REGISTRATION OF CHARGED PARTICLES BY SCINTILLATING FIBERS COUPLED WITH μ-CELL *SI* APD$_G$

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Silicon μ-cell Avalanche Photodiode operating in Geiger mode (APD_G) was used to detect light produced in scintillating fibers of 1 mm diameter by electrons from a ^{90}Sr-source and by α-particles from a ^{238}Pu-source. This recently developed in mesa-technology square 1 mm^2 APD_G, consisting of 1370 μ-cells, has enhanced inter-cell optical isolation and individual quenching resistors. It showed at room temperature and low biasing voltages (45-47 V) very high gain (up to 10^6), low dark counting rates (below $3 \times 10^5 sec^{-1}$) and high detection efficiency for photons of green light ($> 35\%$). Basic characteristics - internal gain, dark counting rate and average number of detected photoelectrons as a function of bias voltage were measured.

INTRODUCTION

In the last decade there have been numerous attempts to use Metal-Resistive layer-Semiconductor (MRS) Avalanche Photo-Diodes working in "Geiger mode" (APD_G), i.e. operating at voltages slightly above breakdown, as photo-detectors in scintillating fiber tracking, time-of-flight measurements and bio-medical applications [1,4,5]. Many features, such as: room temperature operation, compactness, low bias voltages, extremely high internal gain and single-photon sensitivity make them very attractive in comparison to conventional photo-detectors and $VLPC$'s [2]. Nevertheless, up to now APD_G's have not found wide application, mainly due to high dark counting rate and low photo-detection efficiency in visible wavelengths. Center of Perspective Technology and Apparatus ($CPTA$, Moscow), one of the patent-holders [6] for these devices, has been working continuously on improving characteris-

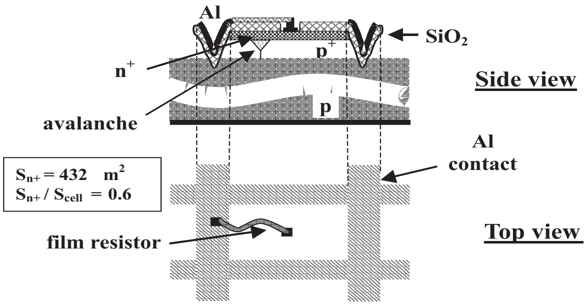

Figure 1. Schematic view of one MRS APD$_G$ μ-cell.

tics of APD_G. Its traditional design was based on "needle" junctions and a distributed quenching resistor formed by a thin resistive layer on the silicon surface. Pixels were formed by readout metallization lines on top of the resistive layer. Although these detectors performed very well in respect of single-photon sensitivity and internal gain, they have shown rather high dark counting rates, low quantum efficiency in visible range, long dead time and secondary photo-ionization effects [3,7]. The present study was performed with newly developed by $CPTA$ square samples of 1 mm^2 area, implemented in mesa-technology with inter-pixel optical isolation and individual quenching resistor in each pixel. These diodes were directly coupled to various round scintillating fibers of 1 mm diameter, 10 cm long. Fibers were exposed to electrons from a ^{90}Sr β-source and to α-particles from a ^{238}Pu source. This work was done mainly in view of application for triggering, tracking and radiation monitoring using scintillating materials.

1 PRINCIPLE OF OPERATION

One $\mu-$cell of a photodiode designed in mesa-technology is shown schematically in Fig.1. Each of 1 mm^2 diodes produced in this technology contains 1370 such cells connected electrically to each other and to common readout by means of Al metallization lines. Photosensitive area composes approximately 60% of the total area. Doping concentrations are such that a high local electric field, exceeding breakdown voltage, is reached in the photosensitive layer at relatively low reverse bias voltages (45-48 V). Each photoelectron, which is created by incident photon or by the leakage current and reaches multiplication zone, initializes an avalanche creating up to $\sim 10^6$ secondary electrons.

The avalanche is locally quenched by a film resistor formed on the surface of each pixel from the n-side, therefore the pulse amplitude from each μ-cell does not depend on the amount of initial charges. Quasi-linearity of the device is reached when it detects light uniformly distributed over the whole area, in this case the total pulse-hight is determined by the amount of fired μ-cells, and the dynamic range - by the total amount of cells on the detector area (typically $\sim 10^4/mm^2$). In mesa-technology pixels are optically isolated due to deep inter-pixel etching and metallization. Each cell has its own film resistor connected to common Al grid. This layout gives the following advantages:

- optical separation reduces probability of photo-ionization, i.e. secondary avalanche ignition in adjacent pixels by UV photons emitted from a primary avalanche,
- resistor values are under better control,
- avalanche process in one cell does not influence sensitivity of the others,
- localized quenching by individual film resistors reduces total dead time, which in this case is defined by a single pixel and does not depend on the total amount of fired pixels.

EXPERIMENTAL SETUP

Schematic view of experimental setup is shown in Fig.2. The main feature of this layout is the original design of triggering for electrons traversing scintillating fiber, which proved to be very efficient. It is based on the idea of using photons of scintillation light, which escape from the fiber through the cladding ($\sim 90\%$ of total light produced). These photons are collected by means of a reflective cone surrounding the fiber and directing light towards the triggering phototube (PM1 in Fig.2). A flat scintillator positioned underneath the fiber and coupled to PM2 provides additional signal for coincidence. By lifting the discrimination threshold on PM1, which detects large amount of photons, one can select electrons, which traverse the fiber closer to its median and vice versa. Remaining $\sim 10\%$ of generated photons travel along the fiber in both directions. One end of the fiber is mirror-coated, the other one - coupled to the APD_G, which therefore receives $\sim 10\%$ of the scintillation photons. There was an air gap of $\sim 0.2mm$ between the fiber edge and the APD_G. When the measurements were performed with an α-source, it was placed either close to the edge mirror or in the middle of the fiber, in the latter case the cladding being slightly cut for better penetration. Trigger for α-particles was generated solely by PM1. Signals from the APD_G passed through a shaping amplifier and delay to the QDC LRS-2249A, gated by coincidence signal.

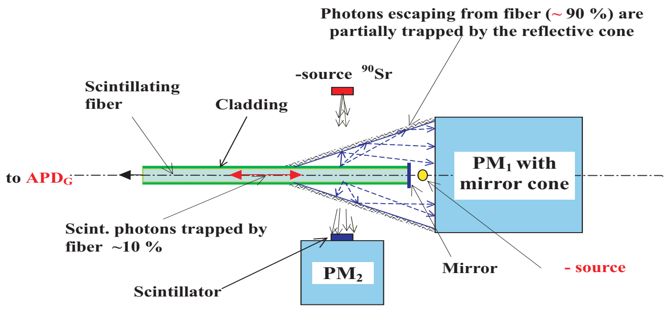

Figure 2. Layout of experimental setup.

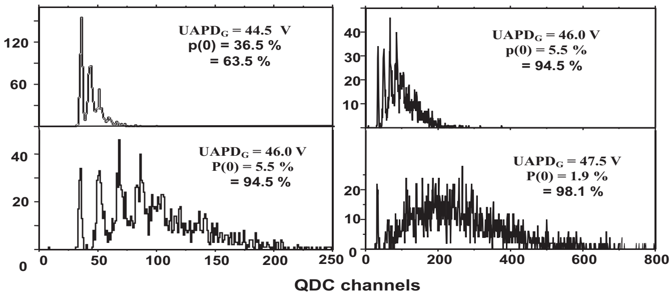

Figure 3. β-spectra for Kuraray 3HF(1500M) at different voltages.

RESULTS

The measurements were performed using three types of scintillating fibers, all of them 1 *mm* in diameter and 10 *cm* long:

1. Kuraray SCSF-78M multi-cladding fiber with λ_{max} = 450 nm (blue),
2. Bicron BCF-60 single-cladding fiber with λ_{max} = 530nm (green),
3. Kuraray 3HF(1500M) multi-cladding fiber with λ_{max} = 530 nm (green).

Spectra from a ^{90}Sr-source were obtained with an external trigger PM1×PM2 and relatively high discrimination threshold on PM1-signal, which ensured mean path of electron in the fiber $\simeq 0.8$ *mm*. Typical spectra for Kuraray 3HF(1500M) fiber at three different bias voltages are shown in Fig. 3. Single-photoelectron peaks are very well resolved at all voltages. The distributions are not expected to exactly follow Poisson law, due to Landau smearing and to the round fiber geometry, resulting in lower peaks enhancement. Good peak separation means that fluctuations of gain from one μ-cell to another are small, σ_{rms} being $\simeq$ 15% according to our measurements. Photo-detection efficiency (average number of detected photoelectrons) and internal gain (determined as peak-to-peak interval in the spectra, calibrated in electron charge units) are increasing with bias voltage. The dark counting rate is also growing rapidly with voltage, therefore the operating voltage cannot be set very high. All these basic characteristics are shown in Figure 4. Operating voltage of 47-47.5 V was found optimal, since it ensures stable operation with high detection efficiency for β-particles (about 99%) and still tolerable dark counting rate (below $3 \times 10^5 sec^{-1}$). Comparative spectra from a β-source at V_B=47.0 V for all three types of fiber are shown in Fig.5. Combination of the APD$_G$ and green scintillating fiber Kuraray 3HF(1500M) with double cladding gave best results in terms of average number of detected photoelectrons: $< N_{phe} > = 7.9$, $\varepsilon_{det} = 98.6$ %. This is a lower estimate, since up to 50% of the light could be possibly lost due to non-perfection of the optical contact fiber-APD. Detection efficiency for α-particles is close to 100% ($< N_{phe} > = 9.9$). The dead time of a μ-cell was measured by sending two consecutive intense pulses from an LED on the detector surface and measuring the minimal time interval at which the detector sensitivity recovers to 90% level. This was found to be $\simeq$100 nsec, which is $>$ 10 times smaller than for former versions of APD_G's.

SUMMARY

New APD_G's designed in mesa technology were used for detecting light in 1 mm round scintillating fibers, produced by traversing electrons or α-

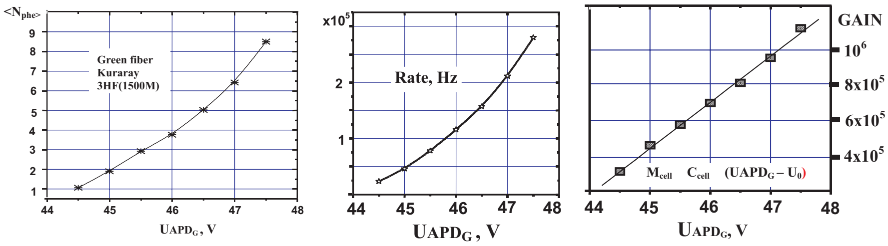

Figure 4. Number of detected photo-electrons (left, dark counting rate (middle) and gain (right) as a function of applied voltage.

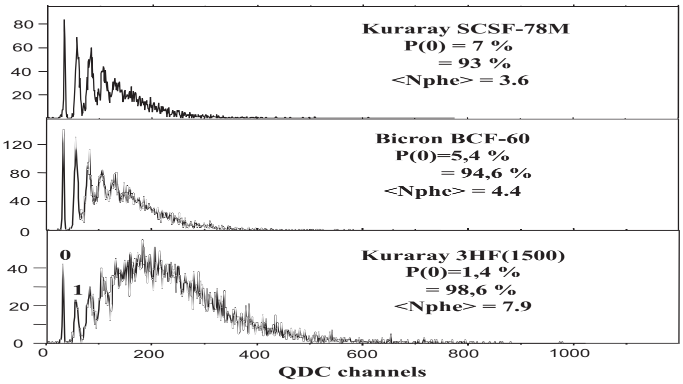

Figure 5. β-spectra for three different types of scintillating fiber at V_B=47 V.

particles. Best results (> 10 photo-electrons/mm) were obtained with Kuraray 3HF(1500M) green fibers having double cladding. Photodiodes were operated at room temperature and bias voltage 47.5 V. New design significantly improves detection efficiency, reduces dark counting rate and dead time and improves inter-pixel electrical and optical decoupling.

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