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NOVEL MICROPIXEL AVALANCHE PHOTODIODES (MAPD) WITH SUPERHIGH PIXEL DENSITY

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Новые микропиксельные лавинные фотодиоды (МЛФД)
со сверхвысокой плотностью пикселей

В большинстве сцинтилляционных детекторов, как правило, в качестве фотодетекторов используется фотоэлектронный умножитель (ФЭУ). В настоящее время фотодиоды находят широкое применение. Твердотельные фотодетекторы позволяют работать в сильных магнитных полях, которые часто присутствуют в установках, например, некоторые калориметры работают вблизи магнитов, комбинированный ПЭТ- и МРТ-томограф и др. Эффективность регистрации фотона (ЭРФ) фотодиодов может достигать значений в несколько раз больше, чем у ФЭУ. К тому же они обладают высокой жесткостью, компактны и имеют относительно низкое рабочее напряжение. В последние несколько лет разработаны и начали использоваться микропиксельные лавинные фотодиоды (МЛФД). МЛФД сочетают большинство преимуществ полупроводниковых фотодетекторов и имеют высокий коэффициент усиления, который близок к ФЭУ. Однако они имеют и некоторые недостатки, один из них — ограниченный динамический диапазон, соответствующий числу пикселей. Новые глубинные микроканальные МЛФД с большой плотностью пикселей, производимые компанией «Zecotek», частично лишены данного недостатка. В настоящей работе представлены характеристики этих фотодетекторов в сравнении с характеристиками ФЭУ. Приведены результаты измерений коэффициента усиления, ЭРФ, перекрестных наводок, счета фотонов. Описаны применения: тесты на пучках частиц двух разных ЭМ-калориметров типа «Шашлык» для экспериментов COMPASS (ЦЕРН) и NICA–MPD (ОИЯИ) со считыванием МЛФД. Показана возможность использования МЛФД в ПЭТ.

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Novel Micropixel Avalanche Photodiodes (MAPD)
with Superhigh Pixel Density

In many detectors based on scintillators the photomultiplier tubes (PMTs) are used as photodetectors. At present photodiodes are finding wide application. Solid state photodetectors allow operation in strong magnetic fields that are often present in applications, e.g., some calorimeters operating near magnets, combined PET and MRT, etc. The photon detection efficiency (PDE) of photodiodes may reach values a few times higher than that of PMTs. Also, they are rigid, compact and have relatively low operating voltage. In the last few years Micropixel Avalanche PhotoDiodes (MAPDs) have been developed and started to be used. The MAPD combines a lot of advantages of semiconductor photodetectors and has a high gain, which is close to that of the PMT. Yet, they have some disadvantages, and one of them is a limited dynamic range that corresponds to a total number of pixels. The novel deep microwell MAPD with high pixel density produced by Zecotek Company partially avoids this disadvantage. In this paper characteristics of these photodetectors are presented in comparison with the PMT characteristics. The results refer to measurements of the gain, PDE, cross-talks, photon counting and applications: beam test results of two different «Shashlyk» EM calorimeters for COMPASS (CERN) and NICA–MPD (JINR) with the MAPD readout and a possibility of using the MAPD in PET.

The investigation has been performed at the Dzhelepov Laboratory of Nuclear Problems, JINR.

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The deep microwell MAPD devices have a common $p{-}n$ junction on the n-type silicon substrate and a clear sensitive surface as a standard APD. Here both the matrix of the avalanche regions and the individual passive quenching elements are placed inside the silicon substrate [1]. The independent avalanche regions (vertical channels) with individual microwells for charge trapping/collection are created at a depth of about $3{-}5$ μm using a special distribution of the inner electric field. Charge collection in individual microwells provides the local self-quenching of avalanche processes in the MAPD. This design allows production of devices with extremely high pixel densities without the Photon Detection Efficiency (PDE) loss.

The first versions of the deep microwell MAPD produced by Zecotek Company [2] were MAPD-3A/B with the pixel gain $2 \cdot 10^4/1 \cdot 10^4$, PDE about 10% in the green region and density of pixels 15 000/40 000 mm^{-2} with the total active area of 3×3 mm.

A new generation of deep microwell MAPDs is represented by the MAPD-3N. This device has improved characteristics in comparison with the previous versions. The MAPD-3N pixel gain, average number of fired pixels for one detected photon due to optical cross-talk [3] and PDE for different light wavelengths depending on bias voltage are shown in Fig. 1. The MAPD properties were studied by means of a fast LED using low-intensity light flashes [4]. The PDE was estimated against the standard spectral response of the Hamamatsu photosensor H6780-04.

To study a possibility of using the MAPD in the positron emission tomography (PET), we made a direct comparison of the PMT and MAPD-3N characteristics using the ^{137}Cs source and the Lutetium Fine Silicate (LFS) scintillation crystal [2]. The γ spectra of ^{137}Cs on the LFS scintillation crystal are shown in Fig. 2. One can see that the energy resolution obtained with the MAPD-3N is comparable with that of the PMT EMI 9814B. For the PET applications, special 8×8 arrays of MAPDs being developed by Zecotek Company are shown in Fig. 3.

Another field of application for the MAPD is high energy physics, especially, EM calorimetry. We are developing prototypes of «Shashlyk» EM modules with the MAPD readout.

The «Shashlyk» EM calorimeter consists of a stack of alternating layers of lead and plastic scintillator read out by means of WLS fibers running through the holes in the scintillator and lead. A few different modules have been tested. In this paper we report measurements of two modules with different samplings and readout by different MAPDs.

The first prototype of the EM module intended for the MultiPurpose Detector (MPD) of the future NICA experiment (JINR) [5] is made from the alternating layers of 0.275 mm thick lead and 1.5 mm thick scintillator plates with dimensions 11×11 cm, which are read out by means of 144 WLS fibers [6] grouped into 9 bundles of 16 fibers each. The module consists of 300 lead/scintillator pairs, which corresponds to the total length of 55.5 cm, or 15.9 radiation lengths.

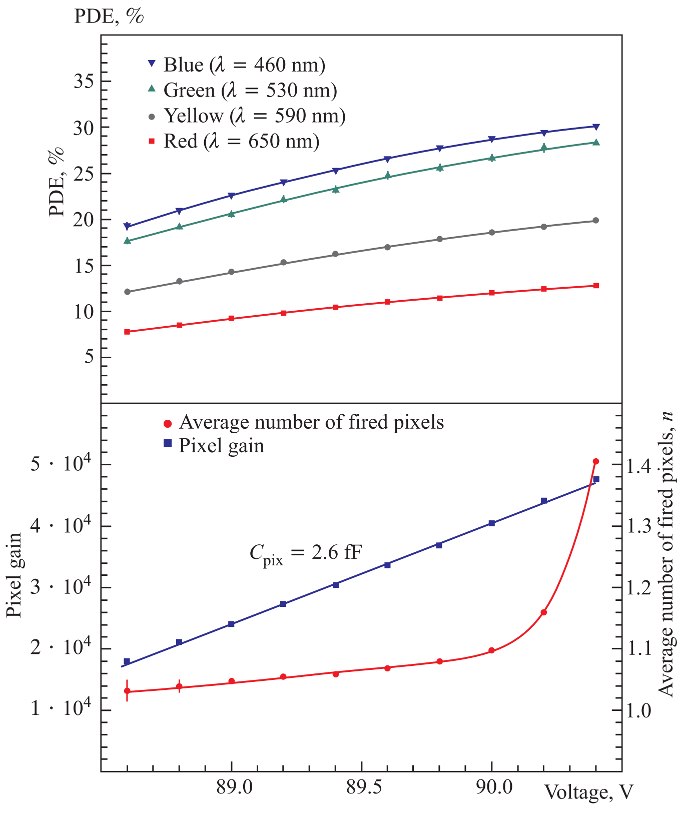

Fig. 1. Pixel gain, PDE and average number of fired pixels versus bias voltage for MAPD-3N at $T = 15\,^{\circ}\mathrm{C}$

At the end of the module the fiber bundles are glued to the simple cone light guide, with the other side diameter matching the MAPD sensitive area.

The second prototype of the EM module intended for the projected electromagnetic calorimeter ECAL0 of the COMPASS experiment (CERN) is made from the alternating layers of 2 mm thick lead with dimensions 12×12 cm and nine 4 mm thick scintillator plates with dimensions 4×4 cm combined together into a common plate and optically separated from each other (towers). These plates are read out by means of 144 WLS fibers grouped into 9 bundles of 16 fibers each. The module consists of 40 lead/scintillator pairs, which corresponds to the total length of 25 cm, or 15 radiation lengths.

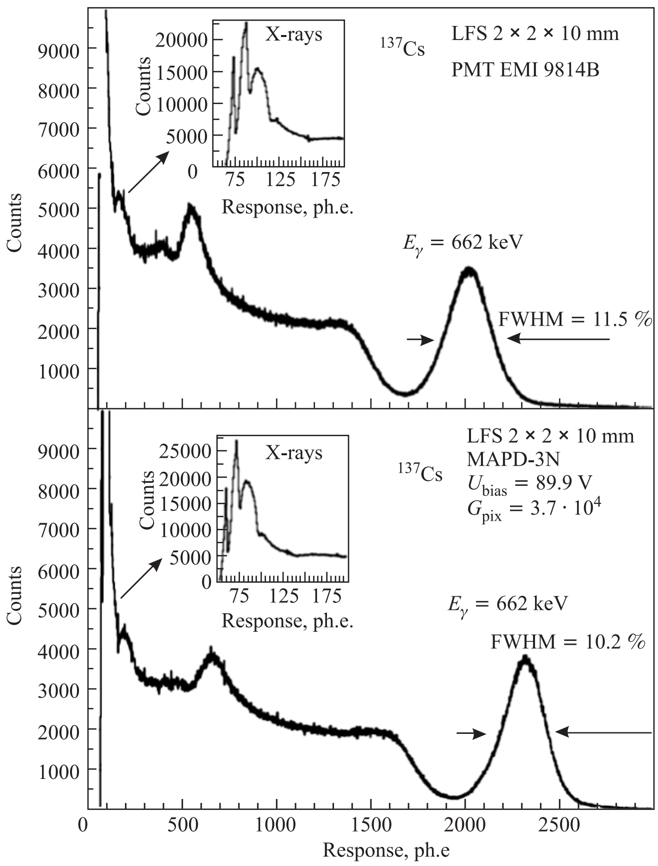

Fig. 2. Amplitude spectra obtained with PMT EMI 9814B and MAPD-3N at detection ^{137}Cs γ quanta a LFS scintillation crystal of size $2 \times 2 \times 10$ mm at $T = 15\,^\circ$C

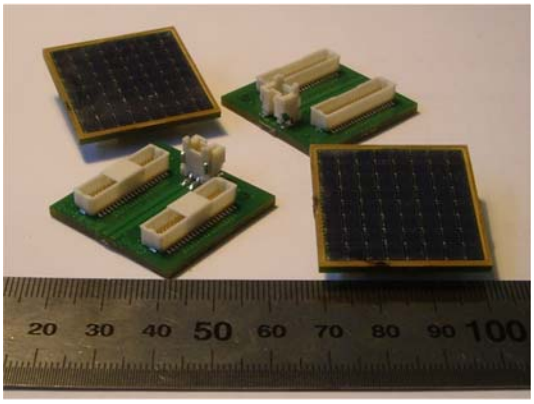

Fig. 3. Photo of 8×8 MAPD arrays being developed by Zecotek Company [2] for PET applications

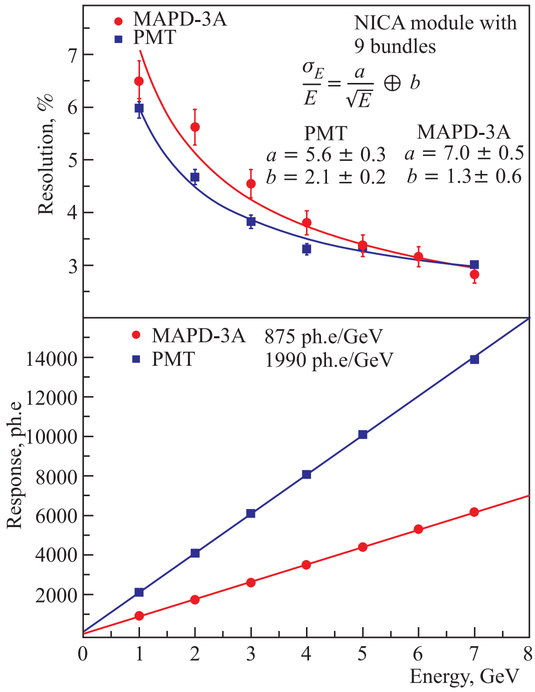

Fig. 4. Responses and energy resolutions of the NICA module prototype read out by PMT EMI 9814B and MAPD-3A at $T = 15\,^{\circ}$C versus electron beam energy

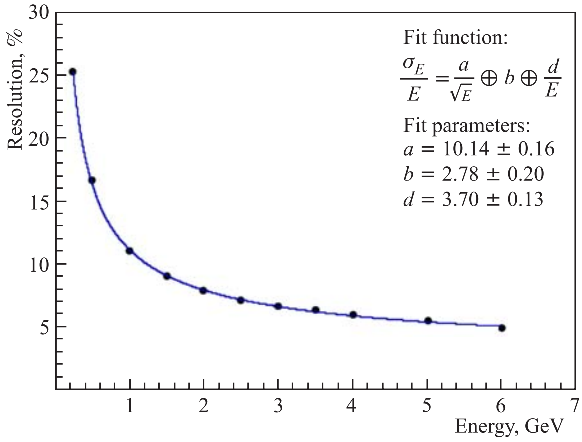

Fig. 5. Energy resolution of the ECAL0 module prototype read out by MAPD-3B at $T = 15\,^{\circ}\mathrm{C}$ versus electron beam energy

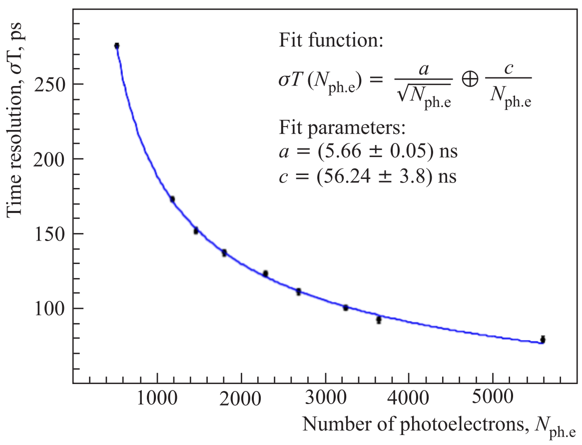

Fig. 6. Time resolution of one calorimeter cell of the NICA module prototype read out by MAPD at $T = 15\,^{\circ}\mathrm{C}$ versus the number of collected photoelectrons

At the end of the module the fiber bundles are connected to the Winston cone light guide [7] glued to the MAPD surface, with the diameter matching the MAPD sensitive area.

For comparison, the calorimeter cells (bundles) of the NICA module prototype were read out by the PMT EMI 9814B and then by the MAPD-3A. The calorimeter cells (towers) of the ECAL0 module prototype were read out by the MAPD-3B.

In the prototypes the MAPDs were fixed on the copper plate placed in a thermally insulated cooling unit. During the tests the temperature was kept at $15\,^{\circ}$C by the thermal stabilization system based on the Peltier element. The signals from the MAPD were amplified by amplifiers with a gain of about 14 and measured by the QDC V792 (CAEN) for the prototype of the NICA module. For the prototype of the ECAL0 module the signals from the MAPD were amplified by amplifiers with a gain of about 37 and measured by the 1.6V/14-bit 100 MHz sampling-ADC ADCM16-LCT (JINR) [8].

The main properties of the calorimeter modules were studied at the T9 CERN PS (NICA) and at the T21 DESY (ECAL0) test-beam facilities. The comparative results of the studies are presented in Fig. 4. One can see that good linearity and energy resolution comparable with those of the PMT were obtained for the MAPD readout in the whole energy range. For the prototype of the ECAL0 module the required energy resolution ($\approx 10\%/\sqrt{E}$) was obtained (see Fig. 5). The term d/E in parametrization of energy resolution arises due to the Coulomb multi-scattering of electrons on the air in spectrometric tract. Due to its higher pixel density, the MAPD-3B has obviously better linearity than MAPD-3A. The time resolution of the NICA module prototype was studied by our group at the T21 DESY test-beam facility. The signals from the MAPD were amplified by the same amplifiers but measured by the ADCM16-LCT [8] that allows the acceptable amplitude and time resolutions. The time resolution of calorimeter was obtained from a correlation of times registered by the neighboring cells of calorimeter when signals have approximately the same amplitudes. The experimentally estimated time resolution of one calorimeter cell of the NICA module prototype is shown in Fig. 6 [5].

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