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Scintillation readout with MAPD array for gamma spectrometer

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Abstract: In this study, we present the gamma-ray detection performance of LYSO, YSO(Ce) and BGO scintillators read out by a 9 ch. micropixel avalanche photodiode (MAPD) array with a high pixel density (PD) and photon detection efficiency (PDE). The array with an active area of $11.5 \times 11.5\,\mathrm{mm}^2$ was assembled using single MAPDs with an active area of $3.7 \times 3.7\,\mathrm{mm}^2$. It had a single output signal and was developed for gamma spectroscopy. Breakdown voltage measurements were carried out for each channel, as a result of which the optimal operating voltage for the array was found. The linearity range and energy resolution for each crystal were determined in the energy range from 30 to 1770 keV. The high pixel density of the array allowed to achieve good linearity in the studied energy range.

Keywords: Photon detectors for UV, visible and IR photons (solid-state) (PIN diodes, APDs, Si-PMTs, G-APDs, CCDs, EBCCDs, EMCCDs, CMOS imagers, etc); Scintillators, scintillation and light emission processes (solid, gas and liquid scintillators)

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2020 JINST 15 C01001

Contents

2020 JINST 15 C01001

1 Introduction

Traditional vacuum photomultiplier tubes (PMTs) have been successfully used as a light readout for a long time. However, modern technologies lead to the development of new types of photodetectors, which currently have competitive features in comparison to PMTs. Some photodetectors include silicon photomultipliers (SiPM), which have advantages such as high detection efficiency, low operating voltage, compactness, insensitivity to magnetic fields, low cost, etc. [1–3]. Despite the advantages, they have some disadvantages as a limited number of pixels, the active area, etc. Because of the limited number of pixels, SiPM response is a non-linear with increasing number of photons [4]. The PD is one of the key parameters to avoid the compression of the energy spectrum and to improve the linearity of SiPM in high-dynamic-range applications, such as the scintillation light readout in gamma-ray spectroscopy [5]. Although the PDE and the PD determine the dynamic range of SiPM [6], there is a certain trade-off between them. Increasing pixel size makes it possible to achieve a higher pixel fill factor and therefore higher PDE [7]. However, this fact decreases the dynamic range of SiPM [7]. The SiPM non-linearity becomes evident when the number of incident photons approaches $\sim 60\%$ of the saturation level [8]. Therefore, it is necessary to develop SiPM with high pixel density while maintaining PDE. A significant improvement of the SiPM dynamic range is provided by the innovative design of the MAPD from Zecotek Photonics Inc. [3, 9–11]. MAPD consists of a double n-p-n-p junction with micro-well structures located at a depth of 3–4 µm below the surface. By means of this structure, a pixel density of 10000–40000 mm^{-2} is possible on an area up to $3.7 \times 3.7\,mm^2$. Due to the high geometrical fill factor of MAPD with a high pixel density, both wide dynamic range and high PDE can be realized at the same time, which satisfactorily resolves the conflict between dynamic range and PDE existing in most commercial SiPMs. For more information on the design and operation of MAPD, see [10, 11].

In many applications, the size of the used crystals is necessary due to the requirements of the high efficiency of the detector. Therefore, the active area is considered as another limiting parameter of the SiPM, since most of SiPMs produced up today having maximum $6 \times 6\,\text{mm}^2$ active area [12]. For scintillation detectors, the efficiency increases with the area of the photosensor and the crystals. A larger detector volume means a higher sensitivity for radiation detection. Because of the small active area of the SiPMs, it is necessary to use multiple SiPMs to increase the efficiency of photon collection for larger scintillators.

This paper presents the validation of the 9 ch. MAPD array with high PD/PDE relation as light readout in gamma-ray spectrometry with three scintillators with various light output and decay time.

2 MAPD array

An array of 9 single-element MAPD-3NK photodiodes from Zecotek Photonics Inc. was assembled on a specially designed PCB board with contacts on the rear side. Each MAPD element was mounted with a conductive glue onto the PCB board and wired in parallel. MAPD-3NK was an area of $3.7 \times 3.7\,\text{mm}^2$ with a pixel quantity of 10000 per mm^2 and a high PDE level of 40%. The array has a total capacitance of $\sim 1.8\,\text{nF}$. The geometrical fill factor (GFF) of the MAPD array was 76%. The gap between the two adjacent MAPDs was $200\,\mu\text{m}$ in the array. The whole size of the array considering the gap of each element was $11.5 \times 11.5\,\text{mm}^2$.

3 Characterization of scintillators

Three scintillators type of LYSO, YSO, and BGO have been tested with the MAPD array. The scintillator crystals were supplied by Epic-crystal and their properties [13] were summarized in table 1. The crystals wrapped with multiple layers of white Teflon tape on all sides except the side attached to the MAPD array with special optical grease. All surfaces of the crystals were polished.

Table 1. Properties of the scintillators used in this study.

	LYSO (Ce)	YSO	BGO
Density (g/cm^3)	7.25	4.50	7.13
Emission wavelength max (nm)	420	420	480
Light output (Photons/Mev)	28000–34000	21000–24000	8000–10000
Decay time (ns)	42	50–70	300
Refractive index	1.82	1.8	2.15
Hygroscopic	No	No	No
Size (mm)	$10 \times 10 \times 10$	$10 \times 10 \times 10$	$10 \times 10 \times 10$

4 Experimental results

4.1 Experimental setup

The diagram of the experimental setup is depicted in figure 1. During the measurements, the detector and the preamplifier were placed in a shielded light-tight black box. The signal was

2020 JINST 15 C01001

amplified by a preamplifier (with a signal gain of 40 and bandwidth ~ 50 MHz) and recorded by a CAEN DT5720B Desktop Waveform Digitizer (4 Channel 12-bit 250 MS/s). The input resistance of the digitizer was 50 Ohm, since the preamplifier had 140 Ohm input resistance. The data were taken in the self-triggering mode of the digitizer and saved for offline analysis on a computer. All data analysis was performed using a script written in a data analysis framework ROOT developed by CERN. The array was biased by a desktop module housing 4 independent high voltage power supply channels (CAEN 5533M). The measurements are carried out in the air and a temperature of 22 °C. ^{57}Co, ^{137}Cs, ^{152}Eu, and ^{207}Bi, were used as gamma radiation sources in the experiment. The energy of the gamma rays ranged between 30–1770 keV. Measurement time was selected to be 5 minutes. All measurements were done using the same experimental setup and at the same conditions.

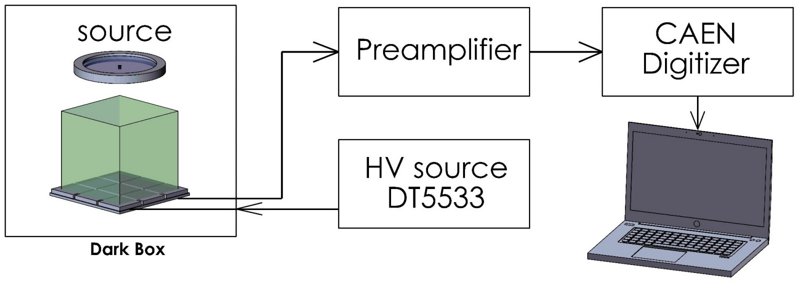

Figure 1. Block diagram of the experimental setup.

4.2 Optimal bias voltage determination

The breakdown voltage for the SiPMs varies individually due to the manufacturing processes. Therefore, it was needed to determine the breakdown voltage for each MAPD. For these purposes, reverse-bias I-V measurements were performed and measured for all MAPDs.

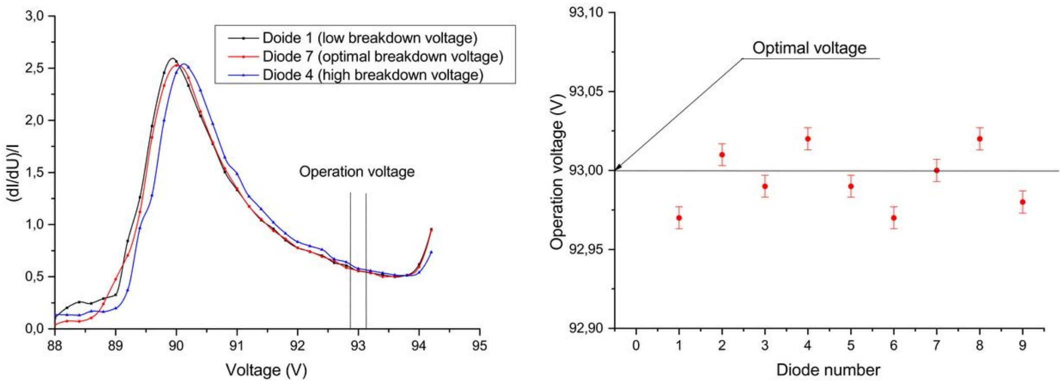

Figure 2. Current-voltage characteristics (left) and operation voltages (right) for all MAPDs in the array.

The figure 2 (left) showed the results from the I-V measurements ((dI/dV)/I vs V) for MAPDs with lower, normal, and higher operation voltage in the array. The plot showed clear peaks around 90 V. The difference between breakdown voltages did not exceed 0.05 V in the array. The right panel of figure 2 showed a dependence between the operation voltages and MAPD number. This value was

2020 JINST 15 C01001

selected to be equal to 93 V for the array. Moreover, another measurement was also carried out to show the variation in the breakdown voltage between elements and the consequent high uniformity in the gain values. The response of LYSO coupled with the array to the 662 keV gamma-ray from ^{137}Cs was determined from the dependence of energy resolution on the bias voltage. An operation voltage corresponding to the minimum energy resolution (9.25%) was found to be 93 V.

4.3 Gamma-ray detection performance

The gamma-ray detection performance of the scintillators coupled to the MAPD array was tested with ^{57}Co, ^{137}Cs, ^{152}Eu, and ^{207}Bi point sources. During the measurements, the gate for charge integration was selected according to the decay time of scintillator. This value was set 400 ns for LYSO and YSO, while it was 750 ns for BGO. The characteristic energy spectra for LYSO and YSO scintillators are shown in figure 3 and 4, respectively. LYSO crystals feature intrinsic radioactivity

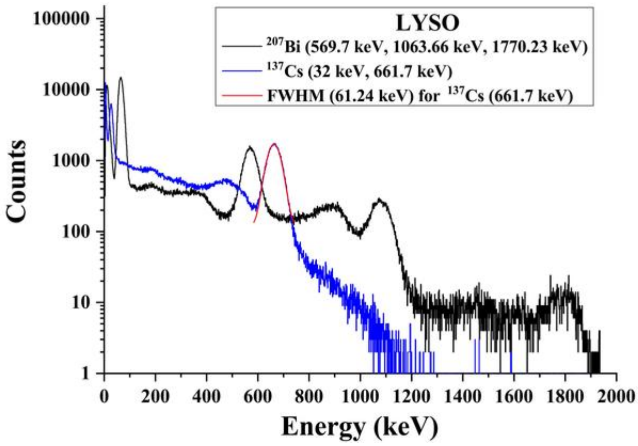

Figure 3. Energy spectra of gamma rays from ^{137}Cs and ^{207}Bi sources measured with LYSO scintillator coupled to the MAPD array.

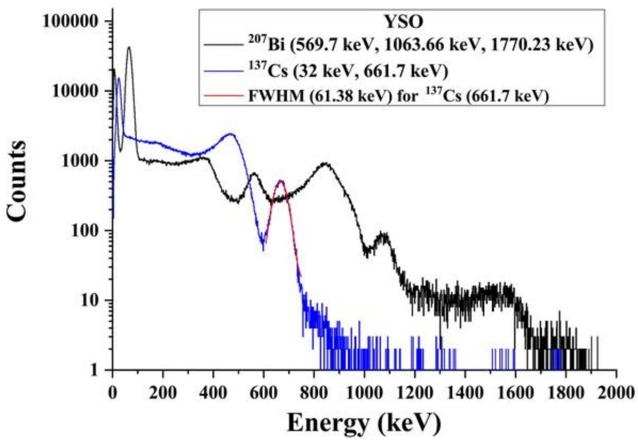

Figure 4. Energy spectra of gamma rays from ^{137}Cs and ^{207}Bi sources measured with YSO scintillator coupled to the MAPD array.

2020 JINST 15 C01001

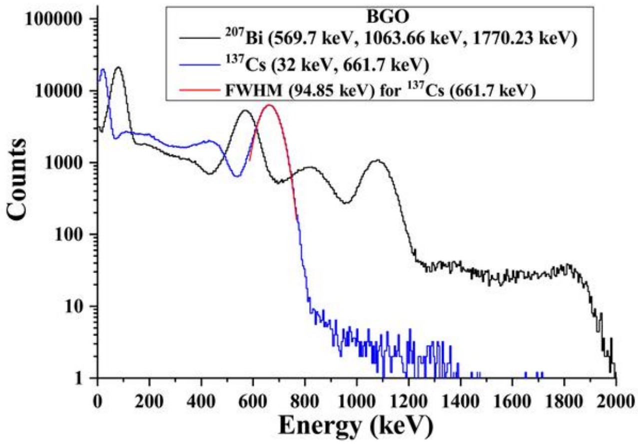

Figure 5. Energy spectra of gamma rays from ^{137}Cs and ^{207}Bi sources measured with BGO scintillator coupled to the MAPD array.

due to lutetium β decay with a maximum electron energy of 596 keV ^{176}Lu$\rightarrow$^{176}Hf followed by emission of three prompt gammas with energies of 88, 202 and 307 keV. The intrinsic background of YSO and BGO is very low for the same crystal size. Background subtraction was not made in the results. Figure 5 presents the energy spectra for the BGO scintillator coupled to the MAPD array. As shown in the figures, base gamma-ray lines of the sources were clearly discriminated against.

4.4 Verification of linearity and energy resolution

The pulse heights and energy resolution have been determined to fit the peaks with the Gaussian function. An energy calibration curve has been drawn for the MAPD array, taking all points obtained from measured spectra. The linear dependence of the energies and the experimentally measured pulse heights has been observed. This dependence is shown in figure 6. The calibration curve has

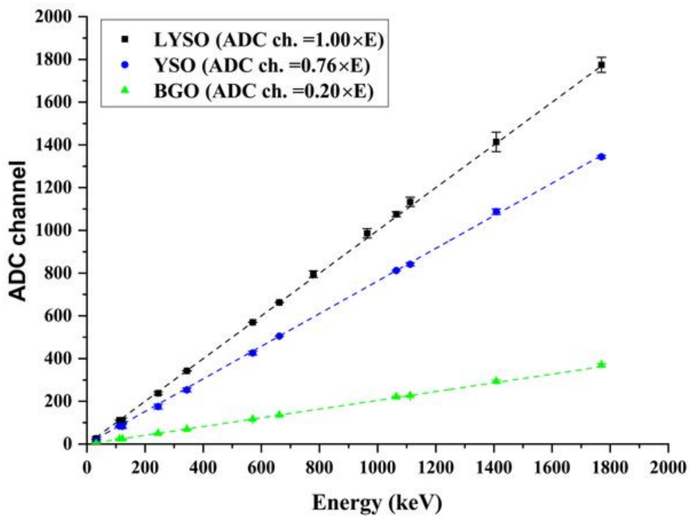

Figure 6. The pulse heights of gamma rays as a function of energy.

been fitted with a linear function. The results showed that the MAPD array proved a good linearity behaviour in a wide energy range (30–1770 keV). We could explain such linearity by the high pixel density of MAPD. There was not observed any non-proportionality in the studied energy range. Figure 6 also allows determination of the relative light output of the scintillators used. Relative light outputs were found by coefficients of linear fit results. The ratio of the coefficients is in good accordance with relative outputs given in table 1.

Figure 7 shows the energy resolution as a function of gamma-ray energy for all three scintillators along with a fit function. The energy resolution was 9.25% (LYSO), 9.28% (YSO), and 14.33% (BGO) for 661.7 keV gamma-rays of ^{137}Cs. BGO crystal exhibited a poor energy resolution due to light yield. In the case of the BGO, the 32 keV X-ray peak could hardly be detected, probably because of the long BGO decay time, the gate width should be correspondingly extended, which hampers efforts to exclude dark count contamination. We did not take into account this point in figure 6 and 7.

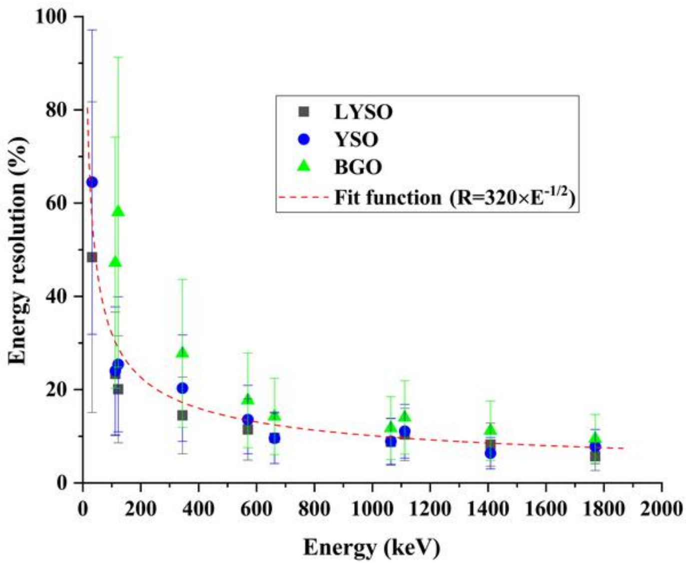

Figure 7. Dependence of the energy resolutions on gamma-ray energies. The energy resolution was comparable between LYSO and YSO for 661.7 keV gamma rays, although this value was poor for BGO.

5 Conclusion

The array of 9 ch. MAPD was assembled forming an active area of 11.5×11.5 mm^2 and with 200 μm dead space between the single elements. The array has one common signal output considering its use in gamma spectroscopy measurements. The array was tested with LYSO, YSO, and BGO scintillators with dimensions of 10×10×10 mm^3. For gamma-rays of 662 keV from ^{137}Cs, the energy resolution was obtained 9.25% (LYSO), 9.28% (YSO), and 14.33% (BGO). The array exhibited a very good linear dependence between the ADC channels and the energy of gamma rays in the gamma-ray energy range up to 1770 keV (last gamma line of ^{207}Bi). In the case of the BGO crystal, signals related to dark counts and 32 keV gamma rays were collected in the same ADC channel. Therefore, energy resolution for 32 keV gamma-rays was very poor due to dark counts of the MAPD array. Unlike the BGO, 32 keV X-rays could be detected clearly for LYSO and YSO. The major cause

2020 JINST 15 C01001

was the fact that the light outputs of these scintillators are more than that of BGO. Energy resolution characteristics for LYSO, YSO, and BGO showed the same shape of curves. The relative light output values obtained with the LYSO, YSO and BGO scintillators matched very well with data [13].

The obtained results showed that the 9 ch. MAPD array is suitable as a light readout for scintillator detectors which are used in medicine, space applications, and public security. Moreover, the high pixel density (10000 pixels/mm^2) could be considered as the most important advantage which allows quite good linearity of the response while maintaining PDE (40%).

Acknowledgments

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