 5 faces are covered with a reflective coating. Also shown is a 3mm×3mm SiPM from SensL.

II. SCINTILLATORS FOR MEDICAL IMAGING

The need for high quality images, particularly for medical imaging, places high demand on the scintillator, read-out detector and electronics. The scintillators require a high photon yield, fast response and decay time, high stopping power, good chemical stability and an absence of intrinsic radiation. In addition the ideal scintillator should have an emission spectrum closely matched to the spectral response of the detector, be non-hygroscopic and cheap to manufacture.

A. *Cerium doped GAGG*

Growth of GAGG crystals by the Czochralski method and its scintillation properties were first reported in 2011 [7]. Preliminary studies of energy resolution and timing performance of GAGG crystals readout by a variety of photon detection technologies (PMT, MPPC, PIN diode) show that the crystal has promise in medical imaging and gamma spectroscopy applications [8], [9].

Figure 1 shows a photograph of the 3mm×3mm×30mm GAGG scintillator crystals together with a packaged 3mm×3mm active area SiPM detector. All faces of the crystals have been polished and 5 of the faces were covered in a white reflective coating.

The crystal has a emission peak in the 520nm to 530nm region while the light yield has been reported as 33,100 photons/Mev [9] and 46,000 photons/Mev [10]. The data sheet from Furukawa quotes a light yield of 60,000 photons/MeV [11]. The intrinsic energy resolution of the crystal has been

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TABLE I
SCINTILLATOR PROPERTIES

	Ce:GAGG	Ce:LYSO	BGO
Light Yield (photons/Mev)	46,000	32,000	9000
Emission Peak (nm)	520-530	420	480
Density (g/cm^3)	6.63	7.1	7.13
Decay Time (ns)	90	41	300
Intrinsic Energy Resolution (%)	5.2	7.9	12

TABLE II
SIPM DETECTOR PARAMETERS

Parameter	P-on-N (B series)	N-on-P (M series)
Microcell Dimensions	35 μm × 35μm	35μm × 35μm
Number of Microcells	4774	4774
Fill Factor	64%	64%
Breakdown Voltage	24.5V	27V
Peak Response	420nm	500nm

reported as 5.2% [9]. The main properties of Ce:GAGG are summarized in table I together with the properties of the scintillators LYSO and the Bismuth Germanate (BGO).

B. Silicon Photomultiplier Detectors

Silicon Photomultiplier detectors have been proposed as a suitable replacement for the incumbent vacuum tube technology currently utilized in medical imaging since their inception. Moreover, the SiPM detector platform is considered essential for the development of a new generation of hybrid scanner such as PET/MRI (Magnetic Resonance Imaging) since they are immune to the high magnetic fields used in MRI [12].

Two different SiPM structures are assessed in this study; an N-on-P (M Series) device and a P-on-N (B Series) device. The engineering sample detectors studied here are equivalent to commercial devices with part numbers MicroFM-30035-SMT and MicroFB-30035-SMT. Both detector types have a total of 4774 microcells and a fill factor (FF) of 64%. Each microcell has an active area of 35μm×35μm. The detector parameters are summarized in table II.

III. EXPERIMENTAL SETUP

The scintillator crystals and SiPM detectors were aligned using a mechanical holder which allowed the fast and reliable exchange of both the crystals and the SiPM detectors. Figure 2 shows a photograph of one of the GAGG crystals inside the holder. The detector package fits into the holder recess and aligns the SiPM with the crystal. Radioactive sources are placed on the opposite face of the cylinder adjacent to the coated facet of the crystal. The packaged SiPM detectors have an epoxy fill to protect the surface of the silicon and the wire bonds. The crystal was optically coupled to the surface of the epoxy fill using optical grease. Reflections at the interfaces will, however, reduce the number of photons reaching the silicon and degrade the energy resolution.

The SiPM detector bias voltage was supplied by a Keithley 2410 source-measure unit (SMU). The SiPM signal was amplified using a high bandwidth MiniCircuits amplifier circuit containing a Gali 55+ chip. The amplifier has a gain of approximately ×19. The amplified signal was displayed on a 1GHz LeCroy oscilloscope. Oscilloscope signals were transferred to a PC over GPIB using a C++ program for analysis offline. The SiPM, crystal, source and MiniCircuits amplifier were housed in a Heraeus Votsch HT 4004 environmental chamber. The chamber provided a dark, temperature controlled environment. All measurements reported here were conducted at 20°C. The chamber temperature was monitored using a thermocouple placed in close proximity to the SiPM detector.

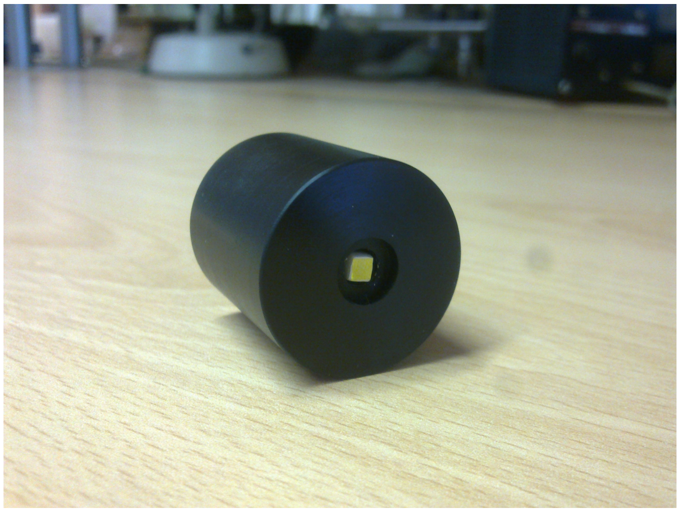

Fig. 2. GAGG crystal inside the mechanical holder. The SiPM detector package fits into the recess and aligns the SiPM detector with the uncoated facet of the crystal. The holder allows both the crystal and the detector to be quickly and reliably changed.

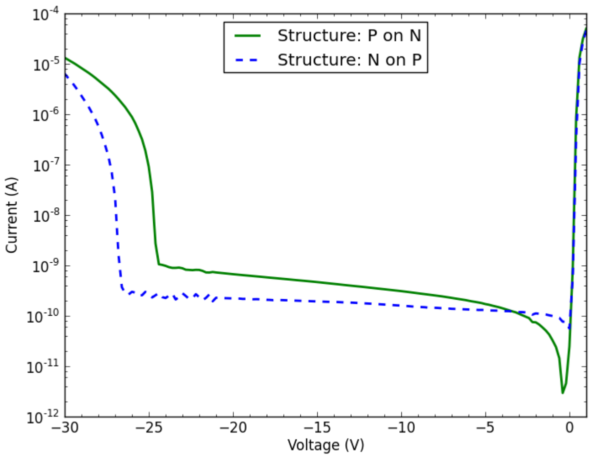

Fig. 3. IV characteristics of P-on-N (solid green line) and N-on-P (blue dashed line) 3mm×3mm SiPM devices. Both IV characteristics were recorded at 20°C.

A. IV Characteristics

Figure 3 shows the current-voltage (IV) characteristics of both the N-on-P (M series) and P-on-N (B series) SiPM detectors recorded at 20°C. The IV characteristic was recorded using the Keithley SMU controlled by a LabView program.

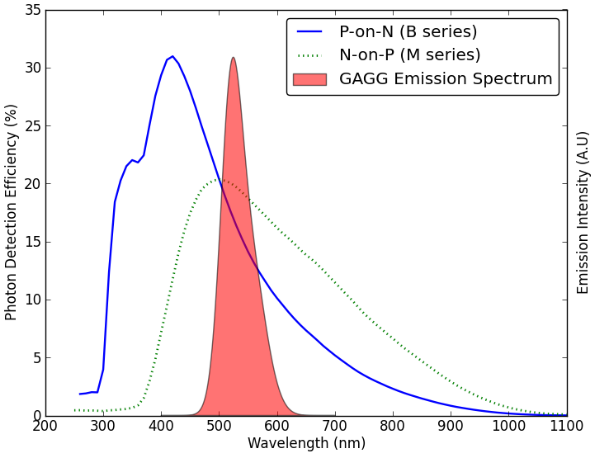

Fig. 4. Primary y-axis: Typical spectral response of a P-on-N (solid blue line) and N-on-P (dashed green line) SiPM. The spectral responses were measured at 2.5V above the breakdown voltage of the device. Secondary y-axis: Typical emission spectrum of Ce:GAGG.

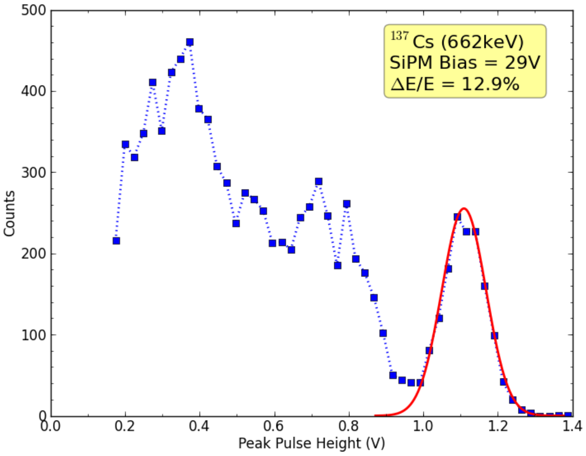

Fig. 5. Pulse height distribution (^{137}Cs) from an N-on-P SiPM coupled to Ce:GAGG. The SiPM was biased at 2V above the breakdown voltage. A Gaussian fit to the gamma peak gives an energy resolution of 12.9%. The measurements were recorded at 20^{o}C

The figure shows that the P-on-N device has a break-down voltage (V$_{Br}$) of 24.5V while the N-on-P detector has a break-down voltage of 27V.

B. Spectral Sensitivity

Figure 4 compares the typical spectral sensitivity of the N-on-P (M series) and P-on-N (B series) SiPM devices together with the emission spectrum of the GAGG scintillator. The emission spectrum of GAGG is taken from [9]. While the P-on-N device has a higher overall peak efficiency, the overlap of the spectral response of the N-on-P device with the emission spectrum of GAGG promises a higher detection efficiency and hence an improved energy resolution.

C. Energy Resolution

Figure 5 shows the pulse height distribution from a N-on-P (M series) device optically coupled to a GAGG crystal using a ^{137}Cs (662 keV) source. The distribution was recorded at 20°C and with a bias voltage of 29V or 2V above the breakdown voltage. The energy resolution (ΔE/E), defined as the Full Width Half Maximum (FWHM) divided by the mean of the pulse height, was determined by a Gaussian fit of the peak in the distribution. A fit to the distribution shown in figure 5 gives an energy resolution of 12.9%. The pulse height distribution is uncorrected for the effects of dark rate, crosstalk and after-pulsing. These effects add additional Geiger pulses to any signal photons and can lead to artificially enhanced values for the detection efficiency and hence the energy resolution.

D. Energy Resolution as a function of Detector Overbias

Figure 6 shows energy resolution of both the N-on-P and P-on-N devices as a function of detector overbias. The figure shows that the energy resolution varies linearly with overbias below about 3V above breakdown. Energy resolutions of 9.4% and 11.6% were obtained for N-on-P (M series) and P-on-N (B series) SiPM devices at a bias of 3V above their respective breakdown voltages.

E. Linearity of Response

The linearity and dynamic range of an SiPM are determined by the photon detection efficiency (PDE) and the total number of microcells [13]. When the number of incident photons is much less than the total number of microcells the SiPM response is linear. To investigate the linearity of the response of the 3mm×3mm SiPM detectors the pulse height distribution from Barium-133 (81 keV and 356 keV) and Americium-241 (60 keV) were also measured using the N-on-P device optically coupled to GAGG. Figure 7 shows the SiPM response (mean pulse height), at a bias of 2V above the breakdown voltage, as a function of gamma energy for the three isotopes. The data points are fitted with an equation of the form, $y = M(1 - exp(-Nx))$, where y is the mean pulse height, x is the energy of the gamma photon and N and M are constants. However, over the range of gamma energies studied, the detector is clearly operating in the linear portion of its dynamic region.

IV. SUMMARY AND CONCLUSION

Cerium doped GAGG scintillator crystals have many properties that make them suitable for gamma spectroscopy and medical imaging applications. A high photon yield and emission peak around 530nm makes the material well suited to readout by Silicon Photomultiplier detectors. High photon yield is critical for the reduced crystal dimensions of high-resolution PET block detectors [14].

In addition to the advancement in scintillating materials, significant progress has also been made in improving and optimising the performance of SiPM detectors. In this study SiPM detectors with two different structures have been used to readout GAGG crystals. The SiPM detectors have an active area of 3mm × 3mm and peak spectral responses of 500nm

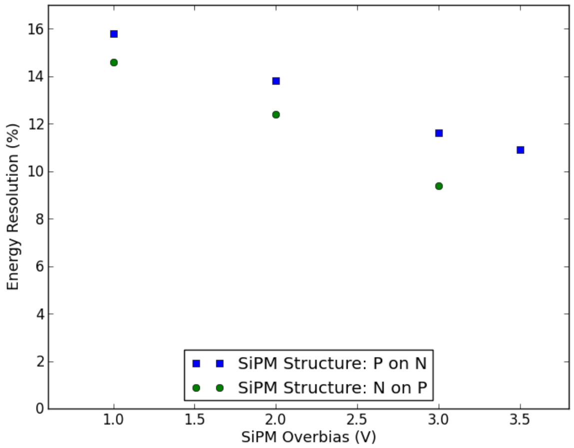

Fig. 6. Energy resolution as a function of detector overbais for N-on-P SiPM (green circles) and P-on-N SiPM (blue squares).

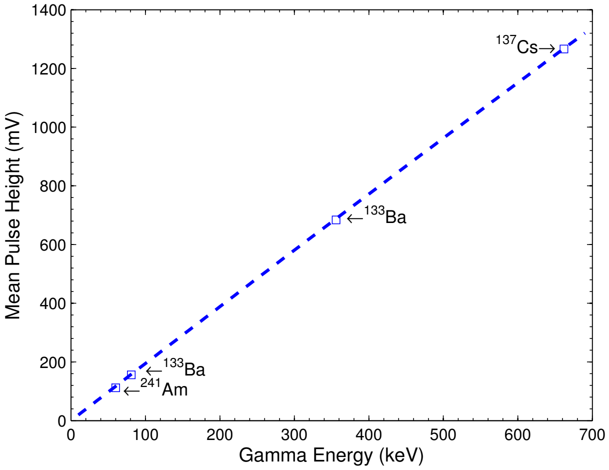

Fig. 7. Linearity of response of a 3mm×3mm×30mm GAGG crystal coupled to an N-on-P SiPM biased at 2V above breakdown voltage.

(N-on-P) and 420nm (P-on-N). As expected, the close match between the emission spectra of GAGG and the spectral response of the N-on-P device leads to a better energy resolution than that achieved with the P-on-N device. In addition, both SiPM devices display excellent linearity in their response up to gamma energies of 662keV.

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