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Sensors

Study of low-energy gamma-ray detection performance of silicon photomultiplier with $LaBr_3$(Ce) scintillator

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Abstract. Recent progress in the field of scintillators and silicon photomultipliers (SiPM) has allowed development of new scintillation detectors capable of detecting low-energy X- and gamma-ray sources that are widely used in medicine, security and industry. Such scintillation detectors are compact, insensitive to magnetic fields, have low operation voltages and are functional at room temperature. These advantages of SiPM are considered to solve the main problems facing scintillation detectors in medicine and industry today. Development of detectors of low-energy electromagnetic radiation is relevant now. Scintillation detectors based on lutetium fine silicate, $LaBr_3$(Ce), NaI and silicon avalanche photomultipliers offer a great potential for use for X- and gamma-ray detection. The present work demonstrates the gamma-ray detection performance of a new micropixel avalanche photodiode (MAPD) array (16 (4×4) elements – 15×15 cm) with a $LaBr_3$(Ce) scintillator (15×15×30 mm) using ^{177}Lu and ^{133}Ba isotopes as the gamma-ray sources.

Keywords: low-energy gamma-ray detection, silicon photomultiplier, $LaBr_3$(Ce) scintillator.

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1. Introduction

Scintillation detectors may be applied to detect low-energy gamma-rays in various fields such as nuclear medicine (diagnosis and therapy), industry and public security [1–3]. Of particular interest are applications of such detectors in nuclear medicine, which uses ^{99m}Tc (Eγ ~ 140 keV), ^{113m}In (Eγ ~ 391 keV), ^{131}I (Eγ ~ 364.5 keV and ~ 637 keV), ^{177}Lu (Eγ ~ 72 keV, ~ 113, ~ 208, ~ 250 and ~321 keV) and other radioisotopes as radiation sources for diagnosing and therapy [3–5].

Operation of a scintillation detector for nuclear medicine applications is based on a number of dependences on the parameters of the scintillator and photosensor such as the dependence of the energy resolution on the light output of the scintillator and photon detection efficiency (PDE) of the photodiode [1, 6–12], dependence of the linearity on the total number of pixels, dependence of the timing performance on the rinsing time of the scintillator and capacitance of the photodiode (electric field *etc.*) and dependence of the temperature stability on the temperature coefficient of breakdown voltage of the photosensor [1, 13–20].

The data collected by a scintillation detector are very important for diagnosing and therapy in nuclear medicine. In particular, these data play a key role in determining the positions of cancer cells and treating cancer [1–5]. That is why development of new types of scintillation detectors based on new scintillator and photodiode structures is a topical issue now [13, 21–28].

In this work, we use a $LaBr_3(Ce)$ scintillator (fast response, high light output and good linearity) as a converter and a new silicon photomultiplier based on micropixel avalanche photodiode (MAPD) structure and referred to as MAPD-3NM-II (high PDE, high pixel density and low temperature coefficient of breakdown voltage) as a readout and demonstrate their low-energy gamma-ray detection performance.

2. Experimental setup

The characteristics of the MAPD photodiodes and the scintillation detector based on MAPD array were measured at 23.5 °C. The experimental setup is shown in Fig. 1. MAPD was powered by a Keithley 6487 picoammeter voltage source, and was used to measure the dark current of the samples. The high internal gain of MAPD and huge light output of $LaBr_3(Ce)$ allowed to detect signals without use of additional amplifier. The analog signals from MAPD were converted to digital signals by a CAEN DT5720 digitizer. The CAEN DT5720 digitizer was connected to PC. CAEN-DPP (Digital Pulse Processing) firmware to obtain spectral characteristics [29]. Origin 2021b software [30] was used to calculate the energy resolution and linearity of the detector.

During measurements with the CAEN DT5720 digitizer, the following parameters were selected: the gate width 300 ns, the threshold 6 mV and the measurement time 300 s. A $LaBr_3(Ce)$ scintillator was used to convert gamma-ray energy into light with the wavelength of 380 nm. $LaBr_3(Ce)$ had the full light output of 68,000 photons/MeV [16, 31, 32]. The sides of the $LaBr_3(Ce)$ crystals were covered with 3 mm thick Al layers except for one side, which was coupled to the MAPD array with silicone optical grease. The dimensions of the used $LaBr_3(Ce)$ scintillator were 15×15×30 mm.

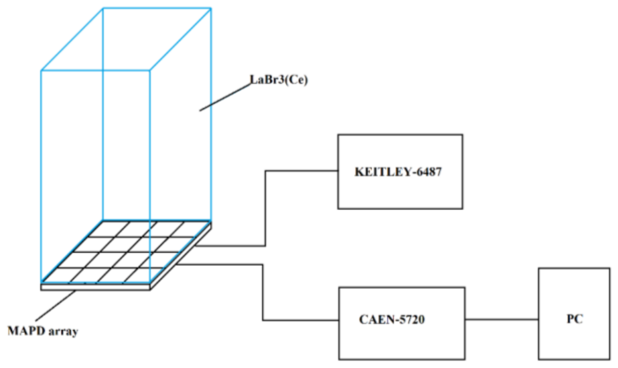


Fig. 1. Schematic diagram of the experimental setup.

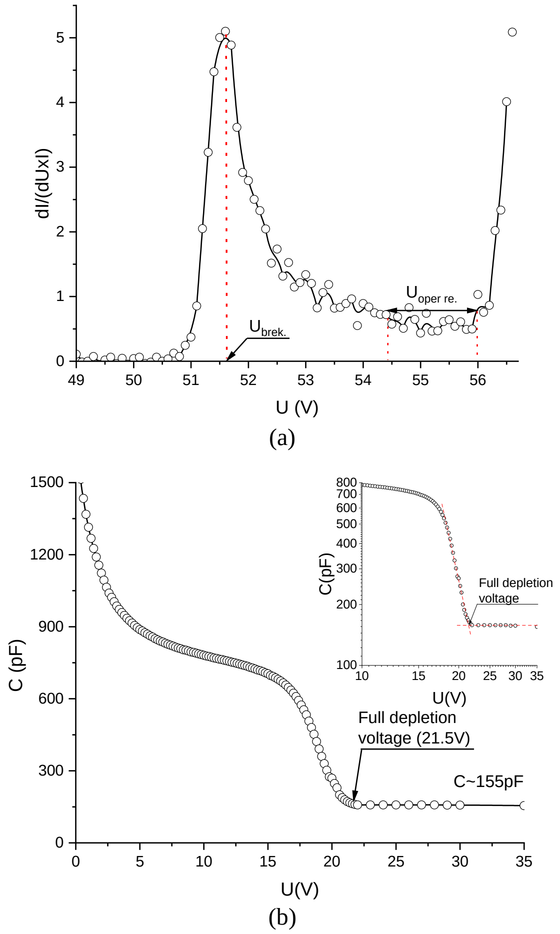
Artificially produced radionuclides ^{177}Lu and ^{133}Ba were used as the gamma-ray sources in the study of the low-energy gamma-ray detection performance of the detector. The half-life of ^{177}Lu is 6.65 days. It transforms to ^{177}Hf by beta decay (–β) emitting gamma-rays with the energies of 72, 113, 208, 250 and 321 keV [5].

The half-life of ^{133}Ba is 10.5 years. It transforms to ^{133}Cs by electron capture, which is accompanied by emission of gamma-rays with the energies of 53.16, 79.62, 81, 160.61, 223.25, 276.39, 302.58, 356 and 383.84 keV [29].

The measurements were done inside an 11.5 thick lead shielding Model 747 Canberra.

3. Results and discussion

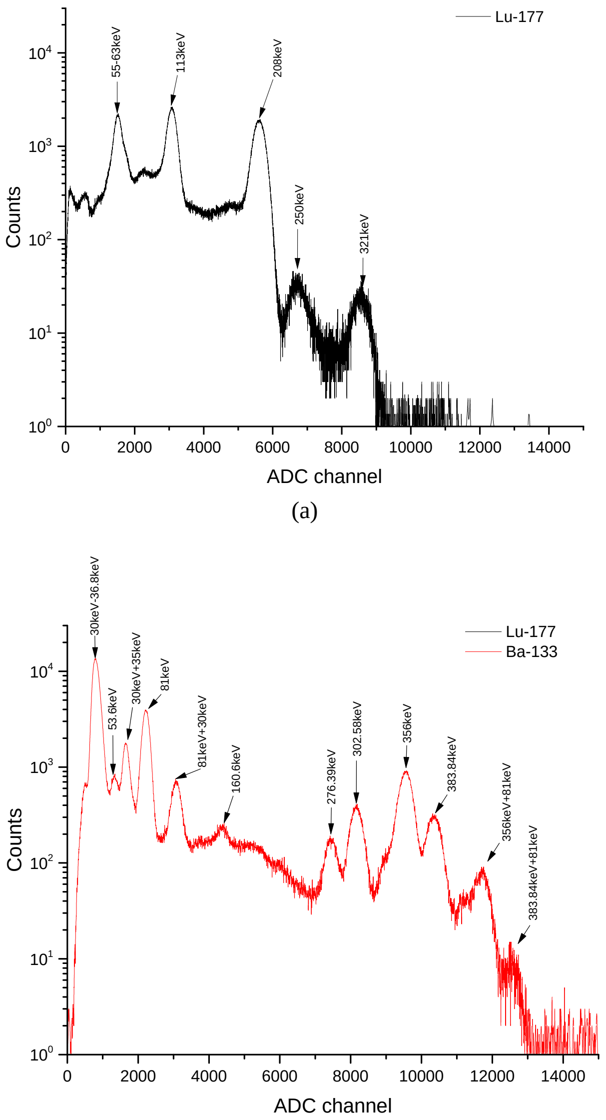
The detailed information about the operation principle and type of the MAPD photodiode is provided in [9, 29]. The MAPD operation voltage is determined from the relative derivative of the *I–V* curve (Fig. 2a). The breakdown voltage (V_{br}) is equal to 51.6 V and the operation voltage range of MAPD is 54.5…56 V [9]. The optimal operation voltage of MAPD-3NM-II is 55.4 V.



(a)

(b)

Fig. 2. Relative derivative of the reverse *I–V* characteristic (a) and capacitance characteristic of the MAPD (b) as functions of applied voltage.



(a)

(b)

Fig. 3. Energy spectra of ^{177}Lu (a) and ^{133}Ba (b) radioisotope at the applied voltage 55.4 V for LaBr$_3$(Ce) + MAPD-3NM-II.

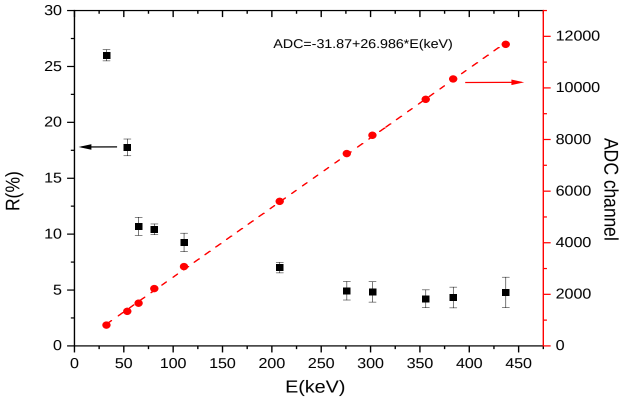


Fig. 4. Energy resolution and amplitude of gamma-ray signals as functions of energy.

The capacitance-voltage characteristic of the photodiode is shown in Fig. 2b. The capacitance of MAPD decreases with increasing bias voltage (Fig. 2b). The full depletion voltage of MAPD is 21.5 V and its capacitance reaches C_p = 155 pF in this case. The total capacitance of 16 MAPD elements connected in parallel is C_{tot} = 16·155 pF = 2480 pF = 2.48 nF [9, 29]. The PDE of MAPD-NM-II changes in the range of 16–35%, while the MAPD-NM-II gain range is (1.5…3)·10^5 [9].

The detection performance of low-energy gamma radiation with LaBr$_3$(Ce) and the new MAPD-3NM-II are shown in Fig. 3. The high PDE of MAPD and high light output of LaBr$_3$(Ce) allow to separate main photopeaks that play a key role in determining the energy resolution for other lines.

The characteristic X-ray lines of ^{177}Hf and gamma-ray lines of ^{177}Lu of 55, 63, 113, 208, 250 and 321 keV are visible in the spectrum (Fig. 3a).

^{133}Ba is transformed by electronic capture into ^{133}Cs in excited states. Transition from the excited states to the ^{133}Cs ground state occurs by emission of gamma-quanta with the energies of 53.16, 79.62, 81, 160.61, 223.25, 276.39, 302.58, 356 and 383.84 keV. Characteristic X-ray peaks of ^{133}Cs, namely K_α at 30.6…31 keV and K_β at 34.9…36.8 keV, are also visible in the spectrum (Fig. 3b). Our detector enables separation of photopeaks with close energies (56.3 and 65 keV). Such property is caused by the low-energy resolution of the developed scintillation detector. The energy resolution is typically defined as the ratio of the full-width at half-maximum (FWHM) to the centroid of a photopeak. The energy resolution of gamma-rays varies in the range of 26–4.2% (Fig. 4, square symbols). The Compton continuum of the detector response and low intensity of gamma-rays do not allow obtaining the resolution of low-energy gamma rays for some photopeaks. The amplitude of the photopeak changes linearly with the energy of gamma-rays (Fig. 4, circle symbols). The total number of pixels in each element of the MAPD array enables detecting several MeVs gamma-rays with linearity performance.

4. Conclusion

The gamma-ray detection performance of a MAPD-3NM-II array with a LaBr$_3$(Ce) scintillator is investigated. The new scintillation detector allows to obtain good linearity in the range of 30…437 keV. The high PDE of MAPD and high light output of the LaBr$_3$(Ce) scintillator ensure good energy resolution that vary in the range of 26–4.2%. All these advantages open up the possibility of using this type of detectors for detecting low-energy gamma-radiation in nuclear medicine diagnosis and therapy.

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References

1. Knoll G.F. *Radiation Detection and Measurement*, 4th Edition. Wiley Press, 2010.
2. Khoshakhlagh M., Islamian J.P., Abedi S.M., Mahmoudian B. Development of scintillators in nuclear medicine. *World J. Nucl. Med*. 2015. **14**, No 3. P. 156–159. https://doi.org/10.4103/1450-1147.163241.
3. Wernick M.N. and Aarsvold J.N. *Emission Tomography*: *The Fundamentals of PET and SPECT*. Academic Press, 2004.
4. Iwanczyk J.S., Iniewski K. *Radiation Detection Systems*, 2nd Edition. CRC Press, 2021.
5. Banerjee S., Pillai M.R.A., and Knapp F.F. (Russ). Lutetium-177 therapeutic radiopharmaceuticals: Linking chemistry, radiochemistry, and practical applications. *Chem.Rev*. 2015. **115**, No 8. P. 2934–2974. https://doi.org/10.1021/cr500171e.
6. Ahmadov F., Abdullayev F., Ahmadov G. *et al*. New phoswich detector based on LFS and *p*-terphenyl scintillators coupled to micro pixel avalanche photodiode. *Funct. Mater*. 2017. **24**, No 2. P. 342–344. https://doi.org/10.15407/fm24.02.341.
7. Ahmadov F., Ahmadov G., Anfimov N. *et al.* Alpha particle detector based on micropixel avalanche photodiodes. *Phys. Part. Nucl. Lett.* 2013. **10**, No 7. P. 778–779. https://doi.org/10.1134/S1547477114010038.
8. Ahmadov G., Ahmadov F., Holik M. *et al*. Gamma-ray spectroscopy with MAPD array in the readout of $LaBr_3$:Ce scintillator. *J. Instrum.* 2021. **16**. P. 07020. https://doi.org/10.1088/1748-0221/16/07/P07020.
9. Ahmadov F., Ahmadov G., Akbarov R. *et al*. Investigation of parameters of new MAPD-3NM silicon photomultipliers. *J. Instrum.* 2022. **17**. P. C01001. https://doi.org/10.1088/1748-0221/17/01/C01001.
10. Nuriyev S., Ahmadov F., Sadygov Z. *et al*. Performance of a new generation of micropixel avalanche photodiodes with high pixel density and high photon detection efficiency. *Nucl. Instrum. Methods Phys. Res. A.* 2018. **912**. P. 320–322. https://doi.org/10.1016/j.nima.2017.12.006.
11. Danilenko I., Gorban O., Maksimchuk P. *et al*. Photocatalytic activity of ZnO nanopowders: The role of production techniques in the formation of structural defects. *Catalysis Today.* 2019. **328**. P. 99–104. https://doi.org/10.1016/j.cattod.2019.01.021.
12. Gorban O., Synyakina S., Volkova G. *et al*. Formation of metastable tetragonal zirconia nanoparticles: Competitive influence of the dopants and surface state. *J. Solid State Chem.* 2015. **232**. P. 249–255. https://doi.org/10.1016/j.jssc.2015.09.026.
13. Nuruyev S., Ahmadov G., Sadigov A. *et al*. Performance of silicon photomultipliers at low temperature. *J. Instrum.* 2020. **15**, No 03. P. C03003. https://doi.org/10.1088/1748-0221/15/03/C03003.
14. Akbarov R., Ahmadov G., Ahmadov F. *et al.* Fast neutron detectors with silicon photomultiplier readouts. *Nucl. Instrum. Methods Phys. Res. A.* 2019. **936**. P. 549–551. https://doi.org/10.1016/j.nima.2018.11.089.
15. Holik M., Ahmadov F., Sadygov A. *et al*., Investigation of the possibility of a new detector based on SiPM in nuclear forensics. *J. Instrum.* 2023. **18**. P. C01015. https://doi.org/10.1088/1748-0221/18/01/c01015.
16. https://www.epic-crystal.com/halide-scintillators/cebr3-scintillator.html.
17. Sadigov A., Ahmadov F., Ahmadov G. *et al.*A new detector concept for silicon photomultipliers. *Nucl. Instrum. Methods Phys. Res. A.* 2016. **824**. P. 135–136. https://doi.org/10.1016/j.nima.2015.11.013.
18. Sadygov Z., Ahmadov F., Khorev S. *et al.* A new method to improve multiplication factor in micro-pixel avalanche photodiodes with high pixel density. *Nucl. Instrum. Methods Phys. Res. A.* 2016. **824**. P. 137–138. https://doi.org/10.1016/j.nima.2015.11.008.
19. Makarova T., Zakharchuk I., Geydt P. *et al.* Assessing carbon nanotube arrangement in polystyrene matrix by magnetic susceptibility. *Carbon.* 2016. **96**. P. 1077–1083. https://doi.org/10.1016/j.carbon.2015.10.065.
20. Lyubchyk A., Filonovich S., Mateus T. *et al.* Nanocrystalline thin film silicon solar cells: A deeper look into *p/i* interface formation. *Thin Solid Films*. 2015. **591**. P. 25–31. https://doi.org/10.1016/j.tsf.2015.08.016.
21. Sadygov Z., Ariffin A., Akhmedov F. *et al.* Technology of manufacturing micropixel avalanche photodiodes and a compact matrix on their basis. *Phys. Part. Nucl. Lett*. 2013. **10**, No 7. P. 780–782. https://doi.org/10.1134/S154747711401018X.
22. Sadigov A., Suleymanov S., AhmadovF. *et al.* A micropixel avalanche phototransistor for time of flight measurements. *Nucl. Instrum. Methods Phys. Res. A.* 2017. **845**. P. 621–622. https://doi.org/10.1016/j.nima.2016.06.081.
23. Akbarov R., Nuriyev S., Ahmadov F. *et al.* Scintillation light detection with MAPD-3NK and MPPC-S12572-010P readout. *KnE Energy, The 3rd International Conference on Particle Physics and Astrophysics (ICPPA),* 2018. P. 357–362. https://doi.org/10.18502/ken.v3i1.1767.
24. Akbarov R.A., Nuruyev S.M., Ahmadov G.S. *et al.* Scintillation readout with MAPD array for gamma spectrometer. *J. Instrum.* 2020. **15**, No 1. P. C01001. https://doi.org/10.1088/1748-0221/15/01/C01001.
25. Holík M., Ahmadov F., Ahmadov G. *et al.* Miniaturized read-out interface “Spectrig MAPD” dedicated for silicon photomultipliers. *Nucl. Instrum. Methods Phys. Res. A.* 2020. **978**. P. 164440. https://doi.org/10.1016/j.nima.2020.164440.
26. Ahmadov F., Abdullayev F., Akberov R. *et al.* On iterative model of performance of micropixel avalanche photodiodes. *Nucl. Instrum. Methods Phys. Res. A.* 2018. **912**. P. 287–289. https://doi.org/10.1016/j.nima.2017.11.082.

27. Petrov E., Shevchenko Y., Gorbach V. *et al.* Features of gate-tunable and photon-field-controlled optoelectronic processes in a molecular junction: Application to a ZnPc-based transistor. *AIP Adv.* 2022. **12**. P. 105020. https://doi.org/10.1063/5.0119257.
28. Petrov E., Gorbach V., Ragulya A. *et al.* Gate-tunable electroluminescence in Aviram-Ratner-type molecules: kinetic description. *J. Chem. Phys.* 2020. **153**, No 8. P. 18574. https://doi.org/10.1063/5.0018574.
29. http://dpnc.unige.ch/~cmartin/ADC/GD2080_caen_digitizer_overview_rev2.pdf.
30. https://www.originlab.com/2021.
31. Holik M., Ahmadov F., Sadigov A. *et al.* Gamma ray detection performance of newly developed MAPD-3NM-II photosensor with $LaBr_3$(Ce) crystal. *Sci Rep*. 2022. **12**. P. 15855. https://doi.org/10.1038/s41598-022-20006-z.
32. Petrov E., Shevchenko Y., Snitsarev V. *et al.* Features of superexchange nonresonant tunneling conductance in anchored molecular wires. *AIP Adv.* 2019. **9**. P. 115120. https://doi.org/10.1063/1.5124386.

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Isayev Kenan: sample preparation, conceptualization, programming, project administration.
Naghiyev Jalal Ahadbala: signal analysis, data curation, formal analysis, visualization
Holik Michael: electronic circuit and readout system preparation, supervision.
Tryshyn V.V.: methodology, formal analysis, investigation.
Lyubchyk S.I.: visualization, formal analysis, investigation.
Pekur D.V.: validation, resources, formal analysis.

Дослідження ефективності детектування низькоенергетичного гамма-випромінювання кремнієвим фотопомножувачем зі LaBr$_3$(Ce) сцинтилятором

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Анотація. Прогрес в області сцинтиляторів і кремнієвих фотопомножувачів (SiPM) в останні роки дозволив розробити нові сцинтиляційні детектори, які можуть бути використані для виявлення низькоенергетичних джерел рентгенівського і гамма-випромінювання і широко застосовуються в медицині, сфері безпеки і промисловості. Розроблений сцинтиляційний детектор компактний, нечутливий до магнітних полів, має низьку робочу напругу і може використовуватися при кімнатній температурі. Ці переваги SiPM дозволяють вирішити основні проблеми, які сьогодні виникли при застосуванні сцинтиляційних детекторів у медицині та промисловості. Наразі актуальною є розробка детекторів для низькоенергетичного променя електромагнітного випромінювання. Сцинтиляційний детектор на основі дрібнодисперсного силікату лютецію, LaBr$_3$(Ce), NaI та кремнієвого лавинного фотопомножувача (MAPD) відкриває широкі можливості для детектування рентгенівського та гамма-випромінювання. У представленій роботі продемонстровано ефективність детектування гамма-квантів новою матрицею MAPD (16 (4×4) елементів – 15×15 см) зі LaBr$_3$(Ce) сцинтилятором (15×15×30 мм) до гамма-випромінювання. Як джерела гамма-випромінювання використовуються ізотопи ^{177}Lu та ^{133}Ba.

Ключові слова: детектування низькоенергетичного гамма-випромінювання, кремнієвий фотопомножувач, LaBr$_3$(Ce) сцинтилятор.