Nuclear Instruments and Methods in Physics Research A 787 (2015) 117–120

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

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

Radiation hardness investigation of avalanche photodiodes for the Projectile Spectator Detector readout at the Compressed Baryonic Matter experiment

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ARTICLE INFO

Available online 27 November 2014

Keywords:
Avalanche photodiodes
Single photons detection
Radiation hardness
Neutron irradiation tests
Compressed Baryonic Matter experiment
Projectile Spectator Detector

ABSTRACT

In this paper, we discuss results of avalanche photodiodes radiation tests for Projectile Spectator Detector at future Compressed Baryonic Matter experiment. The tests were carried out in Nuclear Physics Institute of ASCR in Řež using the cyclotron facility. Secondary neutron beam was used for irradiation because the main radiation damage in the Projectile Spectator Detector is caused by neutrons. Two types of the avalanche photodiodes from Zecotek and Ketek manufacturers were investigated. Special attention was given to the noise investigation and self-annealing after the irradiation. We have irradiated two Ketek PM3375 diodes with equivalent dose for 1 MeV neutrons equal to $2.5 \pm 0.2 \times 10^{12}$ n/cm^2, and single Zecotek MAPD-3N diode with equivalent dose for 1 MeV neutrons equal to $3.4 \pm 0.2 \times 10^{12}$ n/cm^2. All the types of the diodes have shown an increasing level of the noise after the irradiation. From that we can conclude that those avalanche photodiodes are not able to detect single photons anymore due to high noise levels.

1. PSD detector at the CBM experiment

The Compressed Baryonic Matter (CBM) detector will be a dedicated setup for the measurement of fixed target heavy ion collisions at the future FAIR facility [1]. It is being designed for the investigation of the properties of highly compressed baryonic matter. Projectile Spectator Detector (PSD) is a detector of non-interacting nucleons and fragments emitted at very low polar angles in forward direction in nucleus–nucleus collisions [2]. It will be used to determine the collision centrality and the orientation of an event plane.

The PSD is a full compensating modular lead-scintillator calorimeter, which provides very good and uniform energy resolution. The calorimeter comprises 44 individual modules, each consisting of 60 lead/scintillator layers with a surface of 20×20 cm^2. The scintillation light is readout via wavelength shifting fibers by Multi-Avalanche Photo-Diodes (APDs). The main advantages of APDs are very compact sizes, low bias voltage, gain comparable to that of PMT, relative low price, insensitivity to magnetic field and the absence of nuclear counter-effect (due to the pixel structure). Generally, APDs have the following properties: pixel density about $10^4 - 2 \times 10^4$ mm^{-2}, size of 3×3 mm^2, high dynamical range of 5 – 15,000 ph.e., photon detection efficiency of $\sim 15\%$, and high counting rate of $\sim 10^5$ Hz.

The ion beam with very high intensity at the CBM experiment raises a question on the radiation resistance of the hadron calorimeter. The overall radiation dose deposited in the PSD and the neutron flux was simulated by FLUKA [3] with the use of realistic CBM and the PSD geometry and material budget as for SIS100 and SIS300 [2]. While simulated radiation dose is not critical for scintillators, the most crucial effect is the photodetectors degradation caused by the neutron flux trough the rear side of PSD calorimeter. According to FLUKA simulation this flux near the beam hole might achieve 10^{12} neutrons/cm^2 for beam energy 4 AGeV and about $4 \cdot 10^{12}$ neutrons/cm^2 for beam energy 35 AGeV and 2 months of CBM run at the beam rate 10^8 ions per second. Therefore, the main requirement for APDs for PSD CBM is the radiation hardness to neutron fluxes of $\sim 10^{13}$ n/cm^2.

2. Investigated APD types and methods of research

Three types of APD produced by Zecotek, Ketek and Hammamatsu were investigated to understand dependences of APDs radiation hardness on the manufacturing technology. These APDs were chosen as they are widely applied in nuclear and particle

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http://dx.doi.org/10.1016/j.nima.2014.11.071
0168-9002/

physics experiments and many investigations were conducted up to now on these detectors. Current work describes investigation of the Ketek and Zecotek APDs, while the Hammamatsu APDs will be investigated in near future.

For our project we have received 7 SiPM PM3375 Ketek APDs with gain $\sim 10^6$ produced by 50 μm/cell technology [4] and 5 MAPD-3N Zecotek APDs with gain $\sim 10^4$ produced by 65 μm/cell technology [5]. All these APDs have the features of high photon detection efficiency, low noise, huge range of stable operation and low temperature coefficient of the gain. Besides that, Ketek and Zecotek APDs have different internal structure and have slightly different photon detection sensitivity peaks of 420 nm for Ketek APDs and 470 nm for Zecotek APDs.

For our investigation, we used three general methods based on analysis of static characteristics, dynamic characteristics and APD operation. Static characteristics consist of Capacitance–Voltage (*C–V*), Capacitance–Frequency (*C–F*) and Current–Voltage (*I–V*) dependences. Analysis of these characteristics allows us to investigate the internal structure of APD, study of the behaviors of p–n junction during APD operation and measure the parameters of APD for equivalent circuit of APD in SPICE. Dynamic characteristics are based on transient effects inside APD bulk. They allow investigation of generation and recombination processes in APD bulk, study of behaviors of noise sources of APD and measurement of the parameters of noise sources for SPICE model of APD. We also investigated single photon spectrum of APDs with LED, with scintillators using radioactive sources in laboratory and with scintillators for cosmic rays.

Before irradiation, the APDs were tested in single photons detection mode. It was found out that they are fully capable of detecting single photons' peaks due to relatively small intrinsic noise as shown in Fig. 1.

3. Results of irradiation tests

Investigated APDs were irradiated at the Cyclotron facility of NPI Řež using quasi-monoenergetic 35 MeV secondary neutron beam [6]. Single Zecotek APD was irradiated with dose of $3.4 \pm 0.2 \times 10^{12}$ n/cm^2 and two Ketek APDs were irradiated with dose of $2.5 \pm 0.2 \times 10^{12}$ n/cm^2. Doses here are measured by the special PIN diode calibrated for a 1 MeV neutrons equivalent dose; the temperature during the irradiation and measurements was 22 ± 0.5 °C [7].

3.1. General analysis: C–V and I–V characteristics

C–V characteristics of Zecotek APDs show significant decrease of the hysteresis after irradiation (Fig. 2, left). It can be related to decrease of long-living traps number in APD volume and therefore increase of short-living traps number, which is confirmed by *C–F* measurements as well. *C–V* characteristics of Ketek APDs show significant restoration of the initial *C–V* dependence in 4 days after irradiation (Fig. 2, right). However, even after self-annealing one can clearly see significant difference in *C–V* before and after irradiation related to in-volume radiation effects, especially close to operational voltage of 25 V.

I–V characteristics of both Zecotek and Ketek APDs show the increase of the dark current I_{dark} by $\sim 10^3$ times right after irradiation

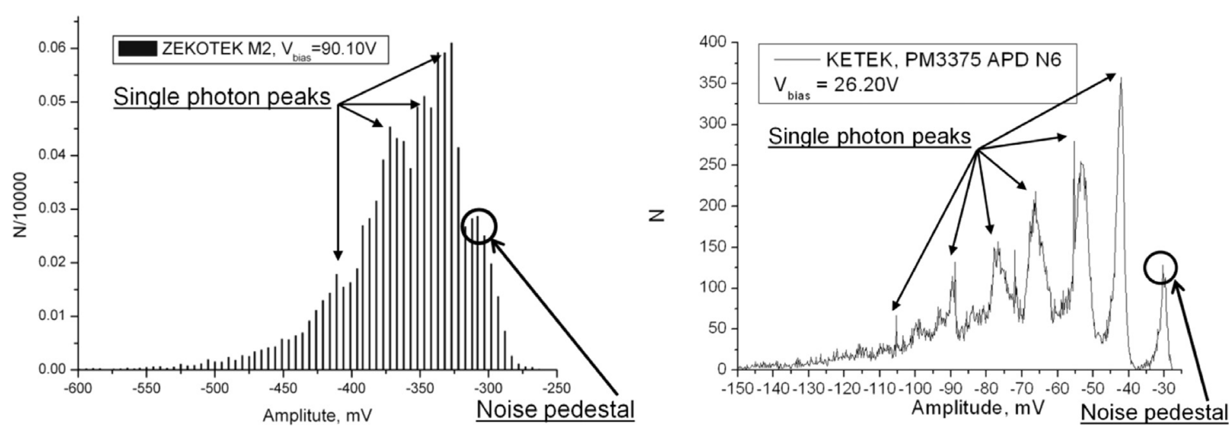

Fig. 1. Single photons detection operation of Zecotek (left) and Ketek (right) APDs before irradiation.

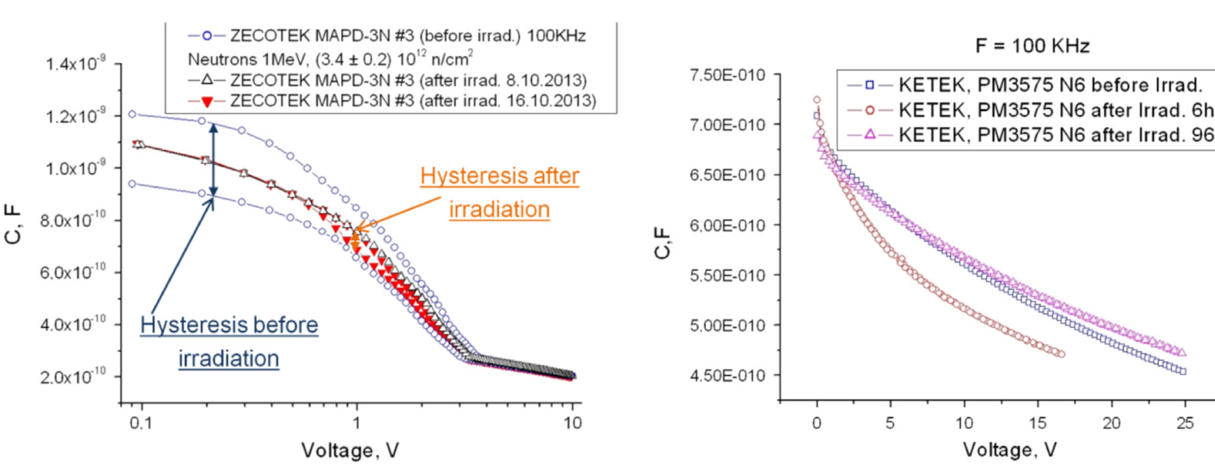

Fig. 2. *C–V* characteristics of Zecotek (left) and Ketek (right) APDs before and after irradiation.