Development of a silicon photodiode-based compact gamma spectrometer using a $\text{Gd}_3\text{Ga}_3\text{Al}_2\text{O}_{12}:\text{Ce,B}$ single crystal scintillator

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Abstract. A compact gamma spectrometer was developed by employing an in-house grown single crystal of $\text{Gd}_3\text{Ga}_3\text{Al}_2\text{O}_{12}:\text{Ce,B}$ scintillator optically coupled with a silicon photodiode. The performance of the detector was characterized in detail. The detector setup works with a low bias voltage of 9 V, drawn from a single battery. Power to the electronic components of the entire system is derived from a single universal serial bus port by employing required DC–DC converters. In addition to the low voltage operation, this developed spectrometer is very compact in size compared to the one developed by employing photo-multiplier tubes. The system offers excellent linearity over the gamma energy range of 344–1408 keV and an optimum energy resolution of about 13% at 662 keV.

Keywords. Single crystal; scintillator; photodiode; gamma spectrometer.

1. Introduction

Single crystal of gadolinium gallium aluminium garnet, doped with Ce^{3+} and co-doped with B^{3+} ($\text{Gd}_3\text{Ga}_3\text{Al}_2\text{O}_{12}:\text{Ce,B}$, abbreviated as GGAG:Ce,B), is a promising scintillator material due to its high effective atomic number (55), high density (6.7 g cm^{-3}), high light yield (about 54,000 photons per MeV), fast decay time (55 ns) and non-hygroscopic nature [1–6]. Furthermore, due to its emission peak wavelength of nearly 550 nm, which matches well with the efficiency of silicon-based photo-detectors, compact gamma spectrometer systems can be fabricated by optically coupling these crystals with photodiodes [1,2]. This also ensures that these systems can be satisfactorily operated at much lower voltages compared to their photomultiplier tube (PMT)-based counterparts [1]. The added advantages of GGAG:Ce,B over conventional single crystal scintillators of CsI(Tl) are its non-hygroscopic nature, higher effective atomic number, higher density and faster decay time [2]. Academic physics experiments, medical imaging, baggage scanning, explosive detection, geological exploration, etc. are some of the possible applications of compact gamma spectrometry systems based on GGAG:Ce,B coupled with photodiodes [1].

In this communication, the design and development of a universal serial bus (USB)-based compact low-power photodiode-based gamma spectrometry system with a GGAG:Ce,B single crystal has been reported. The results of its parameter optimization and spectroscopic performance evaluation of the system have also been presented in detail.

This photodiode-based system offers compactness as well as operation with much lower bias voltage in comparison with the PMT-based system reported by us in [1]. Additionally, it can also be used in magnetic field environment where the use of PMTs is avoided.

2. Materials and methods

2.1 Crystal growth

GGAG:Ce,B single crystals were grown by the Czochralski technique (in an Ar environment) with doping and co-doping concentrations of 0.2 at% each of Ce and B, respectively, with respect to Gd [2]. Figure 1 shows a photograph of the as-grown GGAG:Ce,B single crystal (under UV illumination) with dimensions of about 25 mm diameter and 60 mm length.

2.2 Characterization

2.2a Sample preparation: A sample of dimensions $10 \times 10 \times 10 \text{ mm}^3$ was cut from the grown crystal ingot. It was then annealed at 1000°C for 10 h in air in order to reduce the oxygen vacancies resulting from the crystal having been grown in an Ar environment. The post-growth annealing treatment is reported to increase the light output, reduce the scintillation decay time and improve the energy resolution [1]. After annealing, one surface of the sample, which was to be coupled

Figure 1. As-grown GGAG:Ce,B single crystal under UV illumination.

to the photodiode, was optically polished. All other surfaces were used without any further treatment.

2.2b Emission spectrum: The radio-luminescence spectrum was measured by irradiating the sample with CuK α X-rays (8.04 keV). The light emitted due to scintillation, after being passed through a monochromator, was measured by a PMT, controlled by a data acquisition system and its built-in software.

2.2c Study on reflectors: The polished surface of the sample was optically coupled to the centre of a 51 mm diameter, Head-on type, Bialkali photocathode-based PMT (Hamamatsu R1306, [7]) by using optical grease (Dow Corning). The pulse processing chain consisted of a CAEN preamplifier, a NIM-based spectroscopic amplifier and a USB-based Tukan 8 k multichannel analyser (MCA). The effect of various reflectors was studied by recording the pulse-height spectra with this system for 300 s with a ^{137}Cs test source by using a hemispherical Spectralon (standard high reflectivity diffuse reflector), standard Teflon tape wrapping as well as various numbers of coatings of a reflective paint (EJ-510, Eljen Technology).

2.3 Optical coupling with photodiode

The polished surface of the sample was optically coupled to a photodiode with an active area of $10 \times 10 \text{ mm}^2$ and a depletion layer thickness of 0.3 mm (Hamamatsu S3590-08, [8]). Optical grease (Dow Corning) was used for better light collection. The assembly was tightly wrapped with Teflon tape to ensure minimum light leakage and the presence of

minimum air bubbles in between the crystal and the Teflon wrapping. Teflon was chosen as the reflector based on the results discussed in section 3.2.

2.4 Setup of a compact photodiode-based system

The aim was to make a compact electronic pulse processing chain in order to facilitate the development of a miniaturized gamma spectrometer. The photodiode output was coupled to the input of a compact ($0.85'' \times 0.88''$) charge sensitive preamplifier (CR-110, Cremat, [9]) through a coupling capacitor (10 nF). The output of the preamplifier was fed to two-cascaded stages of an AC-coupled (cutoff frequency of 20 Hz) non-inverting broadband (500 MHz–3 dB) amplifier. The combined gain of the two stages was nearly 44. The broadband amplifiers ensure effective amplification of the high frequency content of the signal. A compact ($0.85'' \times 0.88''$) Gaussian shaping amplifier (CR-200, Cremat, [10]) was used for pulse shaping. Considering a typical bath-tub type noise spectrum in photodiode instrumentation, Gaussian shaping minimizes noise power in the signal. The shaping time was optimized experimentally to obtain the best energy resolution. Pole zero correction was employed by using a 200 k Ω potentiometer. The shaped output pulse was fed to a buffer amplifier. A small printed circuit board (PCB) ($9 \times 6 \text{ cm}^2$) of the pulse processing electronics was designed and fabricated (figure 2) which also included the conversion circuit for generating $\pm 6 \text{ V}$ required to drive the electronics from $\pm 9 \text{ V}$ of battery supply. The output from the PCB of figure 2 was sampled and digitized by using a USB-based Tukan 8 k MCA.

2.5 Performance characterization of the photodiode-based system

The effect of variation of the reverse bias voltage of the photodiode on energy resolution was studied by applying bias voltages in the range of 9–93 V using different numbers of 9 V batteries. The effect of the shaping time of the amplifier on energy resolution was studied by using CR-200 shaping amplifiers with different shaping times in the range of 25 ns–8 μs . Energy calibration of the spectrometer was performed by recording pulse-height spectra using test sources of ^{137}Cs (662 keV), ^{60}Co (1173, 1332 keV), ^{22}Na (511, 1274.5 keV) and ^{152}Eu (344, 1408 keV).

3. Results and discussion

3.1 Emission spectrum

Figure 3 shows the recorded emission spectrum of GGAG:Ce, B crystal. This emission in the green region, peaking at nearly 550 nm, matches efficiently with the spectral response of silicon photodiodes; thereby encouraging the development of photodiode-based low-voltage compact gamma spectrometers.

Figure 2. Pulse processing circuit of the GGAG:Ce,B-photodiode-based gamma spectrometer.

3.2 Reflector optimization

The effect of different types of reflectors on the pulse-height spectrum of a ^{137}Cs test source, acquired with the scintillator coupled with the PMT (see section 2.2c), is shown in figure 4. The full energy peak corresponding to ^{137}Cs (662 keV) was observed to be at the highest channel by employing Spectralon. This indicates that the maximum pulse-height, and, therefore, the maximum light collection at the photocathode of the PMT, are obtained with Spectralon. The peak position with Teflon is slightly to the left of that observed with Spectralon. This indicates nearly ideal but marginally less light collection with the Teflon reflector. Peak positions with reflective paint were significantly to the left. Application of the third coat of paint did not improve light collection, thereby indicating saturation of light collection with only two coats. For making a compact spectrometry

system, therefore, Teflon was chosen as the reflector over the reflective paint. It should be pointed out that the reflectivity of the reflecting materials, their refractive indices, their reflection types (Specular/Lambertian), as well as uniformity of their coating on the scintillator and the presence/absence of air gap between the scintillator and the reflector, all contribute to the efficiency of light collection at the photocathode.

3.3 Effect of reverse bias voltage of the photodiode

Figure 5 represents the energy resolution at 662 keV measured for different reverse bias voltages applied to the photodiode described in section 2.3. Each spectrum was recorded for 300 s using a ^{137}Cs test source. Energy resolution values were determined by fitting a Gaussian function to the 662 keV peak in each spectrum. It may be noted that the estimated values of energy resolution also depend on the accuracy of the

Figure 3. Experimentally measured emission spectrum of GGAG:Ce,B single crystals.

Figure 4. Pulse-height spectra of ^{137}Cs with different reflectors on a GGAG:Ce,B single crystal scintillator coupled with the PMT.

choice of the region of interest (ROI) and the corresponding Gaussian fitting. The full depletion voltage of the photodiode was nearly 70 V [8]. It was observed, as shown in figure 5, that the energy resolution remains fairly constant within experimental uncertainty throughout the tested range of bias voltages (9–93 V). This may be because of the fact that the expected improvement of energy resolution for an increase of bias voltage above the full depletion voltage (due to the minimization of photodiode capacitance and associated series noise) is offset by other factors [5,11] affecting the same in a more dominant way. It was observed that the pulse-height spectra recorded with 0 V photodiode bias voltage were noisy and unstable. It was also seen that spectra recorded with the bias voltage supplied with batteries were less noisy and always had better energy resolution than when the bias voltage was supplied with a regulated power supply, even with a stability

Figure 5. Energy resolution of the GGAG:Ce,B-photodiode-based spectrometer as a function of photodiode reverse bias voltage.

better than ± 0.1 V. Based on these results, it was decided to design the system with bias voltage supplied by a single 9 V battery, in order to make the system as compact along with as less noisy as possible.

3.4 Amplifier shaping time optimization

Figure 6 shows the pulse-height spectra of ^{137}Cs recorded for 300 s with the system by employing CR-200 shaping amplifiers with shaping times of 1, 2 and 4 μs respectively. It is observed that the spectrum with a 2 μs shaping time gives the best energy resolution. It is again to be noted that the estimated values of energy resolution depend on the accuracy of the choice of the ROI and the corresponding Gaussian fitting. The use of other shaping times (25, 50, 100, 250, 500 ns and 8 μs) yielded noisier spectra with poorer energy resolution (not shown). Based on these results, it was decided to make the final design of the photodiode-based system to be with a CR-200–2 μs shaping amplifier. It is to be mentioned that longer shaping times reduce the effect of (detector capacitance related) series noise and simultaneously increase (leakage current related) parallel noise. An optimum choice of the shaping time minimizes the overall noise [11].

3.5 Energy linearity

Figure 7 shows the energy calibration of the spectrometer performed using four test sources (seven energies) as mentioned in section 2.5. Excellent energy linearity could be observed as shown in figure 7 in the energy range of 344–1408 keV.

3.6 Factors affecting energy resolution

The best energy resolution at 662 keV obtained for 300 s spectra recorded with the photodiode-based system operated at 9 V photodiode reverse bias voltage and a 2 μs amplifier

Figure 6. Pulse-height spectra of ^{137}Cs measured with a GGAG:Ce,B single crystal scintillator for different shaping times: (a) 1, (b) 2 and (c) 4 μs .

shaping time is about 13%. On the other hand, the energy resolution (with the Teflon reflector, see figure 4) is about 9.4% when the crystal is coupled with the Hamamatsu R1306 PMT and the bulkier electronics as described in section 2.2c is used. Therefore, despite the fact that the quantum efficiency of the S3590-08 photodiode (about 90% [8]) is significantly higher than that of the photocathode of the R1306 PMT

Figure 7. Energy calibration of the GGAG:Ce,B-photodiode-based spectrometer.

Figure 8. Photograph of the developed USB-based compact gamma spectrometer based on GGAG:Ce,B single crystals coupled with a silicon photodiode.

(about 5% [7]) near the emission peak wavelength of about 550 nm of GGAG:Ce,B; the energy resolution is poorer with the photodiode-based system. This is in line with the results presented in [12], and can be explained to be due to the lower signal to noise ratio, and, consequently, the larger electronic noise associated with the photodiode-based system which has a gain of unity, as opposed to that of 2.7×10^5 of the R1306 PMT.

4. Development of the USB powered photodiode-based compact gamma spectrometry system

The PCB shown in figure 2, together with the small PCB of a USB-based 1 k MCA, was enclosed in a 1.5 mm thick

aluminium box of dimensions $137 \times 86 \times 84 \text{ mm}^3$. $\pm 9 \text{ V}$ required for the conversion circuit of the pulse processing electronics shown in figure 2 was provided from the 5 V input of the USB by employing the DC–DC converter IC IA0509S. The photodiode bias voltage was provided by a single 9 V battery, which was housed inside the aluminium enclosure. Figure 8 shows a photograph of the developed spectrometry system, which is portable and easily usable with a laptop in which the software of the MCA is installed. This spectrometer is more compact in comparison with our recently developed PMT-based portable radiation detectors [1].

5. Conclusion

A compact low power USB-based gamma spectrometer has been developed which utilizes an in-house grown GGAG:Ce, B single crystal scintillator coupled with a Hamamatsu S3590-08 silicon photodiode. Its biggest advantage is that it operates with only 9 V photodiode bias voltage, thereby eliminating the need for bulky high-voltage electronics as well as the PMT. It also uses a miniature hybrid preamplifier and shaping amplifier modules instead of their bulkier NIM-based counterparts. The amplifier shaping time was experimentally optimized at $2 \mu\text{s}$ for optimum energy resolution. The developed spectrometer offers excellent linearity in terms of energy over the range of 344–1408 keV. An optimum energy resolution of about 13% has been achieved at 662 keV. At the cost of some deterioration of energy resolution as compared to the PMT-based system reported in [1], the overall system has been miniaturized to a great extent. Work is underway to improve the energy resolution of the photodiode-based system without increasing its size, by incorporating better low noise electronics.

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