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Novel Micro-pixel Avalanche Photo Diodes and their Possible Application in Cosmic Ray/Astrophysical Researches

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Abstract: The novel Micro-pixel Avalanche Photo Diodes – MAPDs - with high photon detection efficiency and very good single electron resolution which were produced and tested by "Dubna MAPD" collaboration (JINR – INR – IP AZ –"Zecotek Medical Systems Singapore" Company) are described. The excellent parameters of MAPDs with sensitive areas of 1-9 mm^2, spectral range of sensitivity 250-950 nm and operating voltage ~100 V are achieved due to forming an electric field with a specific geometry in the multilayer silicon structure, which ensures the localization of the avalanche processes and limits them to the micro regions (micro-pixels) with a diameter of 3 - 30 microns depending of the design. The multi channel modules (matrix) on the basis of MAPDs have a high potential for using as key elements for light detection in different fields of Astronomy, Cosmic Ray Physics and Astroparticle Physics, as well as in new generations of medical scanners.

Introduction

In May of 2008 colleagues and pupils of Academician M.A. Markov will celebrate the centenary of his birth (13 May 1908). At the end of 50th - beginning of 60th M. A. Markov initiated the development of a new branch of the Cosmic Ray Physics - the High-Energy Neutrino Physics – and suggested carrying out deep underground (deep underwater) neutrino experiments. Theoretical problems of the High-Energy Neutrino Physics and Astrophysics related to such experiments were discussed in [1-3].

M.A. Markov brought great contribution to the development and creation of new experimental techniques for Cosmic Ray Physics: underground scintillation telescope for investigation of atmospheric neutrinos and gallium-germanium detector for solar neutrinos at Baksan Neutrino Observatory; deep underwater neutrino telescopes in lake Baikal and in the Mediterranean Sea; radio wave detector for ultra-high energy neutrinos in Antarctica at Vostok station; etc. Development of hydro-acoustical and radio-astronomical methods of extremely high-energy cosmic neutrinos detection had been in the scope of interest of M.A. Markov too.

In connection with this long list of detectors for studying neutrino we would like to emphasize that M.A. Markov certainly well understood as many others that the development of the research technique could and will stimulate (as a by-product) development of various industrial applications.

It was not by chance that the development of a new type of APD with the local negative feedback – solid state analog of multi channel PMT - was supported in the frameworks of the Soviet DUMAND project led by M. Markov in 1981-1991.

APDs in 70th

In 1978 a possibility to use semiconductor photo receivers in the Deep Underwater Muon and Neutrino Detection (DUMAND) was considered in [4]. It was particularly emphasized that avalanche photodiodes with a high quantum efficiency (~40%) had been developed on the base of a rather cheap planar silicon technology. They could be effective light quantum detectors if to use them together with plastic or glass fibers (with shifters) as light traps [4].

However those APDs which were successfully used for optical communication had a small sensitive area (diameter ~100 micron) and a signal gain ~10-50. Development of lager area APDs for other applications had serious problems because of micro heterogeneities inside of semiconductor lattice. Micro-plasma breakdown phenomena limited the maximum value of applied voltage, consequently the maximum gain.

Development of a New Type of APDs with Negative Local Feedback – from MDS to MRS APDs - in 80th

Since 1981 when the department of deep underwater neutrino detection was organized in INR by Markov the group of V.I. Shubin at Lebedev Institute and group of Z.Ya. Sadygov at INR had studied possibilities of using in DUMAND-type experiments the Metal-Dielectric-Semiconductor (MDS) avalanche photodiodes which were developed at Lebedev Institute. However MDS structures are only worked at pulse supply mode and they had some disadvantages (instability etc). New APDs had to be designed. There were two main approaches to development of new APD's:

1) Improving purity of semiconductor wafers and using high-technology for production, however this may results in high APD cost;

2) Investigation of avalanche process in various multi-layer silicon structures with resistive layer instead of dielectric one for local suppression effect.

The second approach had been chosen by joint APD group which included collaborators from INR (Z. Sadygov, A. Gasanov, et al.) and MELZ Company (V. Golovin, N. Yusipov) about 20 years ago. The MRS (Metal-Resistive layer-Silicon) structures with high resistivity as silicon carbide and amorphous silicon layers have been chosen as a main objects of investigation.

Planar MRS APDs

The first publications on planar MRS APDs were made in 1988-1989 [5], see also [6].

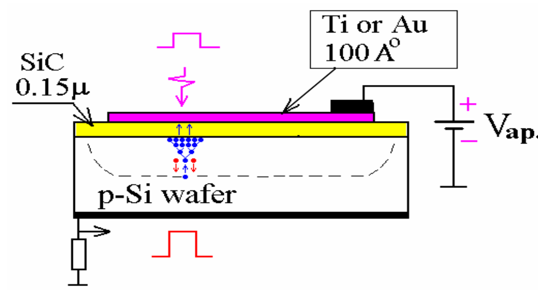

Figure 1: First (planar) Metal-Resistive layer-Silicon APD (1988)

Advantages of such design (Fig. 1) were simple technology and low cost but there were some problems: low yield of APD production because of short circuit effect through SiC resistive layer and limited gain because of charge carriers spreading along Si surface.

Micro-channel MRS APDs

But the next design of APDs with individual vertical resistors – micro-channel APD (Fig. 2) – had good features [7]. Localization of the avalanche micro-regions resulted in the unique device properties: high and uniform gain, abnormal behavior of the excess noise factor that may be reduced up to 1 at high gain!

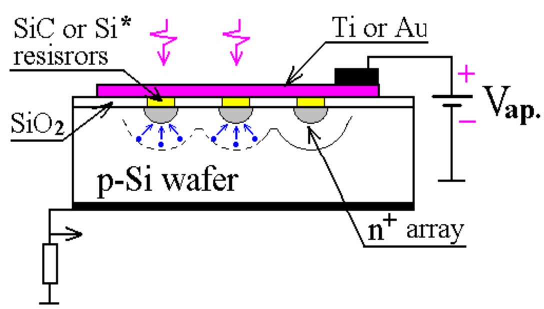

Figure 2: The Micro-channel APD – basic version of MAPD (1989-1991)

Advanced Designs of Micro-pixel Avalanche Photo Diodes developed at INR/JINR after 1991

During last decade different versions of silicon APDs had been widely discussed as advanced photon counters for different applications (for example see talk of Z. Sadygov at the Int. Conf.

in Beaune, France, June 2005 as well as talks of D. Renker, V. Savelev there – http//beaune.in2p3.fr). 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.

The basic design of MAPD [7] had two main problems: a low yield of working devices and a low sensitivity in the blue and UV range. Three advanced designs of MAPDs developed in INR/JINR after 1991, their advantages, restrictions were considered in [8], for their schemes see Fig. 3.1 – Fig. 3.3.

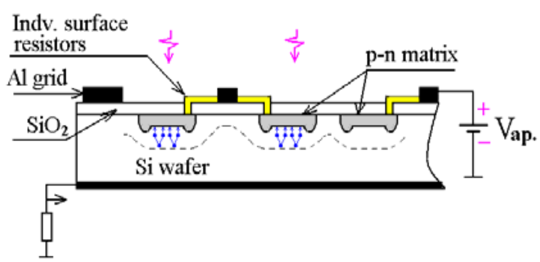

Figure 3.1: the MAPD with individual surface resistors

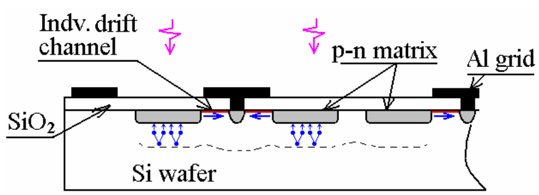

Figure 3.2: the MAPD with surface transfer of charge carriers

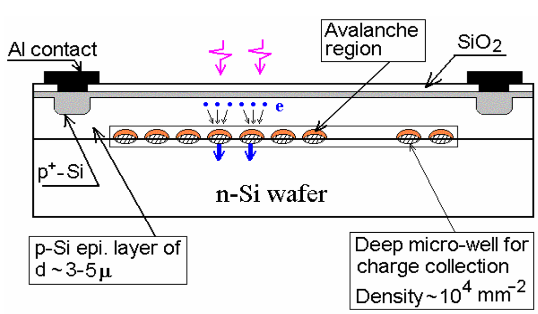

Figure 3.3: the MAPD with individual micro-wells

In these devices the local negative effect is achieved by forming an electric field with a specific geometry in the multilayer silicon structure, which ensures a localization of the avalanche processes and limits them to micro-regions (micro-pixels) of 3-30 microns in diameter depending on the design. About 10^3-10^4 independent pixels per mm^2 are formed on a common silicon substrate. Each micro-pixel is provided with individual passive element (micro-resistor or capacitance) which is connected with a common field electrode. The individual passive element limits multiplication factor (gain) of the avalanche process in the given micro-region.

The micro-pixels operate with bias voltages exceeding the characteristic breakdown voltage by a few Volts. Each photoelectron initiated by photon conversion in the micro-pixel sensitive volume initiates a Geiger-type discharge with a certain number of charge carriers, which is proportional to the product of the excess voltage and the pixel capacitance. This discharge is stopped when the voltage goes down below the characteristic breakdown voltage due to a voltage drop at the individual surface resistor (or micro-capacitance). As a consequence each pixel works as a binary device, while the entire MAPD is in the first order an analogue detector with wide dynamic range because of the high density of pixels as long as the number of incoming photons is much smaller than the number of pixels. This results in a unique combination of high signal amplification (up to 10^6), uniform avalanche multiplication over the sensitive area and low excess noise factor (F~1).

Application of the novel MAPDs in High Energy Physics detectors

Characteristics of the novel MAPDs and their possible applications in detectors for the High Energy Physics, in medical researches (PET), etc had been described in a number of papers [9-10]. The advantages of the third type MAPDs with the active area 3x3 mm^2 which have about 100 thousands pixels (micro-wells), produced by “Dubna Detectors Ltd” and “Zecotek Medical Systems Singapure Pte. Ltd”, are nicely realized by F. Guber, A. Ivashkin, A. Kurepin, et al. in the construction of the hadron calorimeter for heavy nuclei interactions (see http://www.gsi.de/documents/DOC-2006-Jan-140_e.html). Their tests of MAPDs confirmed that the MAPDs had the linear response up to 10000 photoelectrons (Fig.4).

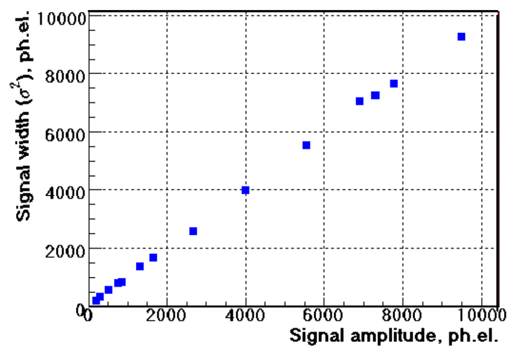

Figure 4: Dependence of signal width (σ^2) on signal amplitude in photoelectrons ($\sigma^2 \sim N_{ph.\ el.}$ in linear case)

Another advantage of these MAPDs is a rather good Photon Detection Efficiency (PDE) - see Fig. 5.

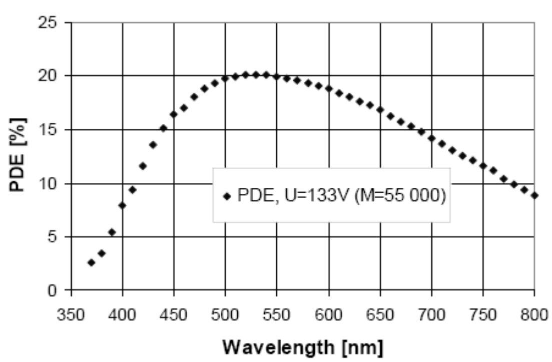

Figure 5: Dependence of the MAPD Photon Detection Efficiency (PDE) on the wavelength.

Possible application of the novel MAPDs

In many experiments observing images of objects a high resolution in time and position of arriving photons is need. Among them are:
- images of EAS produced by high energy gamma rays or protons (selection of gamma from protons depends very much on quality of the image);
- images of Ultra-High Energy EAS in fluorescence light in space experiments where the object is far away and a high position and time resolution of signals is the main issue;
- selection of neutrino induced EAS in the same experiments where the accuracy in the primary particle direction is critical.

In two last experiments the fundamental problem of origin of the extreme energy cosmic rays is under investigation.

MAPDs have good prospects to be relevant in experiments observing images of transient luminous events in the atmosphere observed from the satellites in global scale, see, for example [11].

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