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Radiation resistance of electrical parameters of silicon-based PIN photodiodes

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Abstract. This study investigates radiation resistance of principal electrical parameters of silicon-based PIN photodiodes subjected to high-dose gamma irradiation. The Si PIN photodiodes with an active area of 3.7×3.7 mm^2 fabricated by ion implantation technology were exposed to Co-60 gamma radiation at accumulated doses of 10, 40, 70, and 100 kGy. The evolution of dark current (I_{dk}), capacitance-voltage (C–V) characteristics, pulse amplitude, and energy resolution was systematically analyzed. The experimental results demonstrated that the full capacitance of the photodiodes remained stable (182 pF) even after 100 kGy irradiation, indicating strong structural robustness of the depletion region. In contrast, the dark current exhibited a dose-dependent increase, rising by a factor of 1.6 at 100 kGy under 50 V reverse bias. This increase was attributed to radiation-induced generation-recombination centers formed within the intrinsic layer of the device. Moreover, gamma irradiation resulted in a 14.5 ± 1.4% reduction in pulse amplitude and a 20.5% ± 2% change in energy resolution, reflecting the impact of defect-induced carrier trapping and recombination processes. Despite these effects, the photodiodes maintained operational stability after prolonged irradiation and subsequent monitoring. The obtained results confirm that silicon PIN photodiodes fabricated by ion implantation exhibit high radiation tolerance and may be considered promising candidates for operation in high-radiation environments, including radiation monitoring and dosimetry applications.

Keywords: Si-PIN, PIN photodiodes, dark current, gamma irradiation.

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1. Introduction

Silicon PIN photodiodes are widely used in semiconductor radiation and optical detectors due to the photodiode fast response time, high linearity, and low intrinsic noise characteristics. The mentioned detectors are capable of determining both the intensity and spatial distribution of incident radiation. At this, each diode element can function as an individual pixel enabling digital signal and image acquisition. Owing to these properties, PIN photodiodes are extensively applied in optical communication systems, short-distance signal transmission, optical memory technologies, telecommunications, aerospace and defense systems (including laser rangefinders, missile guidance systems, and night vision devices), thermal neutron detectors and nuclear medicine for registration of low-energy electrons and α-particles using counting techniques [1–6].

Structurally, a PIN photodiode represents a modified form of a conventional *p-n* junction optimized for enhanced photoelectric performance (Fig. 1). Unlike standard *p-n* diodes, the PIN photodiodes incorporate an

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intrinsic (i) layer positioned between highly doped p^+ and n^+ regions. The thickness of the intrinsic region typically ranges from 1 to 200 µm. This region may be either partially or fully depleted under reverse bias conditions. The high resistivity of the *i*-layer significantly influences the electro-optical characteristics of the device, as it expands the depletion region and reduces junction capacitance. An increase in the depletion width results in lower capacitance and reduced dark current, which in turn minimizes electronic noise and improves high-frequency detection performance. Consequently, PIN photodiodes exhibit higher sensitivity and faster photoresponse compared to ordinary *p-n* junction devices, allowing efficient conversion of incident photons into photocurrent within very short time intervals [6–9].

The *p*-type region of the PIN photodiode is typically formed by doping silicon with acceptor impurities such as boron or aluminum. This region contains majority hole carriers and serves as the anode (+). The surface p^+ layer is fabricated with a minimal thickness to ensure high transparency for incident photons. The intrinsic layer, characterized by a low dopant concentration, plays a central role in photon absorption and electron-hole pair generation. Due to its reduced impurity density, the device can operate at relatively low voltages at room temperature. The intrinsic region forms the primary space-charge region separating the *p*-type and *n*-type layers, enabling effective separation and collection of photo-generated carriers even under moderate electric fields [10, 11].

The *n*-type region is typically formed by diffusion or implantation of donor impurities such as phosphorus or arsenic, introducing free electrons as majority carriers. This layer functions as the cathode (−) of the device. Depending on fabrication technology and intended application, the active area of the PIN photodiodes may reach up to 10 cm^2, allowing their implementation in large-area detection systems.

PIN photodiodes are characterized by several advantageous features:

- **low noise factor**, which is essential for detecting weak light fluxes and low charge signals, making them suitable for precision radiation measurements [12];
- **wide operating voltage range**, enabling stable performance under varying bias conditions;
- **high linearity and counting rate capability**, important for quantitative radiation detection;
- **absence of internal gain**, distinguishing them from avalanche photodiodes and ensuring stable and predictable response behavior. At this, the depletion (volume charge) region typically ranges from 10 to 100 µm.

These structural and operational characteristics make silicon PIN photodiodes particularly attractive for applications in radiation detection and dosimetry, where device stability under ionizing radiation exposure becomes a critical performance parameter.

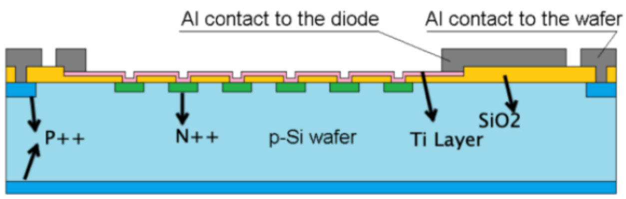

Fig. 1. Schematic representation of a Si-PIN photodiode [11].

2. Experiments and results

In this study, silicon PIN photodiodes with an active area of 3.7×3.7 mm^2 were investigated under gamma irradiation conditions. The devices were fabricated using the ion implantation technique, which enables precise control over dopant profiles and junction depth while minimizing leakage current [6]. The fabrication process was carried out on a *p*-type silicon substrate with a resistivity of 700 Ω·cm. The n^+ and p^+ regions were defined using photolithography, followed by dopant implantation. Boron (B) was used as the acceptor dopant for the formation of the p^+ region, while phosphorus (P) served as the donor dopant for the n^+ region. After dopant activation, a 90 nm thick SiO_2 passivation layer was thermally grown on the surface. Subsequently, aluminum (Al) contacts were deposited, followed by deposition of a titanium (Ti) layer. During metallization, Al contacts were selectively removed at the Ti–Al intersection points to prevent mechanical stress and cracking between layers. The use of ion implantation technology allowed improved uniformity of the junction profiles, reduced dark current levels, and enhanced reproducibility of electrical characteristics [6].

Gamma irradiation was performed using a Co-60 source with an activity of 120 GBq located at the Institute of Radiation Problems of ETN. The photodiodes were irradiated at accumulated doses of 10, 40, 70, and 100 kGy. For each irradiation dose, two PIN photodiodes were used to ensure measurement reliability. In the initial

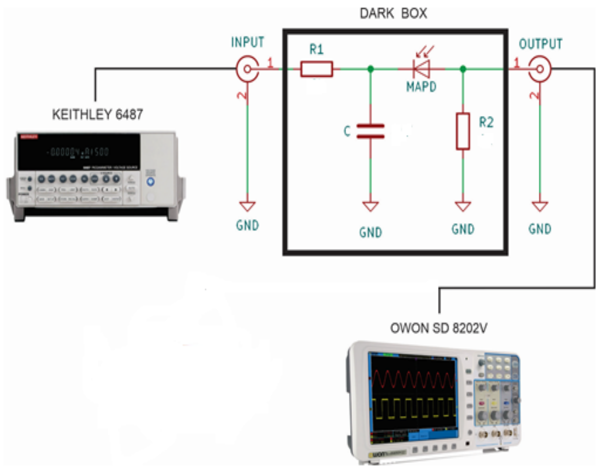

Fig. 2. Circuit used for measuring the characteristics of the PIN photodiodes.

irradiation stage (10 kGy), electrical characteristics were measured immediately after the exposure. In the final stage (100 kGy), one diode was further irradiated and characterized to evaluate cumulative radiation effects. This procedure was implemented to reduce experimental uncertainty and ensure reproducibility of the results. The total irradiation duration was 25 hours. Electrical measurements were carried out 2 hours after irradiation completion at a controlled temperature of 22 °C.

The current-voltage (*I–V*) characteristics were measured using a circuit presented in Fig. 2.

To eliminate the influence of ambient light, the measurement setup was placed inside a light-tight dark box. A Keithley 6487 picoammeter was used to record the *I–V* characteristics with high sensitivity. Fig. 3 presents the *I–V* curves of the PIN photodiodes before irradiation and after exposure at the doses of 10, 40, 70, and 100 kGy. At a reverse bias voltage of 50 V, the dark current exhibited a clear dose-dependent increase:

- Initial value (0 kGy): 5.5 nA
- 10 kGy: 5.8 nA (1.07-fold increase)
- 40 kGy: 6.4 nA
- 70 kGy: 7.6 nA (1.4-fold increase)
- 100 kGy: 8.9 nA (1.6-fold increase)

Hence, after exposure at 100 kGy, the dark current increased by a factor of 1.6 compared to its initial value. The dose dependence of the dark current at 50 V is shown in Fig. 4. To evaluate post-irradiation stability, *I–V* characteristics were measured intermittently over a 10-day period following the 100 kGy exposure. No significant additional variation in the dark current was observed, indicating electrical stabilization after the irradiation.

Capacitance-voltage (*C–V*) measurements were carried out using an E7-20M Impedance Meter. A test signal with a frequency of 1 MHz and amplitude of 40 mV was applied to the photodiodes. The obtained *C–V* characteristics are shown in Fig. 5.

At low reverse bias voltages, the capacitance of the PIN photodiode remained relatively high due to the limited width of the depletion region. As the reverse voltage

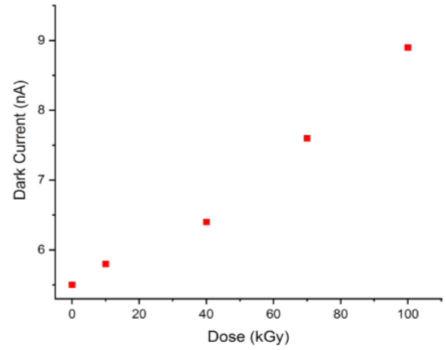

Fig. 4. Dependence of the dark current of the PIN photodiode on the irradiation dose.

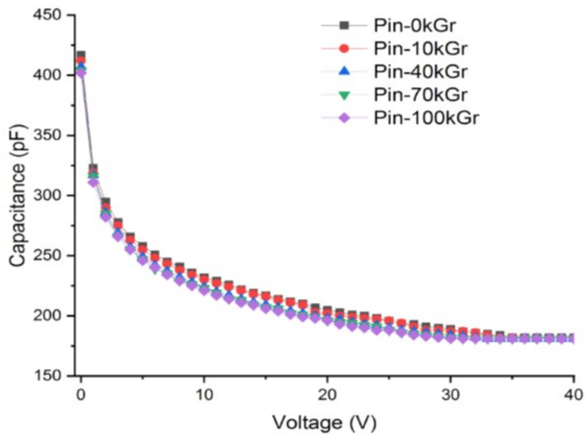

Fig. 5. Capacitance-voltage (*C–V*) characteristics of the PIN photodiodes irradiated with gamma rays.

increased, the depletion region expanded, leading to a sharp decrease in the capacitance. At the voltages between 35…40 V, the capacitance approached saturation at approximately 181 pF. Importantly, no significant change in the full capacitance value was observed after irradiation up to 100 kGy, indicating structural stability of the depletion region and minimal degradation of the junction geometry under high-dose gamma radiation exposure.

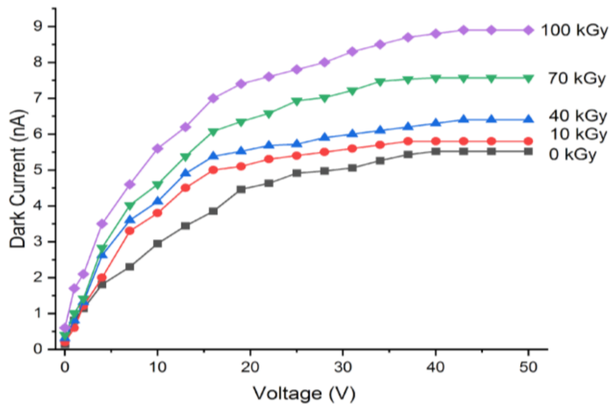

Fig. 3. Voltage dependence of the dark current of the PIN photodiode irradiated at different doses: *1* – before irradiation, *2* – 10, *3* – 40, *4* – 70, and *5* – 100 kGy.

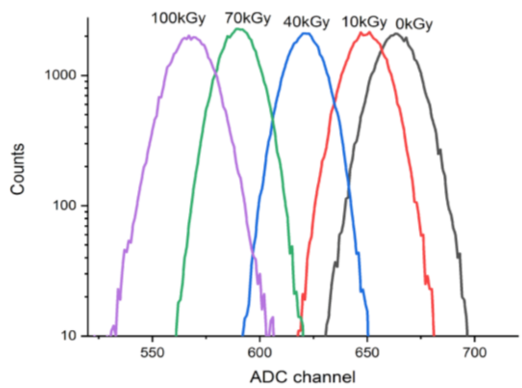

Fig. 6. Pulse height distributions of the PIN photodiode before and after gamma irradiation. The counts are shown in logarithmic scale.

The pulse height distributions recorded before and after the irradiation are presented in Fig. 6. At 0 kGy, the recorded photosignal amplitude corresponded to channel 663. After irradiation at 100 kGy, the amplitude decreased to channel 567. This corresponds to a 14.5 ± 1.4% reduction in the signal amplitude. Simultaneously, the energy resolution changed by 20.5 ± 2% after the irradiation. The observed degradation of the pulse amplitude is attributed to radiation-induced defects formed within the silicon lattice. These defects generate additional generation-recombination centers that enhance carrier trapping and recombination. As a result, charge collection efficiency decreases, leading to a reduction in the amplitude of recorded photosignals. The radiation-induced trapping centers further limit effective transport of charge carriers, thereby influencing detector response stability.

The experimental results demonstrate that while gamma irradiation up to 100 kGy induces a measurable increase in dark current and moderate degradation in pulse amplitude, the capacitance characteristics remain stable, confirming structural robustness of the silicon PIN photodiodes under high-dose gamma exposure.

3. Conclusions

In this study, radiation tolerance of silicon-based PIN photodiodes under gamma irradiation from a Co-60 source up to a total accumulated dose of 100 kGy was systematically investigated. The investigation focused on the evolution of key electrical and spectrometric characteristics, including dark current, capacitance, pulse amplitude, and energy resolution. The experimental results demonstrated a dose-dependent increase in the dark current, which rose by a factor of 1.6 at 100 kGy compared to its initial value. This increase was attributed to the formation of radiation-induced defects within the intrinsic (i) layer of the photodiode. These defects act as additional generation-recombination centers, enhancing the leakage current by continuous generation of charge carriers even in the absence of optical excitation. The observed behavior is consistent with defect-related degradation mechanisms in irradiated semiconductor materials.

The full capacitance of the photodiodes remained practically unchanged across the investigated dose range, indicating structural stability of the depletion region and preservation of the junction geometry under high-dose gamma exposure. Spectrometric analysis revealed a 14.5 ± 1.4% decrease in the pulse amplitude and a 20.5 ± 2% variation in the energy resolution after 100 kGy irradiation, which may be explained by carrier trapping and recombination processes associated with radiation-induced lattice defects. Despite moderate degradation in the dark current and signal amplitude, the structural integrity and functional operability of the devices were maintained. These findings confirm that silicon PIN photodiodes fabricated by ion implantation exhibit substantial radiation resistance and may be considered promising candidates for applications in radiation monitoring and dosimetry systems operating in high-radiation environments.

Acknowledgments

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Mammadli A.: writing – original draft.
Ahmadov G.: conceptualization, methodology, formal analysis.
Berikov D., **Temirzhanov A.**, **Mendibayev K.:** data curation, writing – review & editing.
Aristambaeva A., Kenessarin M., **Huseynzada K.:** formal analysis, data curation.
Mustafayev E.: investigation, resources.
Bacherikov Yu.Yu.: validation, supervision.

Радіаційна стійкість електричних параметрів кремнієвих PIN фотодіодів

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Анотація. Досліджено радіаційну стійкість основних електричних параметрів кремнієвих PIN фотодіодів, що піддавалися гамма-опроміненню у високих дозах. Кремнієві PIN фотодіоди з активною площею 3,7×3,7 мм^2, виготовлені за допомогою технології іонної імплантації, піддавалися гамма-випромінюванню Co-60 у накопичених дозах 10, 40, 70 та 100 кГр. Було систематично проаналізовано еволюцію темнового струму (I_{dk}), вольт-ємнісних характеристик (V–C), амплітуди імпульсу та енергетичної роздільної здатності. Експериментальні результати показують, що повна ємність фотодіодів залишалася стабільною (182 пФ) навіть після опромінення 100 кГр, що свідчить про високу структурну стійкість області виснаження. Навпаки, темновий струм демонстрував дозозалежне збільшення, збільшуючись у 1,6 рази при 100 кГр під зворотним зміщенням 50 В. Це збільшення пояснюється радіаційно-індукованими центрами генерації-рекомбінації, що утворюються у внутрішньому шарі пристрою. Крім того, гамма-опромінення привело до зменшення амплітуди імпульсу на 14,5 ± 1,4% та зміни енергетичної роздільної здатності на 20,5 ± 2%, що відображає вплив процесів захоплення та рекомбінації носіїв заряду, спричинених дефектами. Незважаючи на ці ефекти, фотодіоди зберігали робочу стабільність після тривалого опромінення та подальшого моніторингу. Отримані результати підтверджують, що кремнієві PIN фотодіоди, виготовлені методом іонної імплантації, демонструють високу радіаційну стійкість і можуть вважатися перспективними кандидатами для роботи в середовищах з високим рівнем радіації, включаючи радіаційний моніторинг та дозиметричні застосування.

Ключові слова: Si-PIN, PIN фотодіоди, темновий струм, гамма-опромінення.