Study of the Radiation Resistance of Silicon Photomultipliers

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Abstract. Silicon photomultipliers (SiPMs) represent a new generation of solid-state photodetectors that combine high photon detection efficiency, fast response time, and compact design. Owing to these advantages, SiPMs are increasingly being used in applications requiring precise light detection, such as nuclear spectroscopy, positron emission tomography (PET), and high-energy physics experiments. However, when operating in environments with elevated levels of ionizing radiation, their long-term stability and performance can be significantly affected by radiation-induced damage. Therefore, studying their radiation resistance is crucial for ensuring reliable operation in such conditions. In this work, the radiation hardness of SiPM with burried pixel structure (model MAPD-3NK) was investigated under gamma irradiation with absorbed doses ranging from 10 to 100 kGy. The electrical properties were characterized by measuring current–voltage (I–V) and capacitance–voltage (C–V) characteristics before and after irradiation. The experimental results revealed a pronounced increase in dark current with radiation dose as 2.4 times at 10 kGy, 6 times at 40 kGy, and 10.4 times at 100 kGy which attributed to the generation of radiation-induced defects and charge-trapping centers that enhance carrier generation and leakage current. In contrast, the C–V characteristics remained largely unchanged, indicating that the depletion region and junction capacitance were not significantly affected by irradiation. These results demonstrate that MAPD-3NK possess considerable radiation resistance, maintaining their working stability and structural integrity under high-dose exposure. The findings confirm the potential of MAPD-3NK devices for use in radiation-intensive applications, including nuclear instrumentation, high energy physics, and advanced medical imaging systems where robustness against radiation damage is a key performance requirement.

Keywords: SiPM; silicon photomultiplier; MAPD; micropixel avalanche photodiode; dark current; breakdown voltage.

1 Introduction

1.1 Fundamental Principles of Photomultiplier Devices

One of the key factors determining the radiation hardness of silicon-based devices is the type of radiation and its mechanism of interaction with the device. Ionizing

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radiation—such as alpha, beta, and gamma rays—directly affects the semiconductor structure of the device, generating electron–hole pairs [1]. This, in turn, can lead to changes in the photoelectric properties of the semiconductor material [2]. Radiation can affect the structural and electrical characteristics of devices, thereby degrading their performance and reliability. Therefore, ensuring the radiation hardness of such devices constitutes a major area of research [3]. Silicon-based photomultipliers (SiPMs) are detector systems operating in Geiger (binary) mode, consisting of pixels (10^3 mm^{-2}) fabricated on a silicon substrate with a thickness of 20–30 μm. These devices exhibit high photon detection efficiency (20–35%) and intrinsic gain (10^6) [4]. Silicon-based photomultipliers (SiPMs) are widely used devices in modern radiation detector technology. These devices are capable of detecting both single photons and weak photon fluxes. The recovery time of photomultiplier devices typically lies in the range of 10^{-8} to 10^{-10} seconds, which enables precise detection of photons originating from weak light sources under both ambient and vacuum conditions [5]. Photomultiplier devices are extensively used in scientific research and applied technologies due to their high sensitivity, wide dynamic range, fast photoresponse, and ability to operate in various environments. In the scientific literature, these photodetectors are also referred to as micropixel avalanche photodiodes (MAPDs) or multipixel photon counters (MPPCs) [6]. Micropixel avalanche photodiodes (MAPDs) can have either surface or deep pixel architectures, depending on their fabrication technology. Surface-pixel MAPDs, known for their relatively simple manufacturing process, offer several advantages, including reduced optical crosstalk, short recovery time, high internal gain, and pixel densities reaching up to 10,000 pixels/mm^2 within a 1 mm^2 active area [8,9]. However, in applications where MAPDs are widely used—such as medicine, high-energy physics, space research, and security systems—a photon detection efficiency (PDE) exceeding 20% is typically required. The photon detection efficiency of surface-pixel MAPDs is limited because a significant portion of the photodiode's sensitive area is occupied by quenching resistors and isolation channels. As a result, photons incident on the device surface cannot be fully absorbed by the active region [10–12]. This limitation reduces their effectiveness in applications such as gamma spectroscopy. Deep-pixel MAPDs (Fig. 1), owing to their advanced structural design, overcome the limitations of surface-pixel MAPDs by providing higher photon detection efficiency and greater internal gain. Through optimization of interpixel spacing and pixel diameter, deep-pixel MAPDs such as MAPD-3B, MAPD-3A, MAPD-3N1P, MAPD-3NK, and MAPD-3NM-I demonstrate superior photon detection efficiency and internal amplification [7].

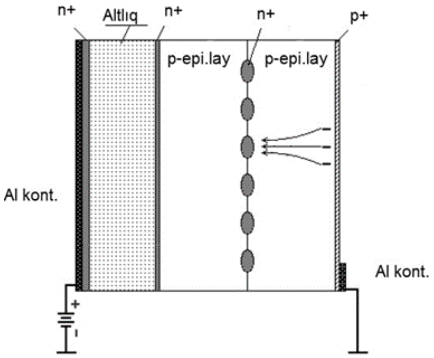

Fig. 1. Structure of deep-pixel MAPD-type avalanche photodiodes.

The main objective of the present study is to investigate the variations in the key parameters and the radiation hardness of silicon-based photomultiplier devices under radiation exposure. After the photodiodes were subjected to different irradiation doses (10 kGy, 40 kGy, and 100 kGy), changes in their electrical characteristics, such as Volt–Ampere (V–A) and Volt–Farad (C–V) characteristics, were analyzed.

2. Experiment

A series of experiments were conducted to investigate the effects of ionizing radiation on silicon-based photodetectors. In this study, MAPD-3NK type photodiodes were used. The MAPD-3NK photodiode features a multilayer epitaxial structure and a high pixel density of approximately 10,000 pixels/mm². It consists of a highly conductive n++ layer with n-type doping, a 7 µm thick n-type epitaxial layer grown on a monocrystalline silicon substrate, and a 4 µm thick p-type epitaxial layer heavily doped with p-type impurities, along with a SiO_2 insulation layer. The pixel size of the MAPD-3NK photodiode is 7 µm, with an interpixel spacing of 3 µm [16].

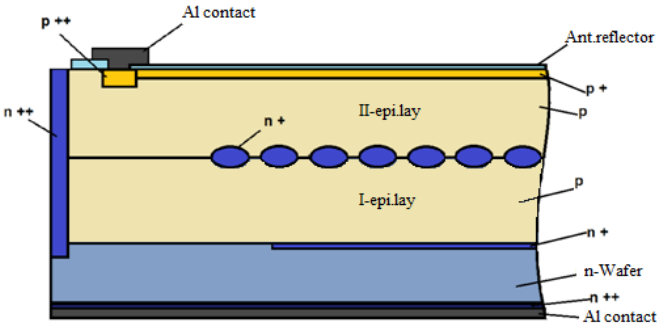

Fig. 2. Structure of the MAPD-3NK photodiode [7].

In silicon-based photomultiplier devices, each pixel functions as an individual diode. The n-type epitaxial layer provides current control and ensures stability of the avalanche process. The p-type epitaxial layer, grown on a high-quality crystalline structure, serves multiple functions: it forms the basis of the p–n junction, acts as the active region that determines the photodiode's photon sensitivity, and facilitates the transfer of charge carriers generated by the absorption of incident photons. The SiO_2 layer on the photodiode surface serves as a protective barrier. It prevents the formation of additional surface defects and leakage current. When a reverse bias is applied to the MAPD-3NK photodiode, a depletion region is formed between the first (n++) and second (p+) epitaxial layers. This space-charge region electrically isolates individual pixels from one another, ensuring their independent operation. The electric field generated between the epitaxial layers separates the electron–hole pairs created by incident photons, and the resulting charge carriers drift into the n-type epitaxial layer. The thickness and resistivity of the n-type epitaxial layer are optimized so that an undepleted region remains beneath the n+ pixel layer. This region serves the function of quenching the avalanche process [14]. When ionizing particles (gamma rays, electrons, alpha, or beta particles) interact with a semiconductor, they create defects in the crystal lattice and the SiO_2 layer. These defects increase the probability of electron transitions from the valence band to the conduction band and act as generation centers for electrons and holes, leading to a sharp increase in the dark current. In micropixel avalanche photodiodes, the total dark current can be expressed as

$$I_{dr}=I_{sur}+M*I_{gen} \qquad (1)$$

Where, I_{sur} is the surface current, I_{gen} is the generation current, and M is the multiplication (gain) factor [15].

In this case, the number of initial photoelectrons that trigger the avalanche process decreases, leading to a reduction in the multiplication factor. At higher irradiation doses, a stronger electric field is required to achieve the same level of gain. This, in turn, causes a shift in the photodiode's breakdown voltage (V_{bd}) [13].

In the present study, the parameters characterizing the MAPD-3NK photodiode, dark current, breakdown voltage, and capacitance—were investigated. The variations in these parameters under the influence of radiation were determined.

2.1. Investigation of Volt–Ampere (V–A) Characteristics

The photodiodes were first irradiated using a Co-60 radiation source (MRH-Gamma-25) with an activity of 128 GBq at predetermined irradiation doses of 10 kGy, 40 kGy, and 100 kGy. After the first irradiation stage, in which both photodiodes were exposed to a radiation dose of 10 kGy, their V–A and C–V characteristics were measured. In the final irradiation stage (100 kGy), only one photodiode was exposed, and the variations in its dark current and breakdown voltage were determined. During the investigation of the V–A characteristics, different bias voltages were applied to the photodiodes, and the resulting currents were recorded. These measurements were used to analyze how the parameters of the diodes changed before and after irradiation. The measurements were conducted at a temperature of 22 °C, approximately two hours after the irradiation process was completed. During the measurements, the temperature variation did not exceed 3%. The experimental circuit used to measure the parameters of the photodiodes is shown in Fig. 3.

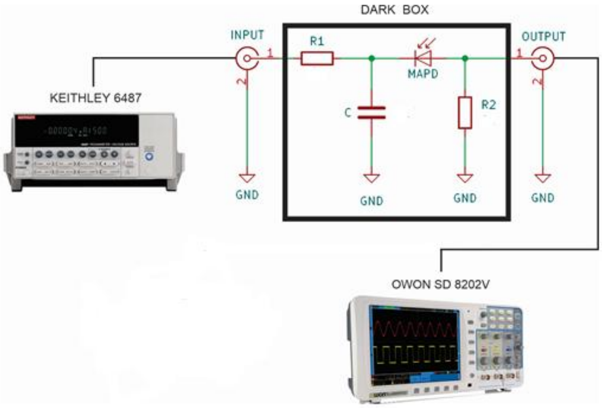

Fig. 3. Experimental circuit used for measuring the parameters of MAPD photodiodes.

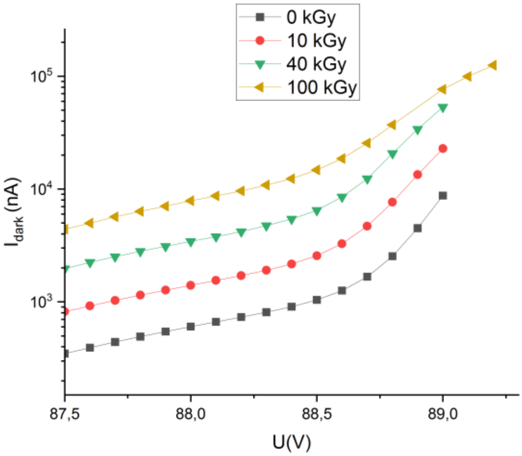

Fig.4. Volt–Ampere characteristics of the MAPD-3NK photodiode at irradiation doses of 0 kGy, 10 kGy, 40 kGy, and 100 kGy.

Fig. 4 shows the Volt–Ampere (V–A) characteristics of the MAPD-3NK type avalanche photodiode at various radiation doses (0 kGy, 10 kGy, 40 kGy, and 100 kGy). The graph illustrates the relationship between the applied voltage (U_{ap}) in the operating mode of the photodiode and the resulting dark current (I_{dark}). In the non-irradiated state (0 kGy), the MAPD-3NK photodiode exhibits a stable and low-level increase in dark current (I_{dark}) with respect to the applied voltage (U_{ap}), indicating normal operating behavior. When subjected to a 10 kGy radiation dose, the dark current increases compared to the 0 kGy condition, showing approximately a 2.4-fold rise. At a dose of 40 kGy, the current exhibits a more pronounced increase, with the graph clearly demonstrating an exponential rise in current as the radiation dose increases. This behavior indicates the formation of significant structural defects within the photodiode and a reduction in carrier mobility. At 40 kGy, the dark current increases by a factor of about 6, while at 100 kGy, it rises approximately 10.4 times relative to the initial (non-irradiated) state. The increase in dark current indicates a rise in the number of defects generated in the semiconductor material of the photodiode as a result of irradiation. This leads to a corresponding increase in the photodiode's dark current caused by radiation-induced defect formation. Figure 4 shows the dependence of the dark current of the MAPD-3NK photodiode on the gamma irradiation dose at a bias voltage of 88.5 V. As can be seen, the dark current varies linearly with the irradiation dose and can be expressed as follows:

$$I_{dark}=829.79+99.98*D \qquad (2)$$

where I_{dark} is the dark current of the diode (nA), and D is the irradiation dose (kGy).

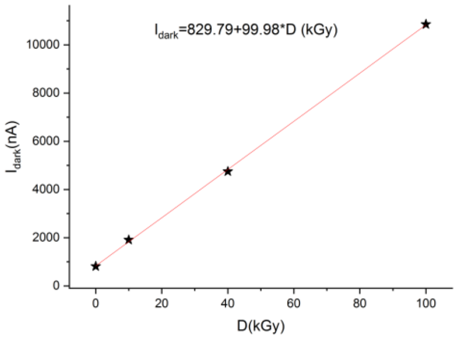

Fig. 5. Dependence of the dark current of the micropixel avalanche photodiode on the irradiation dose.

Figure 6 presents the dependence of the breakdown voltage U_{br} on the irradiation dose for the MAPD-3NK photodiode. A sharp increase in dark current is observed within the voltage range of 85–86.5 V. In this region, the electric field intensity in the p–n junction rises significantly, leading to the onset of the avalanche process within the space-charge region.

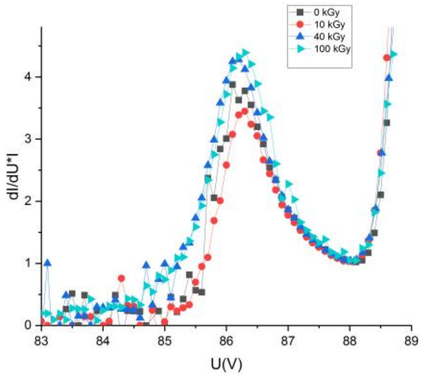

Fig. 6. Dependence of the ratio dI/(dU*I)on the voltage for the MAPD-3NK photodiode at different irradiation doses.

At a voltage of 86.6 V, the dark current reaches its maximum value, indicating the occurrence of the breakdown event. At higher voltages, the avalanche process is quenched by the quenching resistor, leading to stabilization of the differential current increase. At a total irradiation dose of 100 kGy, no change in the breakdown voltage (Ubr) was observed, and it remained stable at 86.6 V.

2.1. Analysis of Volt–Farad (C–V) Characteristics

The V–F (C–V) characteristics of the MAPD-3NK photodiodes were investigated at an irradiation dose of 100 kGy.

- Different voltage levels are applied to the photodiode, and the device capacitance is measured for each voltage value. These measurements provide information about the variation (distribution) of the width of the space-charge region and the electric field within the p–n junction of the device.
- The measurements are carried out at a fixed frequency (1 MHz) using the immittance meter E7-20, which ensures precise investigation of the capacitance variations in the semiconductor p–n junction. Conducting measurements at a constant frequency helps to reveal the influence of radiation-induced defects on changes in the device capacitance.

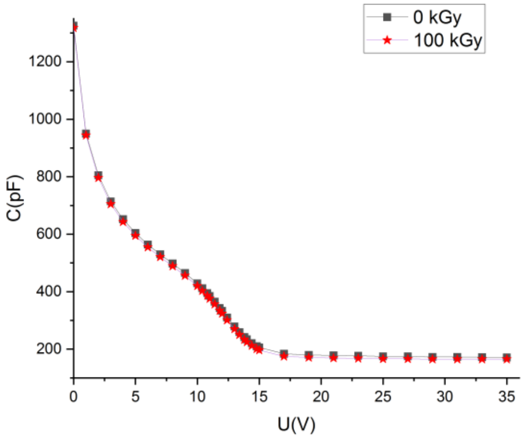

Fig. 6. Capacitance–Voltage (C–V) characteristics of MAPD-3NK photodiodes.

In Fig. 6, the capacitance–voltage (C–V) characteristics of MAPD-3NK photodiodes under a 100 kGy radiation dose are presented. The capacitance of the MAPD-3NK diode was high at low voltages. As the voltage increased, the width of the space-charge region expanded, resulting in a sharp decrease in the diode capacitance. At voltages of 30–35 V, the active volume of the diode became fully covered by the space charge, and the capacitance approached saturation. After exposure to a 100 kGy radiation dose, the capacitance of the MAPD-3NK photodiode decreased by a factor of 2.27, from 171 pF (0 kGy) to 165 pF (100 kGy).

This result indicates that MAPD-3NK photodiodes possess the ability to maintain capacitance stability in a radiation environment. Radiation-induced defects alter the distribution of the electric field within the semiconductor material, which negatively affects the device's electrical characteristics and overall performance. The observed decrease in capacitance is associated with the deterioration of the semiconductor device's electro-optical properties.

3. Conclusion

The results of this study demonstrate that the operational characteristics of silicon-based photoelectron devices are significantly affected by increasing radiation doses. Analysis of the current–voltage (I–V) characteristics indicates that high radiation doses increase the device's reverse (dark) current and reduce electron mobility, thereby degrading overall device performance. At the same time, the breakdown voltage of MAPD-3NK photodiodes remains unaffected by the radiation dose. Analysis of the capacitance - voltage (C–V) characteristics shows that, despite varying radiation doses, there are no significant changes in the diode capacitance, indicating that the devices maintain stability under certain radiation conditions. The graphs show that as the radiation dose increases, the dark current of the diodes rises significantly. This increase is explained by the formation of defects in the semiconductor material due to radiation or by the enhancement of pre-existing defects. These defects alter the internal electric field of the device, leading to additional leakage (dark) currents. As seen from the graphs, at a dose of 10 kGy, the dark current of the MSFD-3NK diode at 87.6 V (1 V overvoltage) increased from 291 nA to 698 nA, representing a 2.4-fold increase. At a dose of 40 kGy, the dark current rose from 291 nA to 1,746 nA. The overall change in the dark current of MSFD-3NK diodes at 87.6 V relative to the initial state was approximately sixfold, while at a 100 kGy radiation dose, the dark current increased 10.4 times (from 291 nA to 3,035 nA). After both irradiation stages, the I–V characteristics were measured intermittently. Analysis of the capacitance–voltage (C–V) characteristics indicates that MSFD-3NK photodiodes irradiated up to 100 kGy with a Co-60 source exhibit no significant change in full capacitance. The main variation was observed in the dark current, which increased 10.4-fold relative to the initial state. Radiation resistance is closely related to device material selection, design optimization, and the implementation of protective technologies. This study provides crucial data for the development of devices with enhanced radiation tolerance and will help guide the direction of future research.

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