Development of compact radiation detectors based on MAPD photodiodes with Lutetium Fine Silicate and stilbene scintillators

Article *in* Journal of Instrumentation · February 2015

DOI: 10.1088/1748-0221/10/02/C02041

3 authors:

Gadir Ahmadov
Joint Institute for Nuclear Research

Farid Ahmadov
Institute of Radiation Problems-Ministry of Science and Education Republic of Az…

Azer Sadigov
Nuclear Research Department of IDDA

PUBLISHED BY IOP PUBLISHING FOR SISSA MEDIALAB

RECEIVED: *August 16, 2014*
ACCEPTED: *January 7, 2015*
PUBLISHED: *February 24, 2015*

16th INTERNATIONAL WORKSHOP ON RADIATION IMAGING DETECTORS
22–26 JUNE 2014,
TRIESTE, ITALY

Development of compact radiation detectors based on MAPD photodiodes with Lutetium Fine Silicate and stilbene scintillators

F. Ahmadov,[a,g,1] **G. Ahmadov,**[a,c,g] **X. Abdullaev,**[d] **A. Garibov,**[a,g] **E. Guliyev,**[e] **S. Khorev,**[f] **R. Madatov,**[a] **R. Muxtarov,**[d] **J. Naghiyev,**[a,g] **A. Sadigov,**[a,g] **Z. Sadygov,**[b,c] **S. Suleymanov**[a,g] **and F. Zerrouk**[f]

[a]*Institute of Radiation Problems of ANAS,*
9, B.Vahabzade Str., Baku, Azerbaijan
[b]*Institute of Physics of ANAS,*
33, H. Javid Ave., Baku, Azerbaijan
[c]*Joint Institute for Nuclear Research,*
Joliot-Curie 6, Dubna, Russia
[d]*National Aviation Academy of Azerbaijan,*
Bina sett., 25th km, Baku, Azerbaijan
[e]*TRIUMF National Research Laboratory on Nuclear and Particle Physics,*
4004 Wesbrook Mall, Vancouver, BC V6T 2A3, Canada
[f]*Zecotek Photonics Inc.,*
Unit 1120-21331 Gordon Way Richmond, BC V6W 1J9, Canada
[g]*National Nuclear Research Centre of Ministry of Communications and High Technologies,*
77, Zarifa Aliyeva str., Baku, Azerbaijan

E-mail: farid-akhmedov@yandex.ru

ABSTRACT: Results of gamma-ray measurements taken with Lutetium Fine Silicate (LFS) scintillators and Micro-Pixel Avalanche Photodiodes (MAPD) are presented in the energy range of 59.6 keV to 834.8 keV. Dependences of energy resolution on gamma-ray energy are studied. Results of several measurements are discussed to assess the performance of gamma ray source identification of the developed detector. The alpha particle and neutron detection performance of LFS and stilbene scintillators coupled to micro-pixel avalanche photodiode are discussed as well.

KEYWORDS: Gamma detectors (scintillators, CZT, HPG, HgI etc); Photon detectors for UV, visible and IR photons (solid-state); Neutron detectors (cold, thermal, fast neutrons)

[1]Corresponding author.

 doi:10.1088/1748-0221/10/02/C02041

Contents

1 Introduction

Scintillators with high light output in combination with various photo sensors are widely used in different areas, one of which is radiation monitoring. Radiation monitoring devices are excellent tools for obtaining information on gamma emitters within a material. When ionizing radiation penetrates into a scintillator, it deposits there its entire energy. The deposited energy is further converted into scintillation light, which is usually detected by a photo electron multiplier (PMT) [1].

Basic requirements for scintillation materials are fast response, high light output, high density, and high atomic number (Z) [2]. Lutetium Fine Silicate (LFS) has extremely high density of 7.4 g /cm^3, as well as a high Z value (Z = 64), making this crystal very attractive for building highly efficient compact detectors. High density of the scintillation material translates into short radiation length and therefore allows development of compact radiation detectors without compromising the energy resolution and timing properties.

Inherent features of PMTs do not allow building compact, high-efficiency, vibration-insensitive, and low-cost scintillation detectors with low operation voltage [3, 4]. Progress in development of micropixel avalanche photodiodes (MAPDs) made them capable of serving as photo sensors in scintillation detectors. Detailed description of the MAPD advantages can be found in [5]–[9].

It is well known that linear detector response, that is a linear dependence between the signal amplitude and gamma ray energy in wide energy range, is a very important requirement. However, it is difficult to ascertain that such dependence for diodes operating in Geiger regime is linear [9, 10]. Taking into account that 662 keV gamma rays produce about $2 \div 4 \times 10^4$ photons in NaI (Tl), CsI (Na, Tl), LFS, and $LaBr_3$(Ce) scintillators and that photon detection efficiency (PDE) of Geiger-mode avalanche photodiodes is $\sim 25\%$ PDE, one can easily calculate the number of photoelectrons ($0.5 \div 1 \times 10^4$) generated in the avalanche process [11]–[12]. Most of Geiger-mode avalanche photodiodes cannot detect such a high number of photoelectrons ($\sim 10^4$) due to their low pixel density. Relatively small number of individual cells in Geiger-mode avalanche photodiodes seriously limits their practicality in applications where the number of detected photons is comparable and even larger than the number of pixels. Saturation effect due to several photons hitting the same pixel within a very short period of time leads to significant non-linear response to high-intensity light pulses. In [13] it is shown that Multi-Pixel Photon Counter (MPPC)

MPPC-33-025C has a linear dependence up to around 1,500 photoelectrons. In comparison with the other prototypes, the new model of Hamamatsu's MPPC (S12571-010C diode) has pixel density of 10,000 pixel/mm^2. However, this device has rather low PDE (10%) [14]. Low PDE figures lead to bad energy resolution in scintillation detectors. Wide-range linearity of an MPPC coupled to a long-decay-time scintillator CsI:Tl (1,000 ns) has been discussed in the literature [15]. In ref. [15], wide-range linearity of the MPPC results from three factors: low PDE ($\sim$10%), long duration of scintillation light pulse ($\sim$1,000 ns), and short recovery time ($\sim$10 ns) of MPPC pixels. In this case, each pixel is fired several times during a 1,000-ns pulse width. On the contrary, for fast scintillators, such as LFS, $LaBr_3$(Ce), and others, the MPPC recovery time is comparable to the scintillation decay time and therefore the linear range of MPPC is dramatically limited [15]. Considering energy measurements using fast scintillators, linearity of the entire device depends not only on recovery time of photo detector pixels, but also on their total number.

The proposed MAPD is an avalanche photodiode with a large number of pixels ($> 15,000$ pix/mm^2) and high PDE ($> 25\%$). These advanced parameters definitely merit evaluation of their performance in combination with fast scintillators in gamma spectroscopy and dosimetric applications. We have also investigated gamma ray, alpha particle, and neutron detection performance using LFS and stilbene scintillators optically coupled to our micro-pixel avalanche photodiodes with high pixel density.

2 Experimental set-up

All studies were performed with MAPD-1P device operating in Geiger mode. MAPD-1P contains a silicon substrate of n-type conductivity (thick wafers with a specific resistivity about 10 $\Omega\times$cm) on which two silicon epitaxial layers of p-type conductivity were grown. The device also contains a dense matrix of independent n+-type pixels buried deep within the epitaxial layers mentioned above. Such design of the device provides super-wide linearity range of photo response due to high pixel density within the sensitive area. Detailed descriptions of design and the operation principle of this device can be found in [4, 6]. The tested MAPD-1P device had a 3×3 mm^2 active area and total pixel count of 1.35×10^5. Full thickness of the depletion layer in MAPD-1P was about 8 μm. The MAPD-1P diode had the following working parameters: operating voltage – 94 V, gain – 5.5×10^4, device capacitance – 120 pF, dark current at the operating voltage – 70 nA, PDE at $450 \div 525$ nm light wavelengths – $25 \div 30\%$ [3].

The LFS-8 (Lutetium Fine Silicate) and stilbene scintillator samples were used as target for gamma rays, alpha particles, and fast neutrons. The dimensions of the LFS-8 scintillator fully matching the sensitive area of the MAPD-1P were $3 \times 3 \times 0.5$ mm^3. LFS-8 had light output of 30,000 photons/MeV and decay time of 19 ns. The wavelength of maximum light emission was 422 nm. The sides of the LFS-8 crystals were wrapped into three layers of 0.1-mm thick white Teflon tape excepting one face, which was coupled to MAPD-1P with a silicone optical grease. Both the MAPD-1P diode and the LFS-8 scintillator were developed in collaboration with the Zecotek Photonics Singapore Pte. Ltd [8].

The stilbene scintillator was used for fast neutron detection. The used stilbene crystals were cylindrical in shape with dimensions of ϕ3 cm $\times$ 2 cm. Its decay time was 3.5 ns. Stilbene has light output of 14,000 photons per 1 MeV of deposited energy [16]. Stilbene's wavelength of maximum

2015 JINST 10 C02041

light emission is 400 nm. The stilbene crystal was wrapped with Teflon tape. Signals from the stilbene crystal were transmitted to MAPD-1P through a Winston cone (L=10.1 mm, D_{ent}=7.2 mm and D_{exi}=3.3 mm). The detector was placed as close as possible to a ^{252}Cf source.

In our measurements, the signal from MAPD-1P was fed to preamplifiers with signal gain from 30 up to 110 and was recorded with a CAEN DT5720B digitizer module with 12-bit resolution and 250 MS/s sampling rate. All measurements were carried out at room temperature without any shielding material against external background.

3 Experimental results

Three types of ionizing radiation sources were used in our experiments: gamma ray sources ^{241}Am (59.6 keV), ^{109}Cd (88 keV), ^{57}Co (122 keV), ^{139}Ce (165.9 keV), ^{113}Sn (391.7 keV), ^{137}Cs (662 keV), and ^{54}Mn (834.8 keV); alpha particle source ^{241}Am (∼5.5 MeV), and fast neutron source ^{252}Cf (average neutron energy ∼2.18 MeV).

Figure 1 presents two pulse-height spectra registered with our "MAPD-1P+LFS" detector module. Rise time of detected signal was ∼20 ns and fall time, 30 ns. ^{113}Sn activity was 70 Bq and measurement time was 1,800 seconds in the experiment. External and intrinsic background of LFS (due to ^{176}Lu) strongly affected low energy tail of spectrum of ^{113}Sn source due to low source activity. In addition, it is well known Compton scattering is dominant at energies above 100 keV (dependence on atomic number of absorber). The result of Compton scattering in a small detector is an observation of partial absorption of incident gamma-ray energy. Therefore, Compton scattering leaded to a low-energy tail appearing on low energy tails of the detected spectra of ^{113}Sn and ^{54}Mn sources due to small size of the LFS-8 scintillator [1].

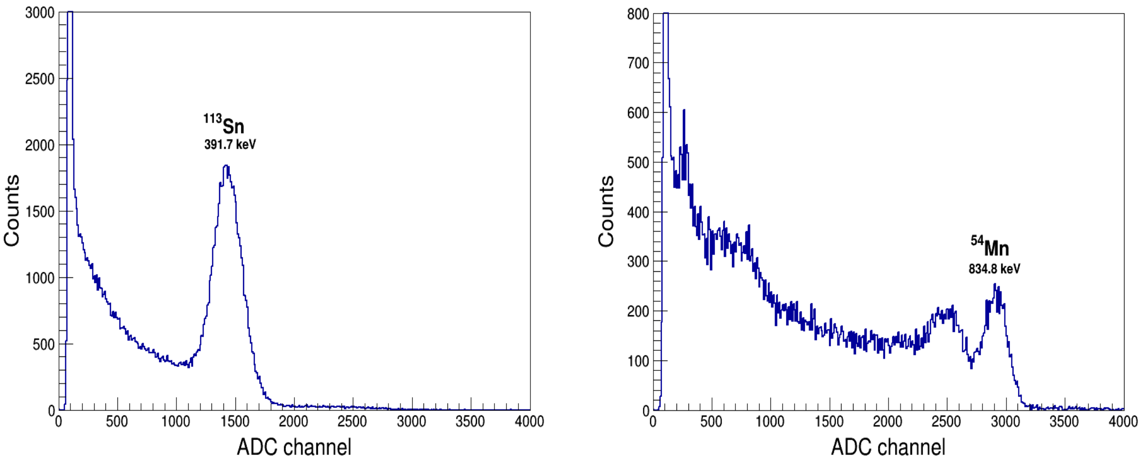

Figure 1. Pulse-height spectra of ^{113}Sn (391.7 keV) (left) and ^{54}Mn (834.8 keV) (right) gamma ray sources.

Two additional measurements were also carried out to confirm gamma ray identification capability of the detector. For this purpose, two sources ^{241}Am and ^{109}Cd or ^{139}Ce and ^{113}Sn were placed in front of the LFS scintillator. As shown in figure 2, peaks corresponding to selected gamma rays are well separated. LFS-8 has intrinsic radiation due to presence of radioactive isotope Lu-176 in the natural lutetium. This causes a problem for detecting low level radioactivity with a large size of LFS-8 crystals. Four major gamma lines were observed in intrinsic gamma spectrum of LFS-8

($3 \times 3 \times 10\,\mathrm{mm}^3$) scintillator measured by HPGe detector: γ-54.4 keV (25.9%), γ-88.3 keV (13%), γ-201.6 keV (84%), γ-306.3 keV (93%). All these gamma lines appears as Compton background continuum in low energy tails of spectra.

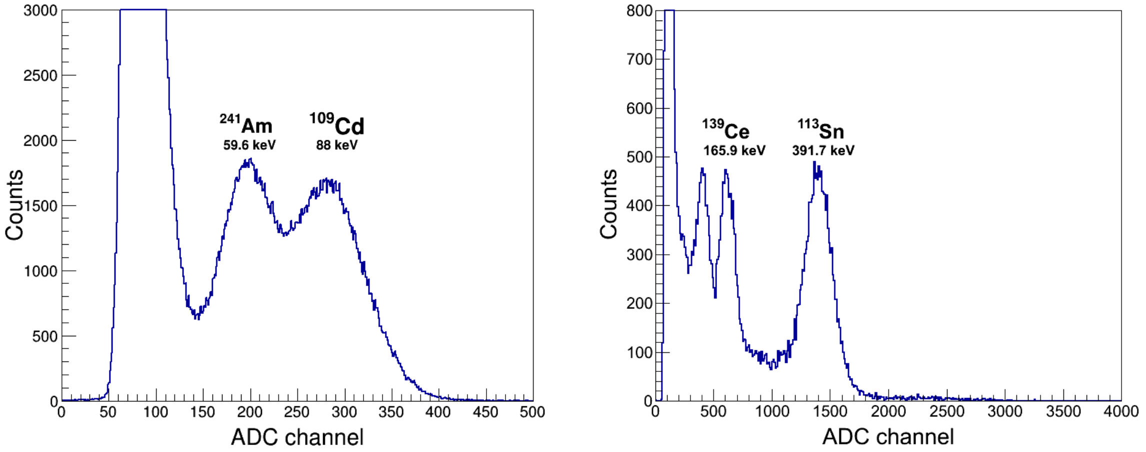

Figure 2. Pulse-height spectra for ^{241}Am (59.6 keV)/^{109}Cd (88 keV) (left) and ^{139}Ce (165.9 keV)/^{113}Sn (391.7 keV) (right) gamma ray sources.

Energy resolution and linear behavior of detected signal amplitudes as a function of the gamma ray energy are shown in figure 3. Due to ultra-high pixel density allows to detect large number of scintillation photons are produced by gamma ray. Number of photoelectrons, in turns, increases with gamma ray energy. Therefore energy resolution of the detector improved by increasing gamma ray energy [1].

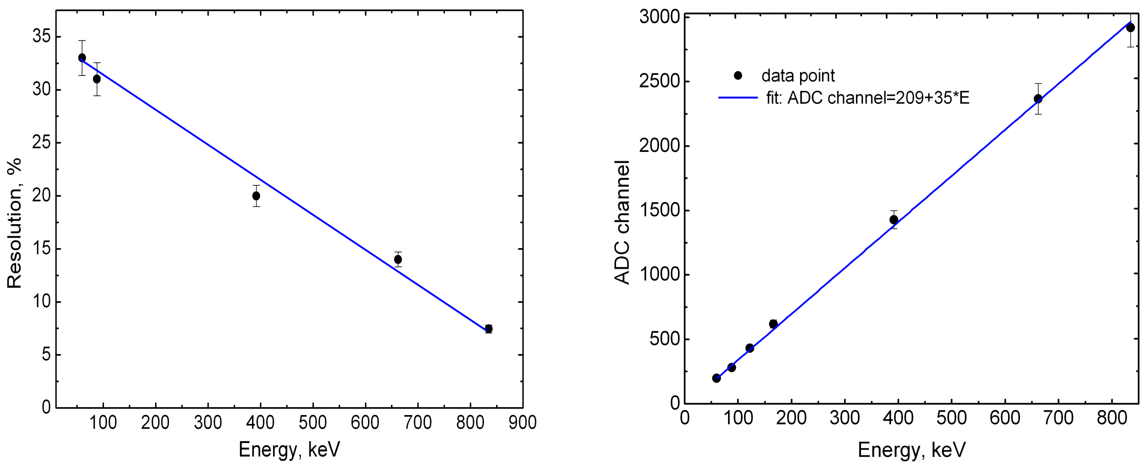

Figure 3. Energy resolution (left) and pulse height (right) of gamma ray signals as a function of energy.

In order to measure alpha particle spectra, the LFS-8 scintillator was placed on top of MAPD-1P separated from it by a thin layer of optical grease. Edges of the scintillator were covered with a 6-μm thick aluminum foil. A rectangular aperture (1*1 mm) in the Al-collimator (thikness$\sim$30 μm) was made to provide a narrow beam of alpha particles. An ^{241}Am alpha particle source with $\sim$5.5 MeV energy was used in the experiment. The source was placed at a distance of

1 mm from the scintillator. The energy spectrum of the ^{241}Am source is shown in figure 4. It is known that ^{241}Am sources emit 59.6-keV gamma rays as well (first peak). The distance between the MAPD-1P diode and the alpha particle source was 1 cm. Energy loss for alpha particle was about 1 MeV in 1 cm of air [17], therefore the energy deposited in LFS-8 scintillator was about 4.5 MeV (second peak). The energy resolution of the 4.5 MeV alpha particles was 8.6%.

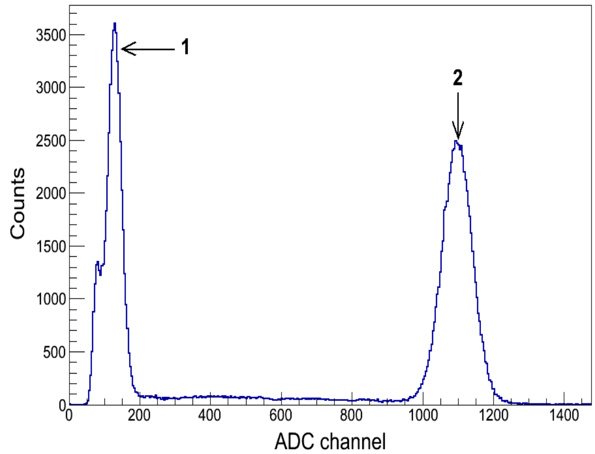

Figure 4. Pulse-height spectrum of the ^{241}Am source (1–59.6 keV gamma rays and 2–4.5 MeV alpha particles) measured with LFS-8 scintillator coupled to MAPD-1P. Air gap (1 cm) between the detector and the ^{241}Am source was taken into account.

Here gamma rays (662 keV) from the ^{137}Cs source and the natural background were used to verify possible background and gamma ray contribution to the neutron spectrum (figure 5). As it is shown in figure 5, there was a high event number for neutrons from 1500 to 5000 channels in the spectrum. Significant mismatch of the scintillator size and MAPD-1P surface area did not allow collecting a larger number of scintillation photons.

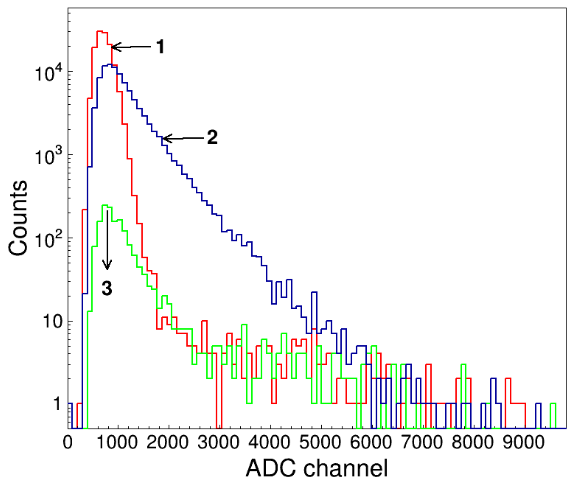

Figure 5. Pulse-eight spectrum of gamma rays (662 keV) from the ^{137}Cs source (1), ^{252}Cf source (2), and background (3) measured with stilbene scintillator coupled to MAPD-1P.

4 Conclusion

Response of the detector based on LFS-8 scintillator and MAPD readout to gamma rays was studied for the energy range of 59.6 keV to 834.8 keV. Thanks to high pixel density and high PDE of MAPD, the proposed detector showed a good linear response within the target energy range despite of intense and fast light pulses of the LFS-8 scintillator. A linear calibration curve for gamma ray energies was calculated. The energy dependence of the detector's resolution was studied using experimental measurements.

The experimental results obtained with gamma ray sources show that it is possible to utilize such combination in low-level radioactivity measurements. The presence of the intrinsic radiation of LFS and background radiation do not significantly affect the detector's ("MAPD+LFS") ability to register high-rate radioactivity. The minimal activity detected in the experiment was 70 Bq from ^{113}Sn source, however this level is not the minimum detectable activity for this detector. "LFS-8+MAPD-1P" combination is suitable in low-level radioactivity measurements of environmental radiation pollution owing to high detection efficiency and ultra-high pixel density of MAPD photosensors and high luminescence light output and a high density of LFS scintillator.

The results obtained from gamma radiation show that the properties of LFS-8 scintillator and the features of MAPD-1P are very suitable for building compact radiation detectors. The use of LFS-8 scintillator coupled to MAPD-1P makes it possible to reduce significantly the dimensions of the detection system.

Alpha particle and neutron detection performance of LFS-8 coupled to MAPD-1P and stilbene scintillators opens application possibilities of this detector type in nuclear physics, public security, industry, and in outer space experiments.

References

[1] G.F. Knoll, *Radiation detection and measurements*, John Willey and Sons, Inc., New York, U.S.A. (2000).

[2] C.W.E. van Eijk, *Development of inorganic scintillators*, *Nucl. Instrum. Meth.* **A 392** (1997) 285.

[3] Z. Sadygov et al., *Development of scintillation detectors based on micro-pixels avalanche photodiodes*, `PoS(PhotoDet 2012)037`.

[4] Z. Sadygov et al. *Three advanced designs of micro-pixel avalanche photodiodes: their present status, maximum possibilities and limitations*, *Nucl. Instrum. Meth.* **A 567** (2006) 70.

[5] Z.Ya. Sadygov, *Microchannel avalanche photodiode*, Russian Patent N. 2316848, priority from 01.06.2006.

[6] Z. Ya. Sadygov, *Avalanche detector*, Russian Patent N. 2102820 (10 October 1996).

[7] Z. Sadygov et al., *Technology of Manufacturing Micropixel Avalanche Photodiodes and a Compact Matrix on Their Basis*, *Phys. Part. Nuclei Lett.* **10** (2013) 780.

[8] www.zecotek.com

[9] Z. Sadygov, A. Olshevski, N. Anphimov, T. Bokova, V. Chalyshev et al., *Microchannel avalanche photodiode with wide linearity range*, *Sov. Tech. Phys. Lett.* **36** (2010) 528 [`arXiv:1001.3050`].

[10] D. Renker and E. Lorenz, *Advances in solid state photon detectors*, 2009 *JINST* **4** P04004.

[11] R. Scafe et al., *Si-APD readout for LaBr3:Ce scintillator*, *Nucl. Instrum. Meth.* **A 571** (2007) 355.

[12] K. Kamada, K. Tsutsumi and Y. Usuki, *Gamma-ray response properties of Pr:Lu3Al5O12 (LuAG) scintillating crystal with avalanche photodiode*, PoS(PD07)040.

[13] A. Nassalski et al., *Multi Pixel Photon Counters (MPPC) as an Alternative to APD in PET Applications*, *IEEE Trans. Nucl. Sci.* **57** (2010) 1008.

[14] http://www.hamamatsu.com/us/en/index.html.

[15] M. Grodzicka et al., *Energy resolution of small scintillation detectors with SiPM light readout*, 2013 *JINST* **8** P02017.

[16] http://detecsciences.com/en/scintillation-materials.html.

[17] www.srim.org.