Prospects of Application of Multi-pixel Avalanche Photo Diodes in Cosmic Ray Experiments

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DOI: 10.7529/ICRC2011/V04/1101

Abstract: Possibilities of using in cosmic ray/astrophysical experiments the Multi-pixel Avalanche Photo Diodes – MAPDs which were developed by "Dubna MAPD" collaboration (JINR – INR – IP AZ – "Zecotek Photonics Singapore" Company) are discussed. The achieved basic parameters of the novel deep micro-well MAPDs with sensitive areas of 1-9 mm^2 are as following: spectral range of sensitivity 300-800 nm, gain 5 10^4, operating voltage 65-90 V, threshold of sensitivity - 1 photoelectron, photon detection efficiency (in maximum) ~30%, maximum density of pixels in a MAPD is 40000 pixels/mm^2. The MAPDs have the linear response up to 60000 photons in a light pulse, their filling factor – the ratio of sensitive area to all area – is equal to 100%. The designed photo sensors are planned to be used in orbital imaging detectors in particular observing transient luminous events (TLE) in the atmosphere. New TLE detector will have advantage of high temporal resolution and a possibility to observe events in various "colors" – from UV (300-400 nm) to red (600-800 nm).

Keywords: Silicon Photomultipliers, SiPMs, Multi-pixel Avalanche Photo-Diode; MAPD; orbital imaging detectors

1 Introduction.

1.1. Avalanche Photo-Diodes as solid state analogs of PMTs

In the recent years a few versions of photon counters based on silicon Avalanche Photo-Diodes (APDs) had been discussed at numerous conferences including Cosmic Ray Conferences. Mosaic APD detectors – solid state analogs of multi-channel Photo Multiplier Tubes (PMTs) - can be widely used in the High-Energy Physics, Cosmic Ray Physics, Astrophysics, Medicine etc., (see Proceedings Beaune – 2005 [1-2], [3], ICRC-2007 [4 -5], ICRC-2009 [6]). The interest in the new APDs is driven by their compactness, high quantum efficiency, low operation voltage, insensitivity to magnetic fields and potentially a lower cost in comparison with photomultipliers.

Very good prospects have CCD APDs – CCD with internal gain [7].

In this paper the Multi-pixel APDs with individual micro-wells (MAPDs) [8, 1, 5] which had been developed by "Dubna MAPD" collaboration (Joint Institute of Nuclear Research, Dubna; Institute for Nuclear Research of Russian Ac. Sci., Moscow; Institute of Physics of Azerbaijan Ac. Sci.; "Zecotek Photonics Singapore" Company) are described. The characteristic features of one of the last designs of MAPDs – MAPD-3N [9] are given. A possible application of MAPDs in orbital imaging detectors is discussed. Multi-channel detectors of gamma quanta based on MAPDs and crystal scintillators LFS [10] are also mentioned.

1.2. Early days of Multi-pixel Avalanche Photo-Diodes (MAPDs)

First successful steps in the development of a new type of APD with the local negative feedback had been made in 80^{th} by a collaboration of the Institute for Nuclear Research (Z. Sadygov et al.) and the MELZ Company (V. Golovin et al.). Investigations of avalanche process in various multi-layer silicon structures with resistive layer to "control" avalanche process in APDs were supported in the framework of the Soviet DUMAND project led by M. Markov in 1981-1991. The MRS (Metal-Resistive layer-Silicon) structures with high resistivity as silicon carbide and amorphous silicon layers had been chosen as a main object of investigation. The first results on planar MRS APDs were published in 1988-1989 [11] (see also [12]).

The next design of APDs with individual vertical resistors – micro-channel MRS APD had good characteristics and became the basic version of MAPDs in 1989-1991 [13].

2 Features and advantages of MAPDs with micro-wells

2.1. Three designs of MAPDs

Three designs of MAPDs developed by INR/JINR between 1991 and 2005 were free of basic design (MRS APD) problems such as a low sensitivity in blue and UV range and a low yield of working devices.

These devices were of following types

- the MAPD with individual surface resistors,
- he MAPD with surface transfer of charge carriers,
- the MAPD with deep buried individual microwells.

Their description was given in [1] (see also [5]).

Characteristics and possible applications of the MAPDs in detectors for the High Energy Physics, in medical researches (PET), etc had been described in a number of papers [14 - 15]

Below some characteristics and the advantages of the third type of MAPD - MAPD-3N produced by "Dubna Detectors Ltd" and "Zecotek Photonics Singapore Pte. Ltd" is presented. MAPD-3N with the active area 3x3 mm^2 has about 3x3x15600~140 thousands pixels (micro-wells). Its structure is shown in Figure 1.

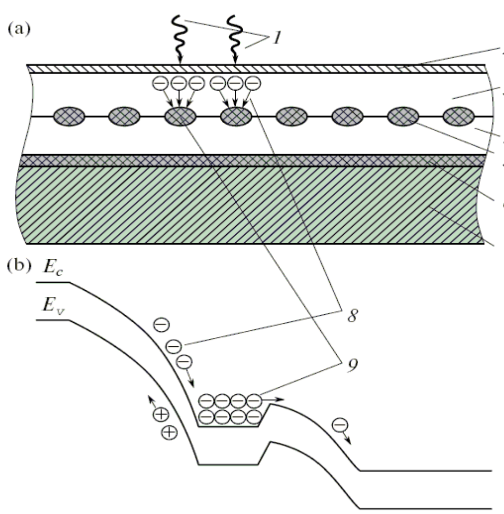

Figure 1. Schematic diagrams showing (a) the cross-section and (b) energy band diagram of MAPD at applied voltage: 1 – incident photons; 2 – high doped p+ layer that provides contact with the p-type epitaxial layer; 3 – second p-type epitaxial layer; 4 – first p-type epitaxial layer; 5 – n+ regions (micropixels); 6 – high doped n+ layer; 7 – n-type silicon substrate; 8 – avalanche region; 9 – charge accumulating microwell of *n*+ type micropixel

2.2. Photon detection efficiency – PDE

In paper [4] photon detection efficiency of SiPM is determined as the product of four factors:

- the light transmission from surface to depletion or drift layers,
- the filling factor of the sensitive area, (sensitive area)/all area),
- the quantum efficiency of silicon,
- Geiger efficiency.

The filling factor of micro-well MAPD is 100% (there are no guard rings, quenching registers, and aluminum conductors around micro-pixels as in SiPM). To increase PDE of MAPDS it is possible to increase their gain. However one has to be careful, if it is necessary, in order not to make worse other parameters, for example the crosstalk.

The PDE of a MAPD-3N is shown in Figure 2.

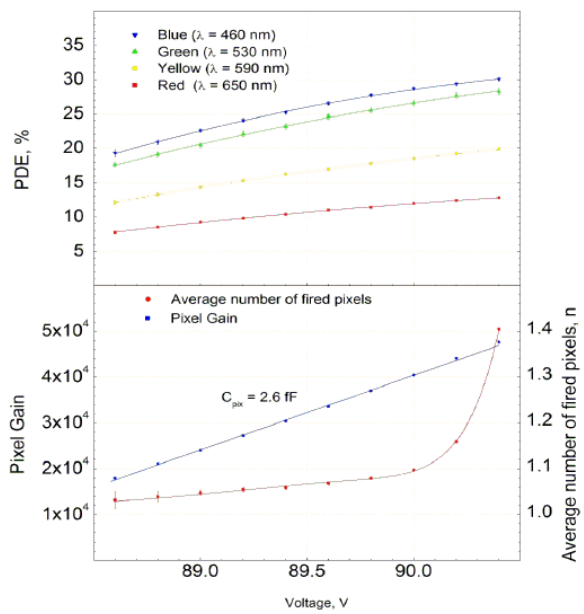

Figure 2. PDE, gain and average number of fired pixels versus bias voltage for the MAPD-3N at T = 15^o C.

2.3. PDE, gain, crosstalk and dark current of MAPD-3N

As it is seen in Figure 2 MAPD-3N has a rather high sensitivity to blue light (PDE =~25-30%). The crosstalk (the average number of fired pixels for one detected photon) is low (<5%), if the gain is 2x10^4 – 4x10^4.

An optimization of MAPD parameters takes place, if the gain is ~3x10^4: then the PDE is ~25% in maximum and the average number of fired pixels is ~5%. And the dark current is ~20 nA (see Figure 3).

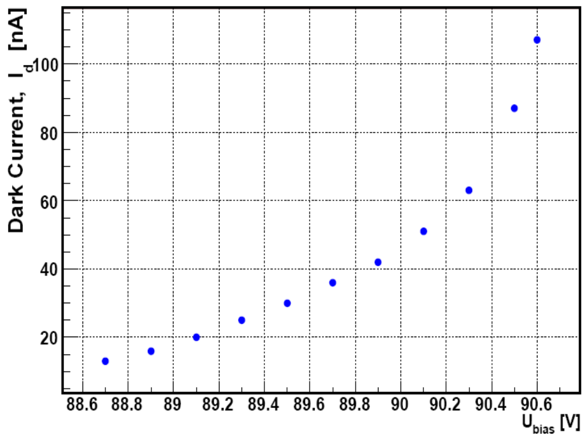

Figure 3. Dark current of MAPD-3N.

2.4. Linear response of MAPD up to 10000 photoelectrons

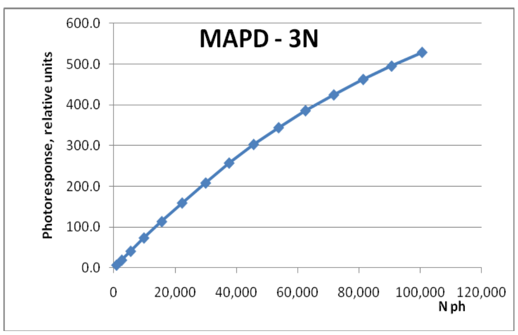

Figure 4. Photo response of MAPD-3N.

Linearity of photo response is a very perspective feature of MAPDs with micro-wells.

2.5. Development of multi-channel modules of gamma detectors based on MAPDs and LFS crystals

4-and 16-channel (mosaic) MAPD-3N modules developed by Dubna MAPD collaboration and the LFS crystal scintillators of 3x3x10 mm^3 developed by Zecotek Innovations [10] were used to construct coordinate-sensitive detectors of gamma quanta.

3 MAPDs and orbital imaging detectors

In many experiments observing various images the high resolution in time and position of photons are needed. Among them the most interesting are images of extreme energy (>50 EeV) fluorescence light tracks of EAS planned in the space experiment JEM-EUSO [16].

Presented above parameters of MAPD (for the MAPD of 3×3 mm^2 size quantum efficiency is ~25% in wavelength range near 400 nm, avalanche dark current 20-30 nA, when gain is $3x10^4$-$5x10^4$ closely suit the needed device parameters in JEM-EUSO – like experiments.

In this case MAPD of 3×3 mm^2 will be the detector pixel in focal plane of the JEM-EUSO lens system with area of 4.5 m^2. Electronics of the detector counts photo electrons in time samples of t=2.5 μs. EAS of energy 100 EeV in maximum of the shower cascade curve produces the count rate of ~100 per time sample. For above mentioned MAPD parameters the internal MAPD noise rate in time sample t is I_d t/(G×1.6 10^{-19}) ~12 counts. Atmospheric noise in the JEM-EUSO MAPD pixel at moonless night expected to be less than 5 counts. Linear response of MAPD to signals with less than 10^4 electrons per 1 mm^2 allows to measure EAS with energies up to 1000 EeV – which is high enough limit as statistics of such very high energy events is negligible due to sharp decrease of EAS event intensity beyond the GZK cut-off. One can see that parameters of MAPD are close to needed in JEM-EUSO – like experiment (although the combination of gain-dark current should be improved for getting lower pixel noise rate).

In experiments devoted to atmosphere transient luminous events (TLE) application of MAPD is even more promising. The TLE signals are six orders of magnitude larger than EAS signals [17]. In study of TLE the imaging detectors with wide field of view (thousands km in the atmosphere) and high space- time resolution (5 km in the atmosphere and 10 μs in time) will be available with MAPD technology.

4 Conclusion.

The current status of MAPDs with deep micro-wells is described. Characterestics of MAPDs produced by the Dubna MAPD collaboration (PDE in blue light ~25-30%, gain ~$5x10^4$, fired pixels ~5%) should be improved and optimized. After that MAPDs might be used in space experiments like the JEM-EUSO project. However the existing MAPDs can be used in space imaging detectors observing transient atmospheric phenomena (luminous events) when global observation of the phenomenon is needed.

Acknowledgements

I. Zheleznykh. and Z. Sadygov are deeply indebted to V. Matveev, A. Olshevski and A. Komar for valuable discussions and support and A. Zagumennyi for given LFS crystals.

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