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Review Article

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Investigation of Silicon Photomultipliers Irradiated by Gamma Rays

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ABSTRACT

In this study, the electrical properties of silicon photomultipliers (SiPMs) manufactured by Zecotek Photonics Inc., with an active area of 3.7 × 3.7 mm² and a pixel density of 4450 pixels/mm², were investigated. The current–voltage (I–V) and capacitance–voltage (C–V) characteristics of the SiPM with an internal pixel structure (model MAPD-3NM2) were examined under gamma irradiation from a Cobalt-60 source at doses of 10 kGy and 40 kGy. The experimental results showed that the dark current increased by factors of 9.4 and 31 at doses of 10 kGy and 40 kGy, respectively, which is associated with radiation-induced defects formed in the silicon crystal lattice and at the pixel boundaries. A slight shift in the breakdown voltage from 52 V to 51.8 V was observed, which can be explained by radiation-induced changes in the electric field distribution within the p–n junction. At a dose of 40 kGy, an approximately 2% decrease in capacitance was recorded from the C–V characteristics, which is related to an increase in the width of the space-charge region. The obtained results indicate that MAPD-3NM2 photodiodes retain their resistance to high doses of gamma irradiation and are promising for applications in nuclear technologies as well as in radiation-hardened detector systems.

Keywords: SiPM, Silicon Photomultiplier, MAPD, Micropixel Avalanche Photodiode, Current–voltage (I–V) and Capacitance–voltage (C–V) Characteristics, Dark Current, Breakdown Voltage.

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Introduction

The development of detectors capable of long-term and stable operation in radiation environments is one of the main directions of modern technological innovations [1]. In particular, the high penetration capability of gamma and proton radiation directly affects the operating mechanism of silicon-based detectors and causes changes in their electronic properties [2]. Silicon photomultipliers (SiPM), which belong to the class of modern photon detectors, are considered one of the most promising technologies in the field of detection of ionizing radiation. These devices are widely used in fields such as nuclear physics, medical diagnostics, space research, and materials science [3].

When ionizing radiation interacts with the silicon crystal lattice, high-energy particles and photons break atomic bonds, creating various types of defects—vacancies, dislocations, donor and acceptor centers. These defects directly affect the electronic and optoelectronic properties of SiPMs, potentially reducing their stability and signal sensitivity [4]. As a result of defect formation, the dark current and dark count rate increase, since the generation process of charge carriers accelerates. This, in turn, leads to an increase in the internal noise level and creates difficulties in the detection of weak signals.

Defects formed in the p–n junction affect the distribution of the internal electric field, leading to a decrease in the avalanche multiplication factor. As the concentration of defects increases, the breakdown voltage shifts toward a higher voltage region, which results in a reduction of the photon detection efficiency (PDE). Vacancies generated by radiation enhance the trapping process of charge carriers and increase the recovery time of the pixel [5].

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The structure of SiPMs consists of numerous micro-pixels, and each pixel functions as an avalanche photodiode operating in Geiger mode. As a result of the parallel connection of the pixels, the total signal of the detector is formed as the sum of the signals of all micro-pixels [6]. The operating principle of the SiPM is carried out in the following stages [2]:

1. When a photon enters the p–n junction, an electron–hole pair is generated.
2. Under the influence of the electric field, electrons are accelerated and impact ionization occurs.
3. Each pixel generates a pulse in Geiger mode.
4. The pulses of all micro-pixels are summed to form the overall output signal.

Thanks to this mechanism, SiPMs make it possible to detect even very weak light fluxes and enable single-photon detection [8].

MSFD (Eng. MAPD–Micropixel Avalanche Photodiode) type photodiodes have a high gain capability and possess a compact and mechanically robust structure. Their ability to operate at low voltage (30–60 V), high photon detection efficiency, stable operation in magnetic fields, and nanosecond-level timing resolution make them a modern detector technology that stands as an alternative to traditional photomultiplier tubes (FEG) [3]. These features make MSFD photodiodes suitable for operation in high-radiation environments and promising for nuclear detector systems.

Experimental Setup

The investigated MAPD-3NM2 photodiode consists of micropixel avalanche photodiodes with a 3.7 × 3.7 mm² active area and has a deep-pixel structure. In terms of its structure, this photodiode is formed on an n-type substrate and includes a highly doped n-type (phosphorus-doped) n++ epitaxial layer with a thickness of approximately 10 µm. On top of this layer, there is a p-type (boron-doped) p++ epitaxial layer with a thickness of approximately 2 µm. The surface of the structure is covered with a SiO_2 insulating layer [9-12]. Figure 1 shows the I–V characteristics of the MAPD-3NM-2 type photodiode.

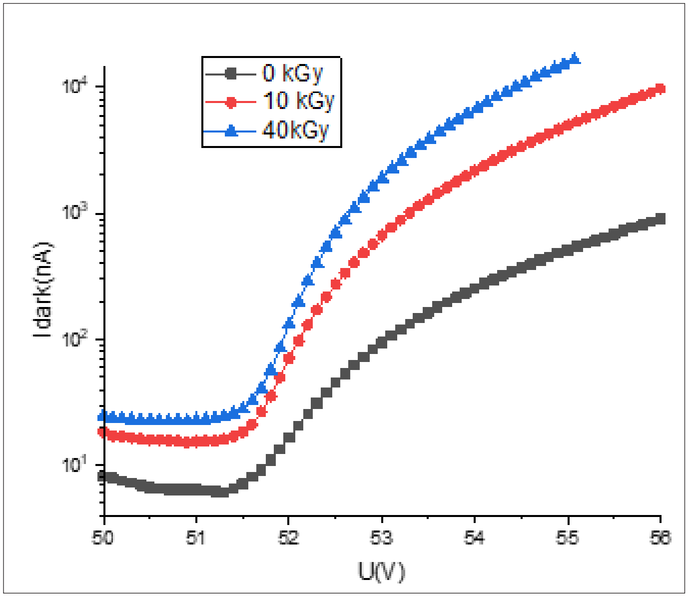

Figure 1: Dependence of the dark current of the MAPD-3NM-2 photodiode on voltage at different radiation doses.

During the investigation of the electrical properties of the photodiode, a Keithley-6487 picoammeter was used as the voltage source. The MAPD-3NM2 photodiodes were irradiated with a Co-60 gamma source with an activity of 110 GBq to total doses of 10 kGy and 40 kGy over 10 hours. When the voltage applied to the MAPD-3NM2 photodiode was in the range of 50–51 V, a gradual increase in dark current was observed. This increase is explained by the diffusion of minority charge carriers in the p–n junction and the generation of new electron–hole pairs due to thermal processes. In this voltage range, no internal gain phenomenon is observed.

When the voltage is in the range of 51.5–54 V, the dark current increases sharply and the avalanche gain process occurs. In the MAPD-3NM2 photodiode, the breakdown voltage was recorded at approximately 52 V. At a radiation dose of 10 kGy, the dark current increased by a factor of 9.4 compared to the initial state, while at a dose of 40 kGy it increased by approximately 31 times. This increase in dark current is explained by the formation of defects on the pixel surface and at the bulk boundaries under radiation exposure, the trapping of electrons and holes by vacancies, and the increase in the concentration of recombination centers.

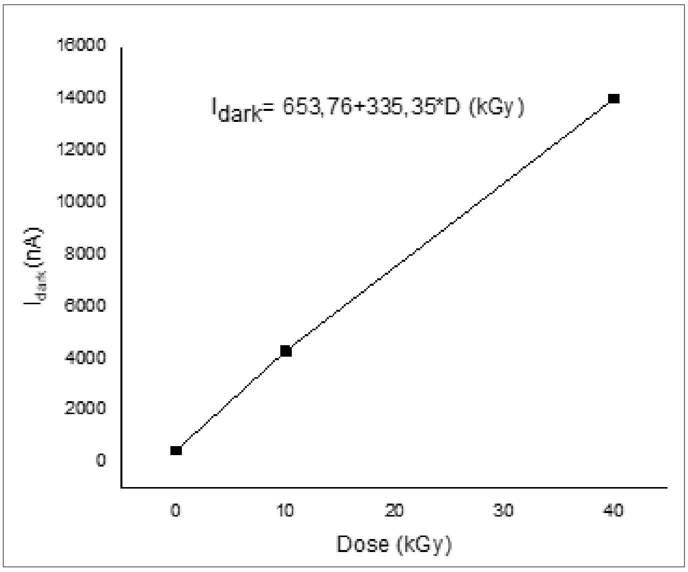

Figure 2: Dose dependence of the dark current in the MAPD 3NM2 photodiode.

During the measurements, the temperature was maintained at 22 ± 1 °C. The differential voltage dependence of the MAPD 3NM2 photodiode is presented in Figure 3.

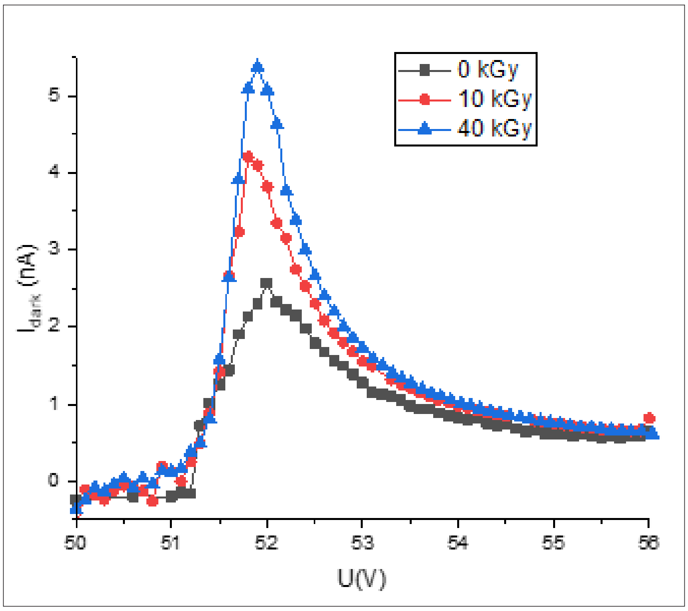

Figure 3: Voltage dependence of the ratio of differential dark current to voltage for the MAPD 3NM-2 photodiode at different doses.

Analysis of the graph shows that at irradiation doses of 10 kGy and 40 kGy, the breakdown voltage of the MAPD 3NM2 photodiode was 52 V and 51.8 V, respectively.

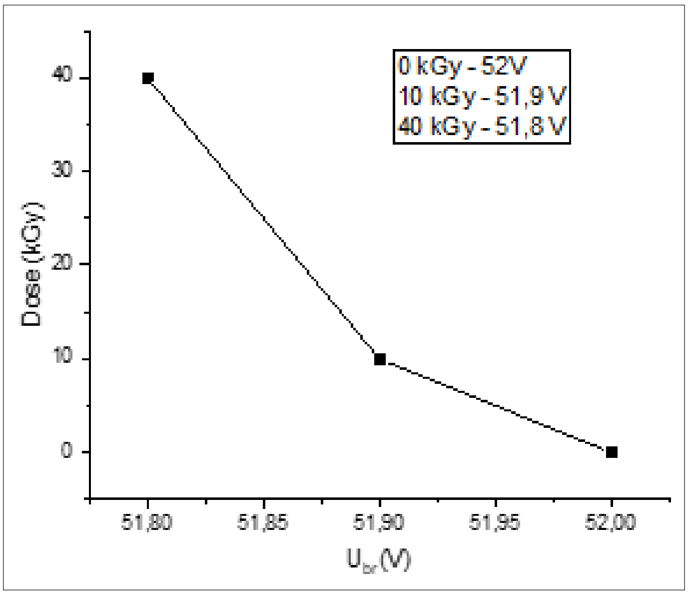

Figure 4: Dependence of the breakdown voltage on irradiation dose.

The radiation-induced shift in the breakdown voltage was 0,2±0.028V. When ionizing radiation interacts with the material, defects are formed in the crystal lattice, which affect the concentration of charge carriers in the p–n junction region and disrupt its electrical neutrality.

Due to the generation of additional charge carriers, the dark current increases. As a result of thermal generation, the motion of charge carriers in the electric field becomes more random, reducing the number of carriers participating in the avalanche process. This, in turn, decreases the probability of avalanche multiplication (i.e., the ionization coefficient of electron–hole pairs).

Thus, as the temperature of the p–n junction increases, the breakdown voltage also rises. The optimal operating voltage range of the MAPD 3NM2 photodiode was found to be between 54.3 V and 55.4 V. No changes in the optimal voltage range were observed after irradiation.

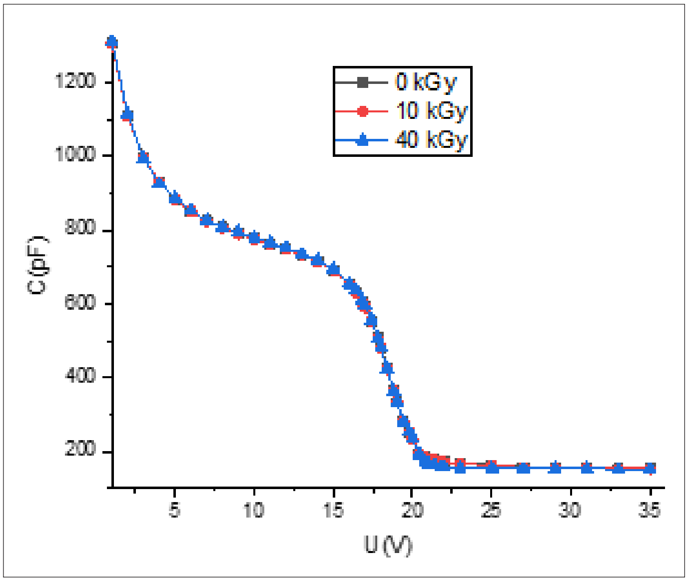

Figure 5: Capacitance–voltage (C–V) characteristic of the MAPD-3NM-2 photodiode.

Figure 5 shows the C–V characteristics of the MAPD-3NM-2 photodiode at irradiation doses of 10 kGy and 40 kGy. During the capacitance measurements, an Immittance E7-20 device was used to apply a signal with a frequency of 1 MHz and an amplitude of 40 mV to the photodiode.

As can be seen from the graph, with increasing applied voltage, the capacitance of the photodiode decreases due to the widening of the space-charge (depletion) region of the p–n junction. The capacitance of the photodiode is defined by the relation (C=εε0S/W), being directly proportional to the diode area and inversely proportional to the width WWW of the depletion region.

At a voltage of 23 V, the p–n junction becomes fully depleted, and the capacitance remains constant. The capacitance of the MAPD 3NM2 photodiode at a dose of 40 kGy was 152 pF. As a result of irradiation, the capacitance decreased by 2%.

Conclusion

Experimental investigations have shown that the main radiation-induced changes in MAPD-3NM2 photodiodes irradiated with a Co-60 gamma source at doses of 10 kGy and 40 kGy are observed in the dark current characteristics. At irradiation doses of 10 kGy and 40 kGy, the dark current increased by 9.4 times and 31 times, respectively, compared to the initial state.

At a dose of 40 kGy, a dose-dependent shift in the breakdown voltage of 52.2 ± 0.028 V was observed in the MAPD-3NM2 photodiode. However, the operating voltage range of the photodiode did not change with irradiation dose and remained stable within the interval of 54.3–55.4 V.

Measurements performed at a dose of 40 kGy also indicated an approximately 2% decrease in the photodiode capacitance.

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