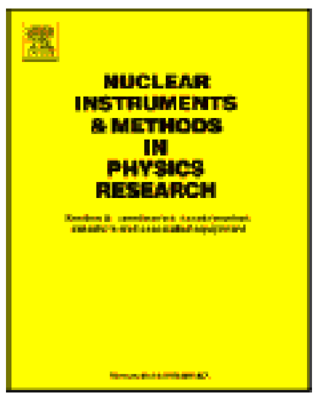
Nuclear Instruments and Methods in Physics Research A 610 (2009) 381–383

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima



Performance of new Micro-pixel Avalanche Photodiodes from Zecotek Photonics

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ARTICLE INFO

Available online 27 May 2009

Keywords:
Micro-pixel Avalanche Photodiode
MAPD
Photodetector
SiPM
APD

ABSTRACT

Two new types of Micro-pixel Avalanche Photodiodes (MAPD) with sensitive area $3\times3\,\text{mm}^2$ and pixel densities of 15 000 and 40 000/mm^2, respectively, were designed and produced by Zecotek Photonics, Inc. Design and operation principles of these devices are described in this work. Measurement results of basic parameters are given as well.

1. Introduction

There has been a significant advance within last decade in the development of semiconductor and hybrid sensors capable of detecting weak light signals with high efficiency. Three types of Micro-pixel Avalanche Photodiodes (MAPD) have been proposed in our collaboration [1,2]. One of them, also called as the Silicon PhotoMultiplier (SiPM), is widely known at present. However, the SiPM design has limited linearity of photoresponse because of low density of micro-pixels. The present work discusses design and operation principles of a new MAPD with ultrahigh pixel density, which results in significant improvement of device linearity.

2. MAPD design and operation principles

The MAPDs are manufactured by Zecotek Photonics, Inc. The MAPD design contains a matrix of deeply buried micro-wells of vertical p–n–p–n structures, which result in development and subsequent suppression of avalanche processes in independent micro-channels. After it is developed, the avalanche process is self-quenched due to opposite electric fields created by free charges collected in these channels. Such MAPD design provides super-high linearity of photoresponse due to the high pixel density on the sensitive area of the device. In the first two production runs, devices with $3\times3\,\text{mm}^2$ active areas were fabricated with two different pixel densities of 15 000 and 40 000/mm^2, referred to as MAPD-3A and MAPD-3B, respectively.

Fig. 1 shows an MAPD structure and an energy zone diagram. The device consists of a silicon substrate of n-type conductivity on the surface of which an epitaxial layer of p-type conductivity of about 8 μm depth has been grown. The substrate and the epitaxial layer make together a flat p–n junction. An array of semiconductor areas (pixels) of n-type conductivity is created in the middle of the epitaxial layer so that the pixels make a p–n junction with the epitaxial layer. As a result, independent p–n junctions (multiplication channels) are formed within the device in the direction orthogonal to the substrate surface.

In the proposed device, photocurrent multiplication by avalanche process takes place only in the p–n–p–n junction areas which are independent of each other. In operation, a voltage with polarity, corresponding to depletion of the semiconductor substrate from primary charge carriers, is applied to the epitaxial layer contact. In this case, middle junction in the triple p–n–p–n junction is biased in forward direction and two external junctions are biased in reverse direction. Areas of the p–n junction between p–n–p–n junctions are also biased in reverse direction. As a result, the shape of the electric field is such that it drives the photoelectrons produced in the upper photosensitive semiconductor layer into the p–n–p–n junction areas.

Photoelectron multiplication takes place first from the top p–n junction of the multiplication channels. The next p–n junction, biased in the forward direction, acts as a potential well about 0.5–0.7 V deep, in which the multiplied electrons are collected. Accumulation of electrons in the potential well for a few nanoseconds leads to a sharp decrease in the electric field in the

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doi:10.1016/j.nima.2009.05.123

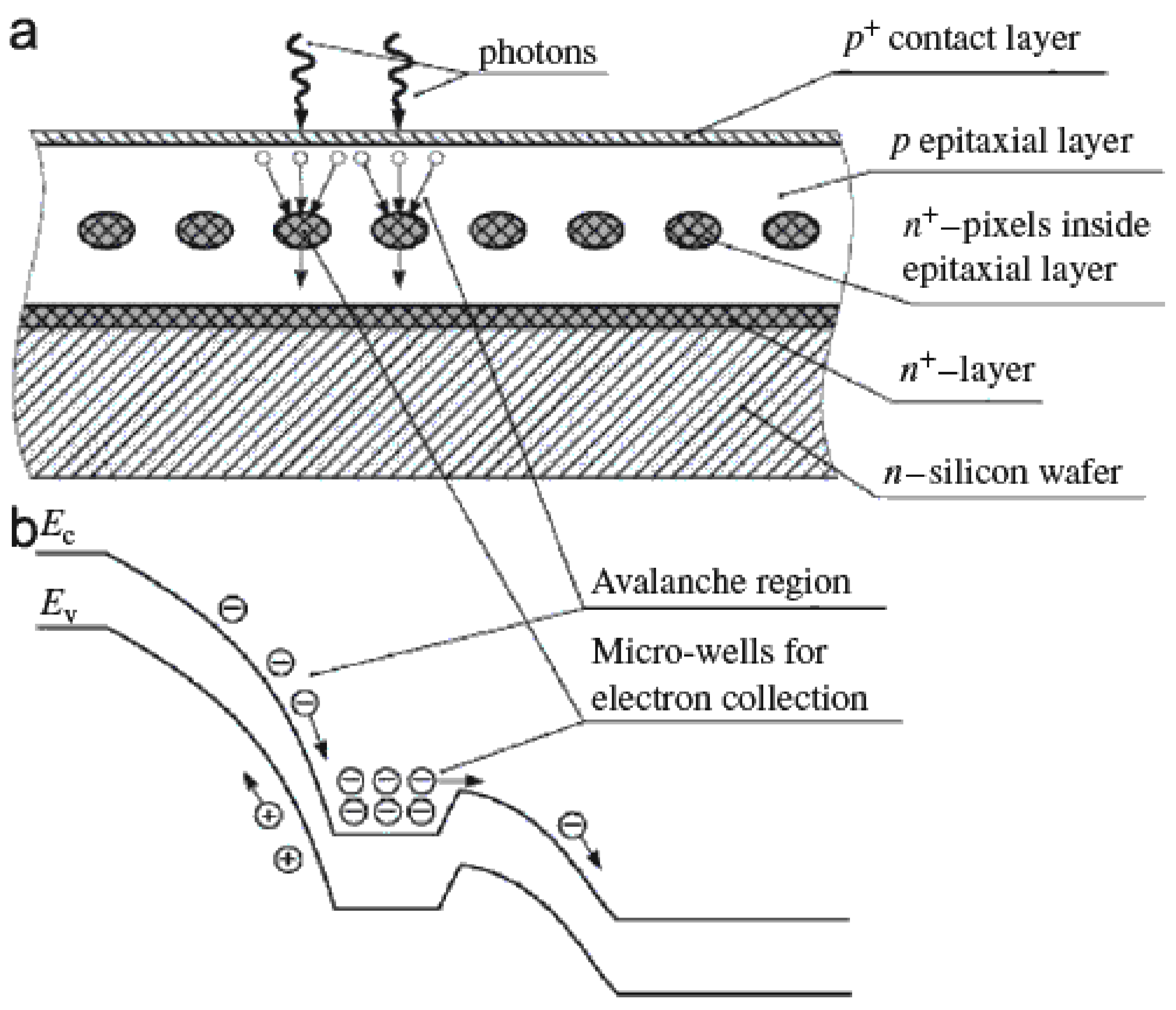

Fig. 1. Structure (a) and energy zone diagram of (b) Micro-pixel Avalanche Photodiode [3].

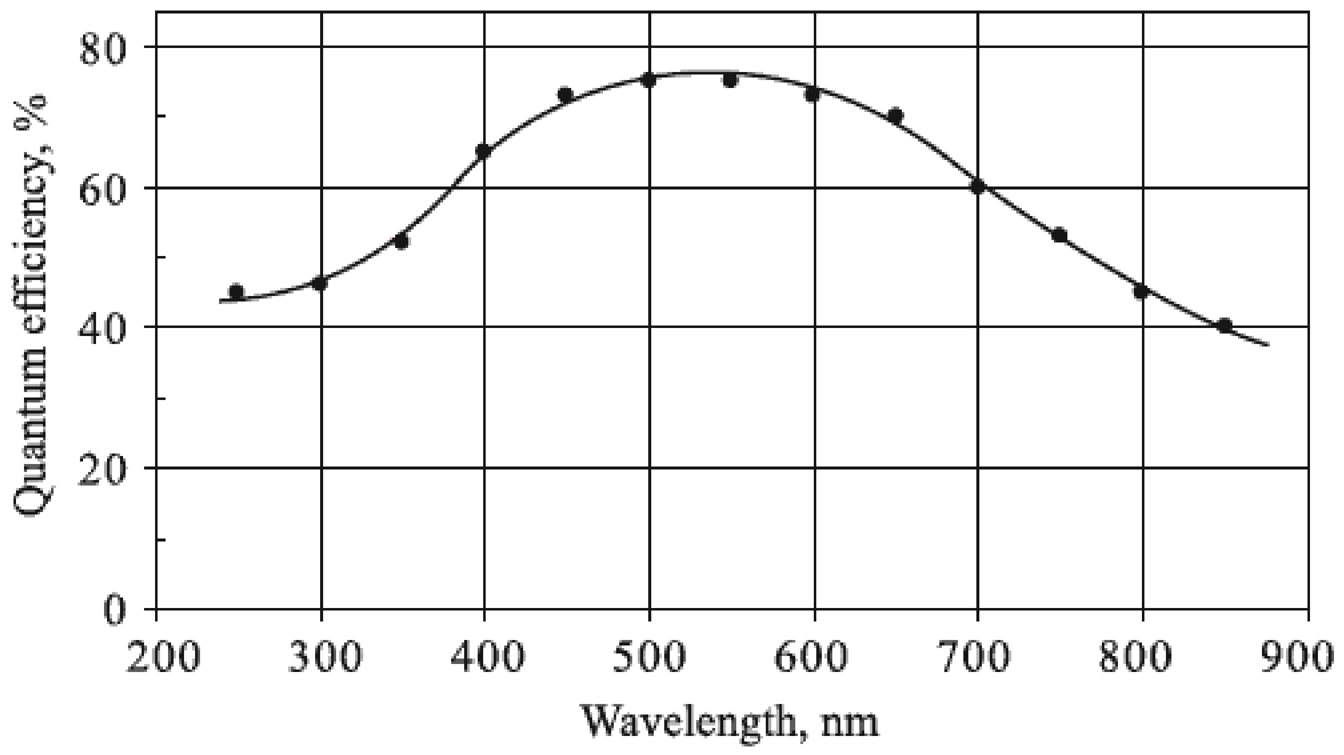

Fig. 2. Spectral dependence of MAPD-3B quantum efficiency. Measurements were conducted with bare devices (no epoxy cover).

avalanche region (i.e., in the first p–n junction) and as a result, the avalanche process in this multiplication channel is quenched. Within a few tens of nanoseconds after the avalanche process is stopped, the accumulated electrons drift into the substrate due to sufficient leakage of the third p–n junction. Thus, the avalanche amplification of photoelectrons takes place in independent multiplication channels that do not have charge coupling between themselves. This results in better operation stability and an increased sensitivity of the avalanche photodiode.

Fig. 2 shows the spectral dependence of the quantum efficiency of the MAPD samples. The quantum efficiency was measured at 10 V MAPD bias voltage. At this voltage the MAPD gain was equal to 1. The photodiode S1223 from HAMAMATSU was used as a reference. The achieved high sensitivity of the MAPD in the short-wavelength spectral range will allow their application both in scintillation and Cherenkov particle detectors.

Dependence of the gain on the applied voltage is shown in Fig. 3. The gain was calculated as a ratio of the photosignal charge at the given bias voltage to the value at bias voltage of 10 V when gain is equal to one. Measurements were made with LED light pulses with wavelength $\lambda = 430$ nm. It was established that in both MAPD types, gains up to 10^5 can be reached. The difference in behaviour of the samples is due to different pixel capacitances of the MAPD-3A and MAPD-3B samples.

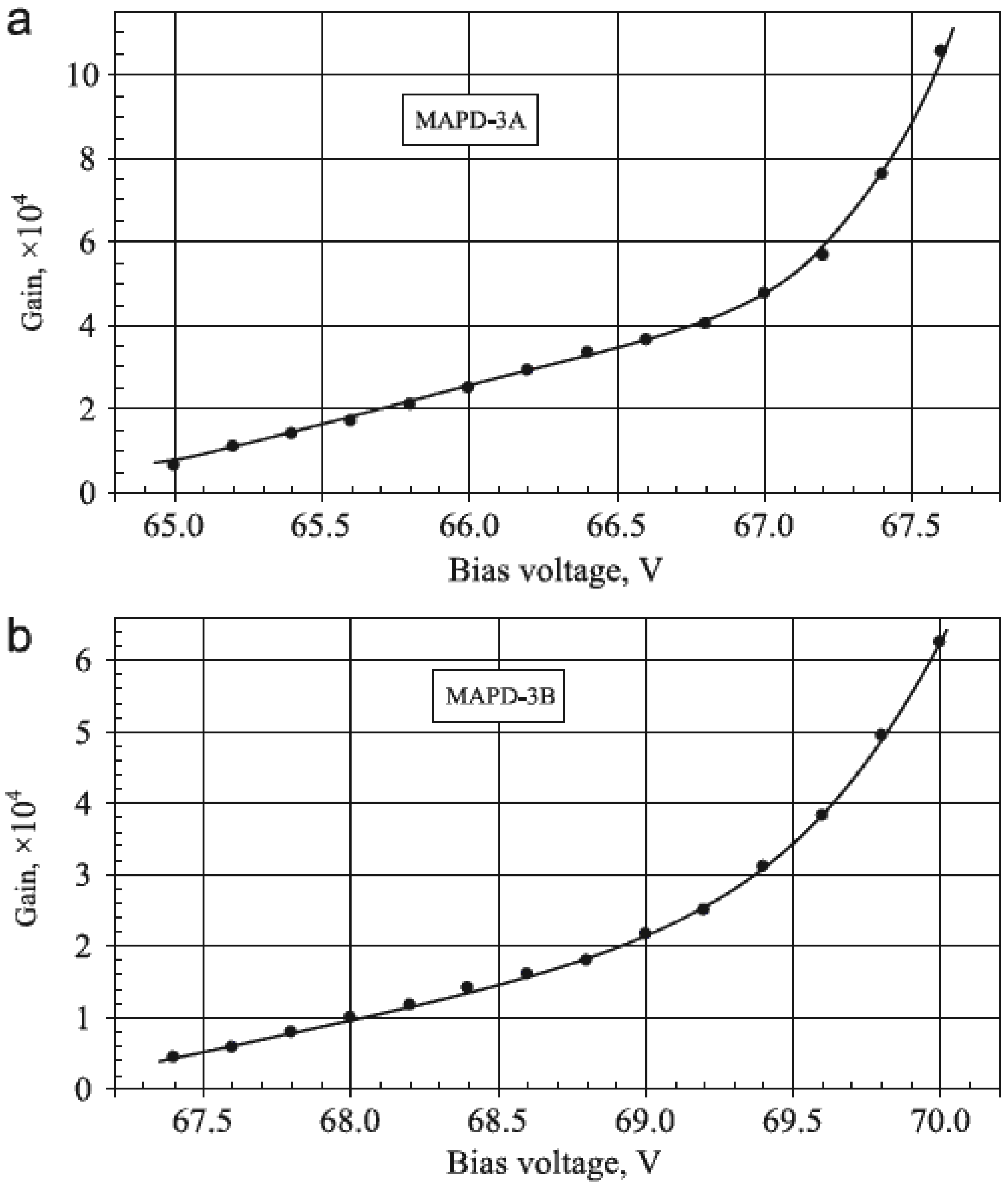

Fig. 3. Dependence of gain on bias voltage for (a) MAPD-3A and (b) MAPD-3B devices. Data were taken at $T = 20\,°C$.

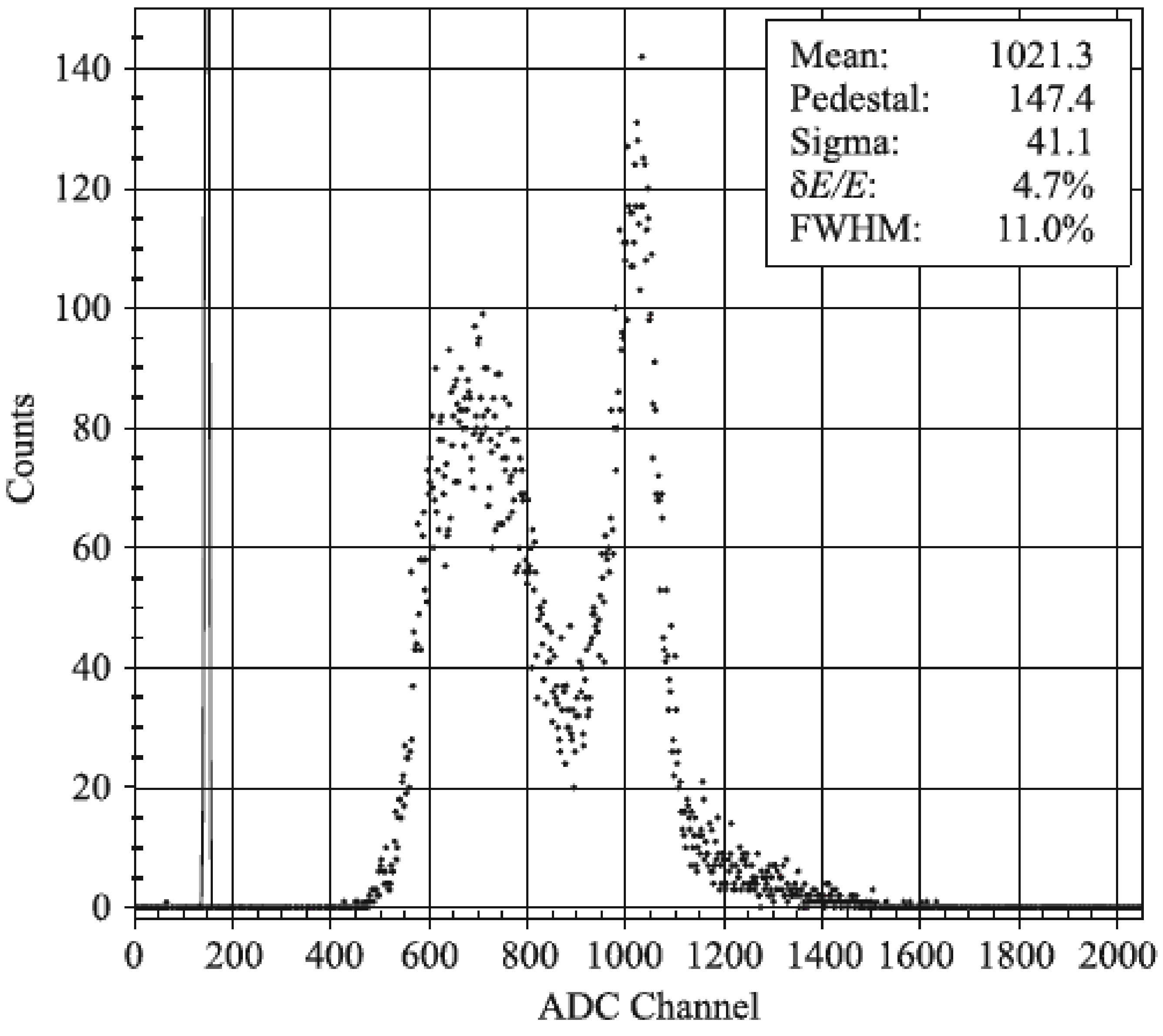

Fig. 4. ^{137}Cs radiation spectrum measured with MAPD-3A and Zecotek LFS-3 scintillator ($3 \times 3 \times 10\,\mathrm{cm}^3$).

The MAPDs themselves cannot be used as particle or γ-radiation detectors and need some medium to convert radiation energy into visible or ultraviolet light. One way is to use them in assembly with scintillating crystals. In this study LFS-3 scintillating crystal with dimensions 3 mm × 3 mm × 10 mm produced by Zecotek Photonics, Inc. was used.

In order to measure energy resolution of the LFS-3 assembly with the MAPD, a ^{137}Cs γ-source was used. The LFS-3–MAPD assembly was shielded from the ^{137}Cs β-radiation by 1-mm-thick lead plate. The MAPD signal after amplification (amplifier gain was 50) was split into two. One part was sent to LeCroy 2249W Analogue to Digital Converter (ADC) and the other was fed into CAEN N-48 discriminator to form a 100-ns-wide gate signal for the ADC.

Fig. 4 shows the ^{137}Cs radiation spectrum detected with the LFS-3 scintillating crystal and MAPD-3A assembly. Energy resolution (Full-Width at Half-Maximum, FWHM) of 11% for the 662 keV γ peak was measured through fitting the distribution by sum of Gaussian and exponential functions. The MAPD-3B has similar resolution.

3. Conclusion

New type of MAPD with ultrahigh pixel density and high energy resolution was developed and tested by Zecotek Photonics Inc. The obtained results show that these devices can be used in new-generation PET scanners (with scintillators), various high-energy physics and astrophysics detectors, as well as in many other fields requiring detectors with high sensitivity and resolution.

Acknowledgements

The research and development work was supported by Zecotek Photonics, Inc. with a grant contribution from INTAS, no. 05-1000008-8114.

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