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The Impact of Successive Gamma and Neutron Irradiation on Characteristics of PIN Photodiodes and Phototransistors

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Additional information is available at the end of the chapter

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Abstract

The aim of this paper is to explore the impact of increased gamma and neutron radiation on the PIN photodiodes and phototransistors and their output characteristics. Special attention was paid to the successive impact of gamma and neutron radiation when the components were located in the field of gamma radiation and after that in the field of neutron radiation. The impact of successive irradiation was compared with the influence of gamma and neutron radiation when they appear individually. An important result of this research is the observation that neutron irradiation of photovoltaic detectors, applied after gamma irradiation, leading to partial reparations of distorted semiconductor structure and increasing disrupted output characteristics (photocurrent, spectral response). Monte Carlo simulation of gamma photons transfer through the crystal lattice of the semiconductor has been shown that the cause of such effect of neutron radiation is a large number of divacancies caused by successive operation of the previous gamma radiation and the neutron radiation itself. Divacancies have created the basis for increased generation of charge carriers by direct transfer (tunneling) of carriers through the traps (recombination centers). This is so called intercenter charge transfer.

Keywords: photovoltaic detectors, gamma and neutron radiation, divacancies, intercenter charge transfer, Monte Carlo simulation

1. Introduction

Science and technology that deals with photovoltaic semiconductor detectors is an area with an extremely rapid development in the last 20 years. The reasons for this are, on the one hand,

practically countless possibilities of application of these detectors (optical communication systems, medical devices, military equipment, automatic control systems, various electronic devices), and, on the other hand, miniaturization of electronic components and development of these devices mass production allowed them to have relatively low cost and to be accessible to the wide population. Particularly interesting applications of semiconductor photovoltaic detectors are in military systems, medical devices and equipment, and cosmic systems. These are areas where the probability for photovoltaic detectors to be in increased radiation field is very large.

The area of photovoltaic detectors and radiation type which they can be exposed is very large. This work is limited to the observation of the PIN photodiodes and phototransistors and their behavior in terms of gamma and neutron radiation considering that with particle emission from the core, as a rule, there have been a simultaneous de-excitations descendant core by a discrete gamma-ray emission. Semiconductor devices, therefore, are exposed to summary effect of neutron and gamma radiation.

The aim of this paper is to explore the impact of increased gamma and neutron radiation on the PIN photodiodes and phototransistors and their output characteristics. Special attention was paid to the observation of semiconductor devices' behavior when they have been exposed to the field of gamma radiation and after that to the field of neutron radiation (successive gamma and neutron radiation).

2. Experimental

Experimental measurement in this paper was carried out on the commercially available photovoltaic detectors. In this experiment, the following were used:

1. four types of silicon PIN photodiodes (BP104, BPW41N, BPW34 all manufactured by Vishay, and SFH203FA by Osram),
2. two types of silicon NPN phototransistors (BPW40 manufactured by Telefunken electronic and LTR4206 by LITEON).

Devices were first exposed to gamma radiation from Co^{60} source and then, after 30 days, to ^{241}Am -Be neutron and gamma source. Both sources were housed in Institute of Nuclear Sciences "Vinča" in Belgrade, Serbia.

The dose of Co^{60} gamma source is 2000 Gy, the energy of 1.25 MeV, and half-life time of 5.27 years. The samples were placed in controlled environment at a distance of 150 mm away from the radioactive source with a glass between them. The dose rate was 100 Gy/hr which was measured by electrometer with ionization chamber TW 30012-0172 produced by PTW, Germany. Measurement uncertainty of the system is less than 1.2%.

^{241}Am -Be source emits gamma photons of low energy (60 and 14 keV) with the activity of 3.7×10^{10} Bq, the intensity of the neutron emission of 2.7×10^6 neutrons s^{-1} and the mean energy of the neutrons $E_{\text{nav}} = 5.5$ MeV. The panels were at a distance of 5 cm from the source,

so the photon equivalent dose rate is $\dot{H}_\gamma = 12$ mSv/hr, and the photon absorbed dose rate is $\dot{D}_\gamma = 12$ mGy/hr. Calculated neutron absorbed dose rate is $\dot{D}_n = 1.714$ mGy/hr and the equivalent dose rate of neutrons is $\dot{H}_n = 12$ mSv/hr with the quality factor $Q_n = 7$. In this experiment, the semiconductor devices were placed at a distance of 5 cm from the ^{241}Am -Be source, and the exposure period was 16.75 hr. Since the total absorbed dose, for that distance, is $\dot{D}_{\text{tot}} = 13.714$ mGy/hr and the total equivalent dose is $\dot{H}_{\text{tot}} = 24$ mSv/hr, the total absorbed dose for material components is $D_{\text{tot}} = 229.71$ mGy and the total equivalent dose is $H_{\text{tot}} = 402$ mSv.

Both irradiation and those from Co^{60} gamma source and those from ^{241}Am -Be source were performed in the air at a temperature of 21°C and relative humidity of 40–70%.

Before and after every step of irradiation spectral response and photocurrent have been measured. The measurement were performed on the photodiodes and phototransistors, in highly controlled conditions at room temperature, which have previously been removed from the irradiation room. Samples have been divided in two groups. First group was irradiated only with neutron radiation and the second one with successive gamma and neutron radiation.

For the first group, there have been performed three measurements of the photodiodes and phototransistors parameters:

1. first measurement: just before neutron irradiation,
2. second measurement: just after neutron irradiation,
3. third measurement: 30 days after neutron irradiation.

For the second group there have been performed five measurements of the photodiodes and phototransistors parameters:

1. first measurement: just before gamma irradiation,
2. second measurement: just after gamma irradiation,
3. third measurement: 30 days after gamma irradiation (just before neutron irradiation),
4. fourth measurement: just after neutron irradiation,
5. fifth measurement: 30 days after neutron irradiation.

In order to perform the long-term isothermal annealing i.e. to give detectors enough time to recovery, the third and fifth measurement have been undertaken 30 days after the irradiation. Because of that, the changes occurring in the samples of the second group after the first irradiation (gamma) can be considered as a permanent. Standard measurement equipment (the professional digital multimeter AMPROBE 33XR) was used for measurement. Combined measurement uncertainty for all measurements was less than 1.2% [1, 2].

In order to understand the state of the semiconductor crystal lattice after exposure to gamma radiation and before neutron irradiation, a Monte Carlo transfer simulation of gamma photons through the photodiode and phototransistor have been performed.

3. Results and discussion

3.1. Photodiodes and phototransistors response to neutron radiation

Free neutrons, in small amounts, are everywhere in nature. The main source of neutrons is cosmic radiation. They also occur in nuclear reactions of natural α radiation and spontaneous fission of heavy nuclei. Neutron is a unique particle, it is uncharged, has a relatively large mass, and leads to radioactive disintegrations. From the point of nuclear reaction, neutrons are much more important than any other particles. As neutral particles, neutrons do not have the ability for direct ionization of materials. The basic mechanism of neutron interaction with the matter is via elastic collisions with atomic nuclei of environment. The interaction with electrons, although it exist, is negligible. Thereby, neutron loses some of its energy and slows down, while the environment can suffer different types of transformation.

Neutrons interact with the material in two different ways:

- through collisions with other particles,
- through the process of absorption.

In the case of high-energy neutrons (fast one), the dominant process is elastic scattering, while with low-energy neutrons, the absorption process is more likely [3].

Displacement of atoms can be compared with a collision between two solid spheres. If the transferred energy higher than the energy required for displacement (*displacement energy Ed*) atom will be shifted from their original positions in the lattice, and there will be defect (*PKA —primary knock-on atom*). Assuming that there is enough energy, displaced atom could be able to move other atoms or to produce electron-hole pairs. In the case of very high energy particles, a cascade distortion can be formed.

Different types of displacement defects could occur due to neutron irradiation (**Figure 1**):

- vacancies,
- divacancies,
- interstitials,
- Schottky defects,
- Frenkel defects.

Figures 2–4 show the results of measurements of PIN photodiodes and phototransistors spectral response before and after neutron irradiation and after a period of 30 days recovery are presented [4]. As can be seen from Figures 2 to 4, neutron radiation caused the deterioration of photodiodes and phototransistors characteristics.

High-energy particles like neutrons create much more displacement damages than gamma radiation. When an atom is ejected from its position, it creates a vacancy in the lattice. The ejected atom may recombine with a vacancy or stay in an interstitial position in the lattice. The

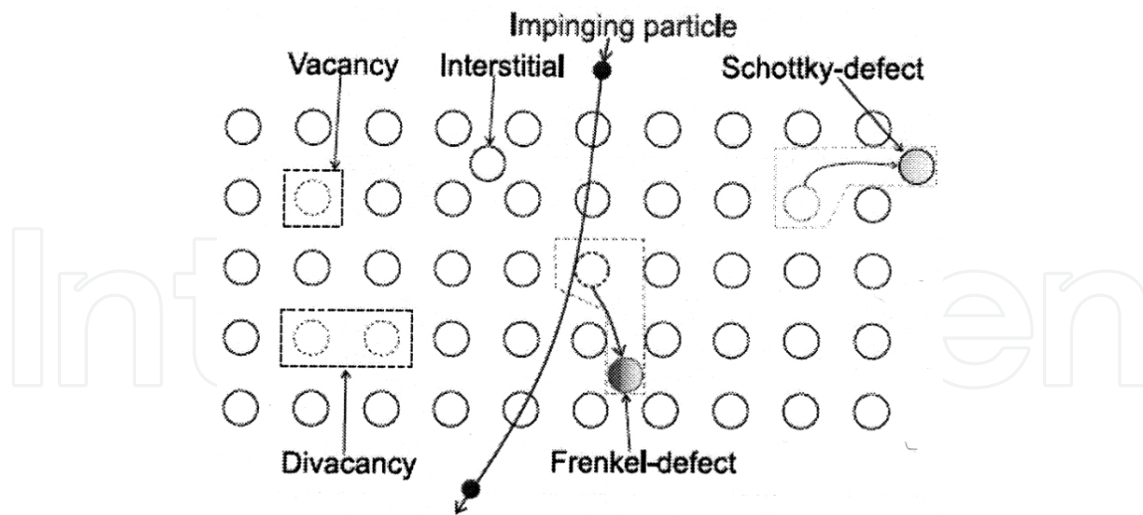


Figure 1. Displacement defects [3].

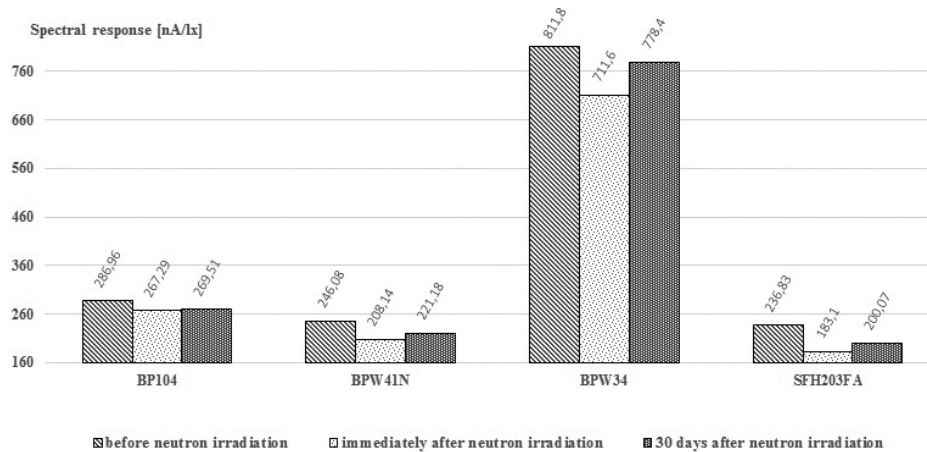


Figure 2. Spectral response of photodiodes before and after neutron irradiation.

vacancies are mobile and combine with other vacancies or with impurities of the semiconductor [5, 6], thus creating recombination centers that cause the reduction of charge carrier lifetime. Axness *et al.* [7] showed that the damage to the crystal lattice and reduction of the charge carriers lifetime are spatially dependent. Sporea *et al.* [8] have calculated that the major degradation of the photodiode responsivity, for the total gamma dose of 1.23 MGy and to the neutron fluence of 1.2×10^{13} n/cm², occurs in the case of neutron irradiation (37.5%) as compared to the gamma irradiation (7.2%).

Steady defects act as recombination centers and traps for charge carriers and because of that the resistance of the material could be increased [6]. Mobile vacancies represent a strong recombination instrument for capturing of minority charge carriers and thus reduce their lifetime. Defects responsible for the capture of electrons called E-defects while the H-defects actually traps holes [3]. Displacement defects mainly affect the electrical characteristics of the semiconductor substrate and thus the electrical characteristics of the whole electronic compo-

nents. As a result, there have been the reduction of the spectral response and lower photocurrent photodiode (Figure 2).

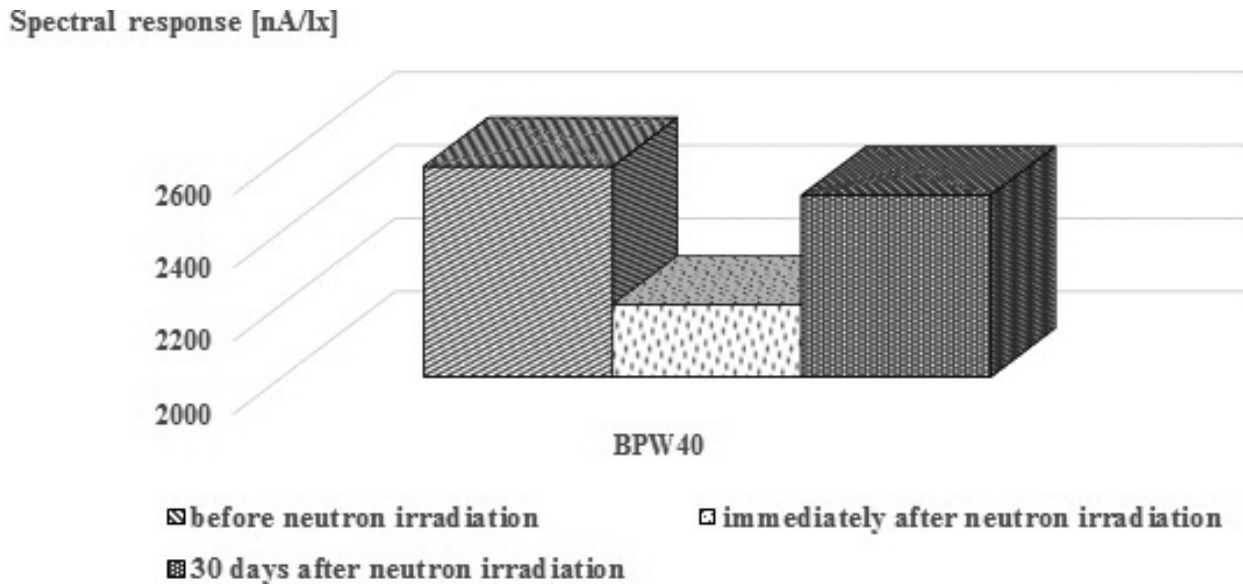


Figure 3. Spectral response of phototransistor BPW40 before and after neutron irradiation.

Phototransistors are very susceptible to neutron radiation. Neutron radiation affects the characteristics of phototransistors primarily by creating defects in the crystal lattice which can dramatically increase the level of charge carriers recombination. On the other hand, the increment of the recombination rate reduces the current gain. Many studies of the damage relocation mechanism in bipolar transistors have shown that the current gain of the transistor with a common emitter decreases with increasing of recombination centers number. The measurement data of phototransistors before and after irradiation showed that the adverse effects of neutron radiation are the most pronounced on transistors base current. Phototransistor is light controlled device where the output current is controlled by the base current and brightness. Cluster defects caused by fast neutrons are the dominant mechanism for damaging of phototransistors exposed to neutron radiation. Number of displaced atoms caused by neutrons is very large. The result is forming of recombination-generation centers. Electron-hole recombination causes a decrease of current gain. Generation of electron-hole pairs cause an increase in leakage current. Removing the majority charge carriers and the reduction of carrier mobility causing an increase in voltage between the collector and emitter. Current gain is determined by the number of majority carriers emitted from the emitter which are passing through the base as minority carriers and are collected by collectors as the major carriers. Increasing of density of recombination-generation centers due to defects created by radiation causes a reduction of minority carrier lifetime, and because of that, the rate of electron-hole recombination in the base increases. Accordingly, the current gain decreases as a result of reduced injection of charge carriers from the emitter to the collector and, as a result, the photocurrent and spectral response decreases (Figures 3 and 4) [9].

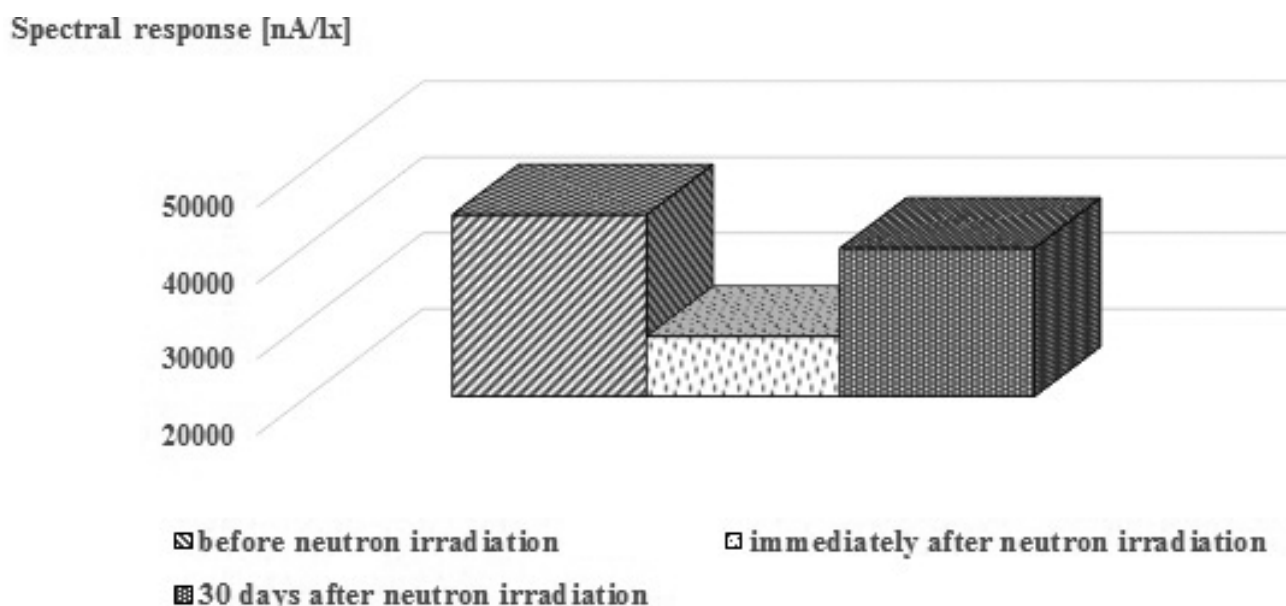


Figure 4. Spectral response of phototransistor LTR4206 before and after neutron irradiation.

In this experiment, a long-term isothermal annealing at room temperature was applied. The recovery period, labelled as a short-term annealing, begins immediately after the occurrence of damage and fully complete within a few minutes to 1 hour after irradiation. Damage, remaining after, that are often referred as a permanent damage. However, relatively slow process of recovery or long-term annealing, continues even after the short-term annealing is completed [10]. Recovery causes partially increasing of spectral response and the photocurrent.

Figures 2–4 show that the response of new, unused photodiode and phototransistor to neutron irradiation is in accordance with the theoretical principles described in the literature.

3.2. Photodiodes and phototransistors response to successive gamma and neutron irradiation

In recent few years there have been carried out a number of studies with the aim of observing the behavior of different photovoltaic detectors in terms of gamma and neutron radiation [11–17]. Most common topics were photodiode, as one of the most used and simplest types of optical sensors. The effect of gamma and neutron radiation on semiconductors is well known and described in the available literature. This chapter will present the results of research of behavior of photovoltaic detector due to successive gamma and neutron radiation. The samples were first exposed to gamma radiation and after 30 days to neutron radiation.

Figure 5 shows the results of the photodiodes and the phototransistors spectral response measurements before and after gamma and neutron radiation [18].

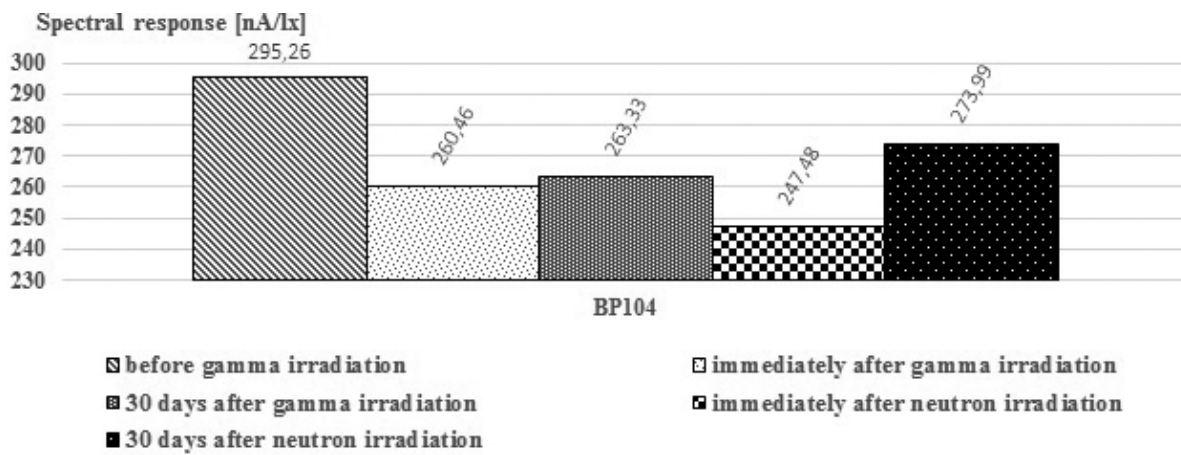


Figure 5. Spectral response of the reverse biased photodiode BP104 before and after gamma and neutron irradiation.

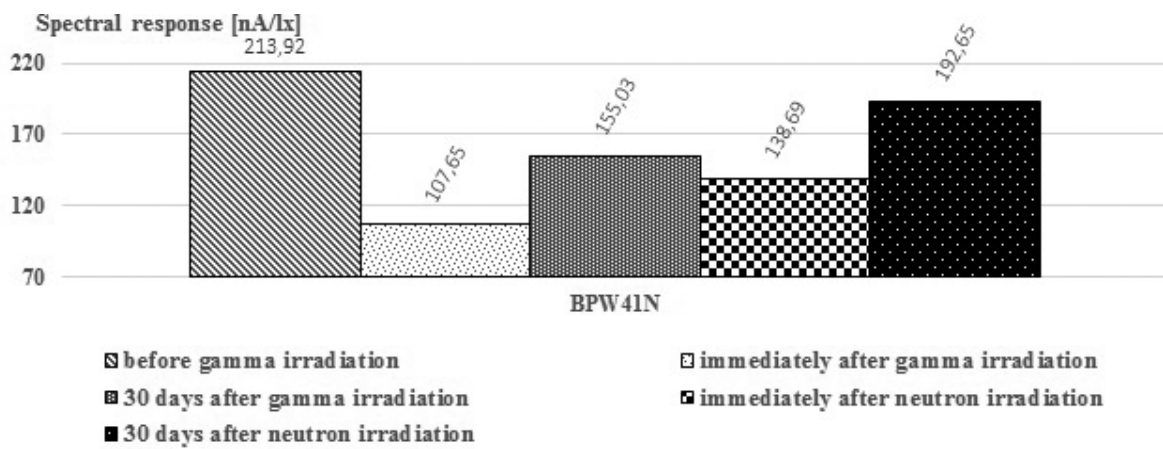


Figure 6. Spectral response of the reverse biased photodiode BPW41N before and after gamma and neutron irradiation.

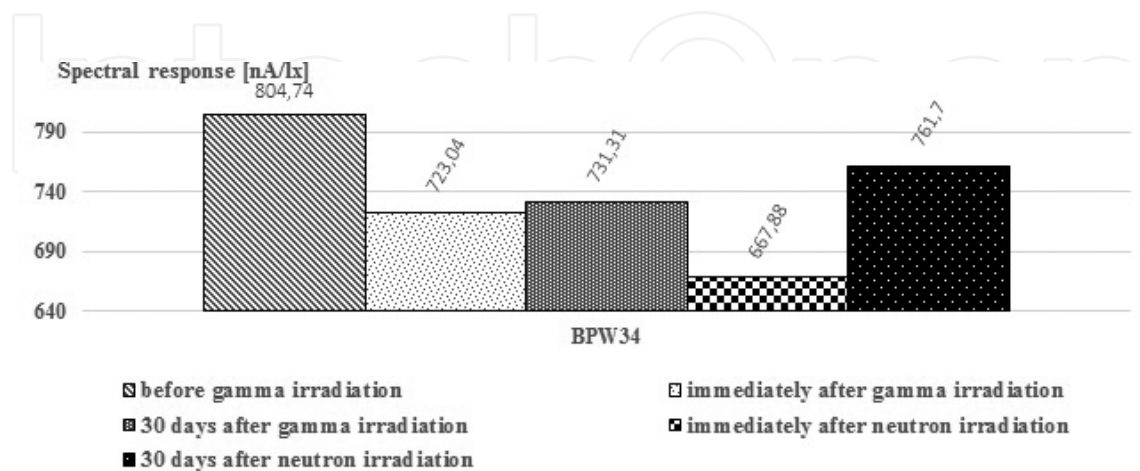


Figure 7. Spectral response of the reverse biased photodiode BPW34 before and after gamma and neutron irradiation.

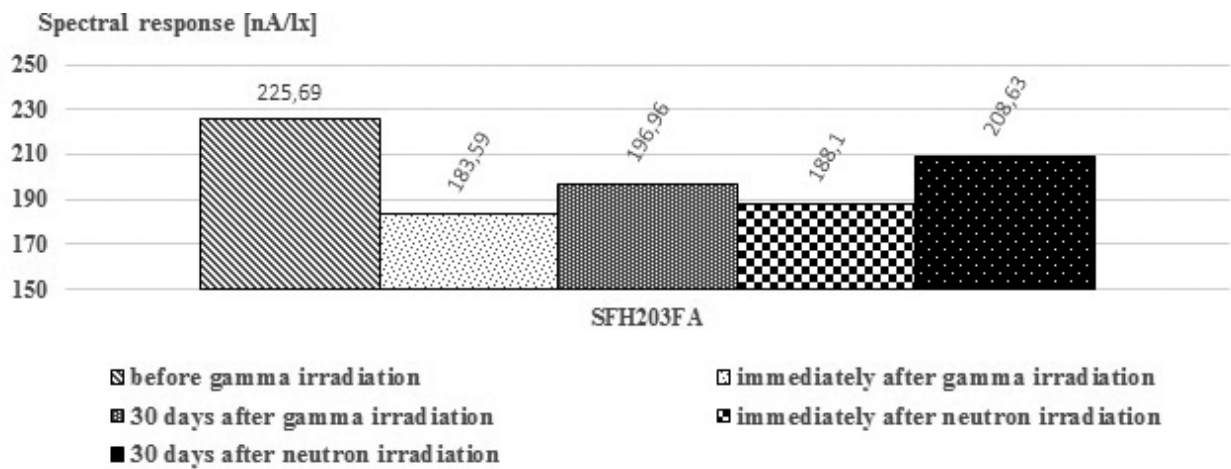


Figure 8. Spectral response of the reverse biased photodiode SFH203FA before and after gamma and neutron irradiation.

As it can be seen from Figures 5 to 10, neutron irradiation, applied 30 days after gamma irradiation, at first was deteriorate response and characteristics of photodetectors. However, after 30 days of recovery, there was a partial improvement of the spectral photodetector response and the increasing of photocurrent. The degree of improvement is different for each type of photodetector.

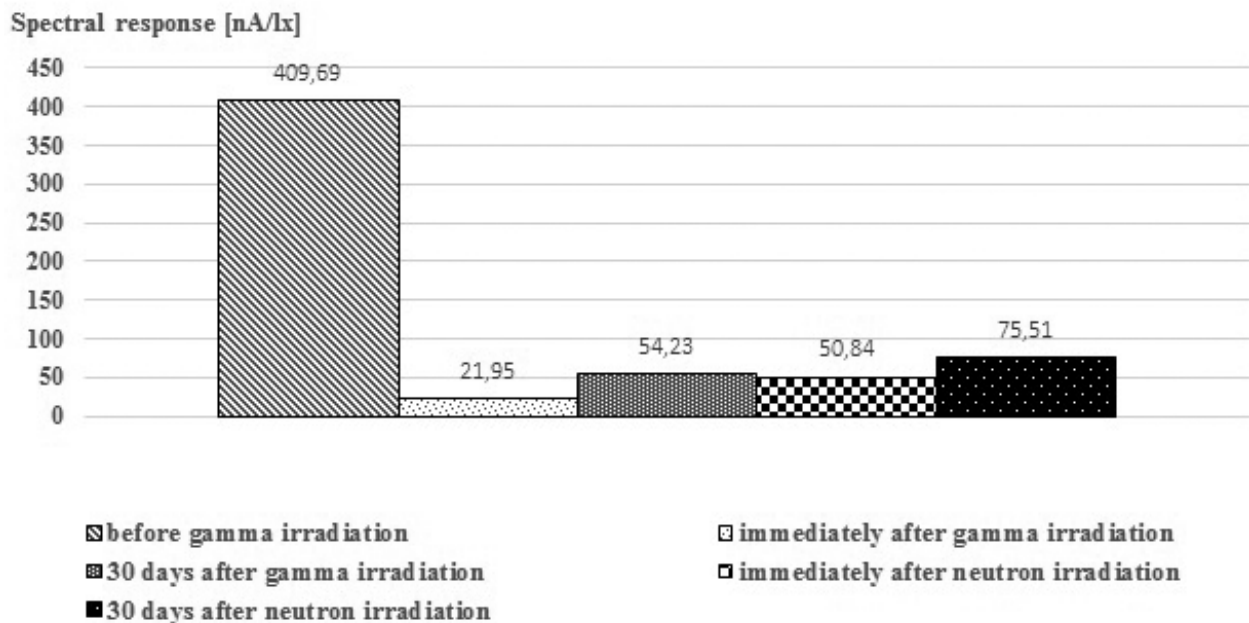


Figure 9. Spectral response of phototransistor BPW40 before and after gamma and neutron irradiation.

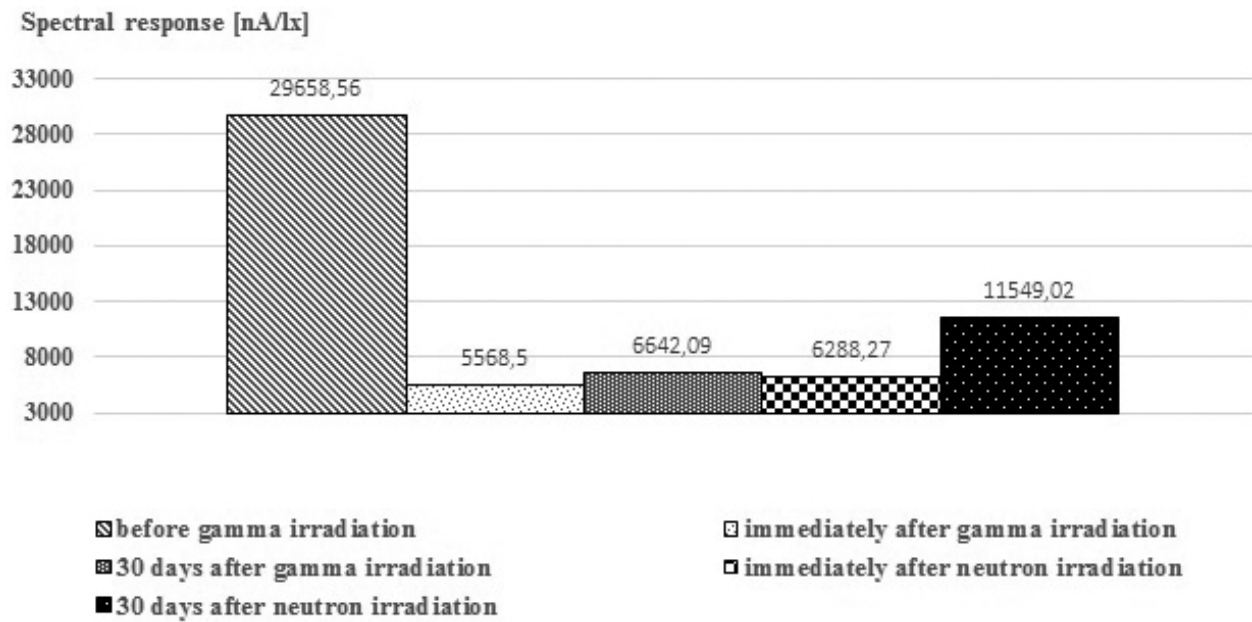


Figure 10. Spectral response of phototransistor LTR4206 before and after gamma and neutron irradiation.

Neutron irradiation, by itself, causes the formation of displacement damage in photodiodes and phototransistors, which leads to the degradation of their electrical characteristics, as is shown in Chapter 3.1 (Figures 2–4). However, if it is applied after the gamma radiation, neutron radiation makes such changes which increasing the efficiency of the recovery process and, as a result, we have improved electrical characteristics. To achieve these effects to be occurred, the concentration of charge carriers must be increased in semiconductor material. Taking previous studies into account [12, 19–21], it can be concluded that the possible cause is tunneling of charge carriers supported by traps and increased generation.

Defects in the material represent traps for the free charge carriers and that can lead to tunneling supported by traps, and this increases the tunneling current at low voltages which are commonly attributed to SILC (*Stress-Induced Leakage Current*) [22–24]. Tunneling supported by traps is a process where particle spend some time trapped in the defect (trap) before tunneling through the barrier (*Trap Assisted Tunneling—TAT*) [20, 21]. This process is caused by inelastic transfer of charge carriers with the help of emission of phonons [21].

Let the electron from the field 1 in **Figure 11** receive enough energy to cross the barrier and came to the area 2. This process undermines the law of conservation of energy for a short period of time determined by Heisenberg's uncertainty principle. Now, if some other electron from the field 2 tunneled in a similar way in a similar time in the area 3, then total number of electrons that are passed from area 1 to area 3 is one. This tunneling is called inelastic tunneling because the excited electron-hole pair occurs, which dissipates after a short time through the interaction carrier-carrier [25].

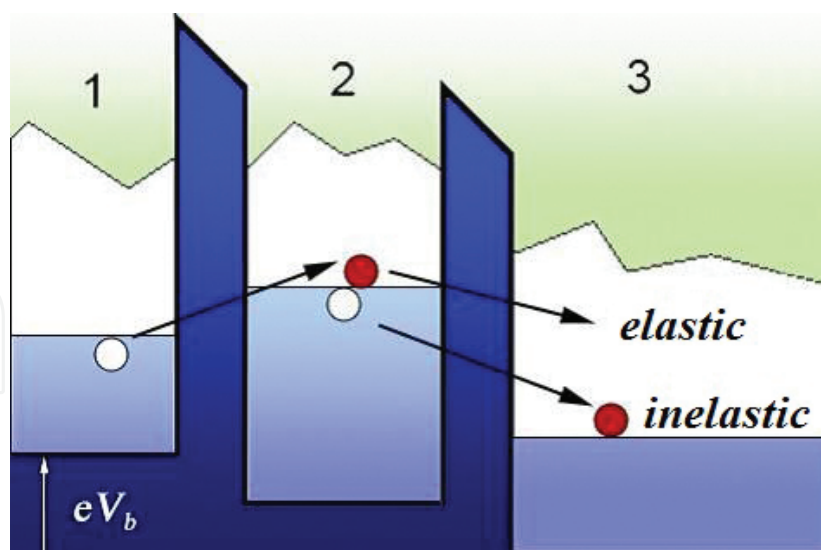


Figure 11. Elastic and inelastic tunnelling through a double barrier [25].

Elastic tunneling is the process of tunneling of same electrons from and in the region 2 with preserving of the phase which is why this process is coherent. Elastic tunneling depends on the internal structure of the area between the barrier and the amount and polarization of the applied voltage. Inelastic tunneling is the dominant process in comparison with the elastic tunneling except in the case of low voltage, low temperature, or low density of quantum dot states [26, 27]. Area 2 is also called a virtual state and simultaneous tunneling through this state, co-tunneling.

Shockley–Read–Hall model describes the process of recombination and the generation of charge carriers in a semiconductor with the help of quantum tunneling mechanism [19, 28, 29]. The transition of an electron from the valence band to the conductive band represents the generation of electron-hole pair, because in the valence band, hole remains in the place of electrons which contribute to the current. The reverse process is recombination. In order to be transferred from the valence band into the conductive band electron must have greater energy than the energy gap. As it may be defects in the crystal structure of the semiconductor caused by impurities (or other causes, eg. radiation), it may appear within the bandgap. Such defects are called traps and they represent energy levels that can trap electrons ejected from the valence band [30]. According to Dharival-Rajvanshi's model, traps can be near the edge of the valence and conduction band (*Tail State*) and near the Fermi level on both sides (*Dangling Bond*). In order to move electron from the valence band into the trap, it requires much less energy than for the transition to the conductive band, so the traps actually facilitate the process of generation of free carriers. The probability that an electron will fall into the trap and spend some time in it depends on the material, the density of defects in the energy gap, the present electric field, temperature, concentration of electrons in the conduction band, and the concentration of holes in the valence band. Schokley–Read–Hall model assumes one level within a gap where electrons or holes can come, which dynamic is quasi-stationary [25, 31, 32].

When gamma radiation and neutron radiation are acting individually on a photodiode there is, as the final result, an increase in the concentration of recombination centers which, according to Shockley-Read formula [33], result in a reduction of minority charge carriers lifetime:

$$\tau = \frac{1}{\langle c_n \rangle \cdot N_t} \frac{n_0 + \delta n + n_1}{n_0 + p_0 + \delta n} + \frac{1}{\langle c_p \rangle \cdot N_t} \frac{n_0 + \delta n + p_1}{n_0 + p_0 + \delta p} \quad (1)$$

where $\tau = \tau_p = \tau_n$ is the life time of electrons and holes and N_t concentration of R-centers (recombination centers which can accept both electrons and holes). The reduction of minority carrier lifetime causes photocurrent decreasing. Previously stated explanation is related to the influence of neutron irradiation on the new, previously non-irradiated photodiodes. However, if we change the initial conditions, i.e. if the photodiode previously has been exposed to gamma radiation, the effects of neutron irradiation will be different. One of the results of gamma radiation are interstitial (PKA), vacancies, and their complexes [34, 35]. Vacancies are also one of the main products of neutron irradiation of the material. When the material, which already contains a number of vacancies, is exposed to the effects of neutron radiation, there is high probability that the defects such as vacancies would be found physically close to each other. When the two vacancies occur next to each other within the grid, they form defective complex called divacancies complex. This complex captures electrons and also can stress the homopolar bonds, which can lead to the termination of the connection. Straining of homopolar connections and its termination can lead to the release of one or two electrons from the defective complex in the conductive band, which results in increased generation.

In some previous studies, increased generation [12] and increased recombination [36, 37] have been observed through the process of electron transfer directly between the defects located close to each other without passing through the conductive belt. This process can be very fast and therefore dominant compared to the Shockley-Read-Hall process. In order to occur the intercenter charge transfer, defects must be physically close to one another. Two irradiation of the same material, such as gamma and neutron, allowing some defects to be close to one another.

The divacancy has three energy levels in the bandgap: a hole trap and two acceptor states. In standard Shockley-Read-Hall theory, current generation in silicon depletion regions is mediated by isolated defect levels in the forbidden bandgap. Generations occurs when a hole is emitted from the defect level into the valence band (i.e. electron captured from it) and an electron is emitted into the conduction band. Each transition occurs with a rate, e_n or e_p , and is governed by the time constant τ_{ne} ili τ_{pe} .¹ If several defect levels exist, they are regarded as the sum of the individual components. In coupled defect generation, illustrated in **Figure 12**, an electron is first captured by the donor state in the bottom half of the bandgap. This is an efficient process with time constant τ_{pe1} being very short hence the fractional occupation of this level is ≈ 1 . The electron can then transfer directly to a higher state in a nearby defect without going

¹ $e_n = 1/\tau_{ne}$ and $e_p = 1/\tau_{pe}$.

via the conduction band. The time constant for this step is denoted $\tau_{1 \rightarrow 2}$. The final transition to the conduction band then occurs as normal with a time constant τ_{ne2} . The enhancement of the generation rate arises because the large transition from the valence band to the above midgap level is mediated by the donor level. This shortens the time taken for the upper state to become filled and hence increases its fractional occupancy [12, 38].

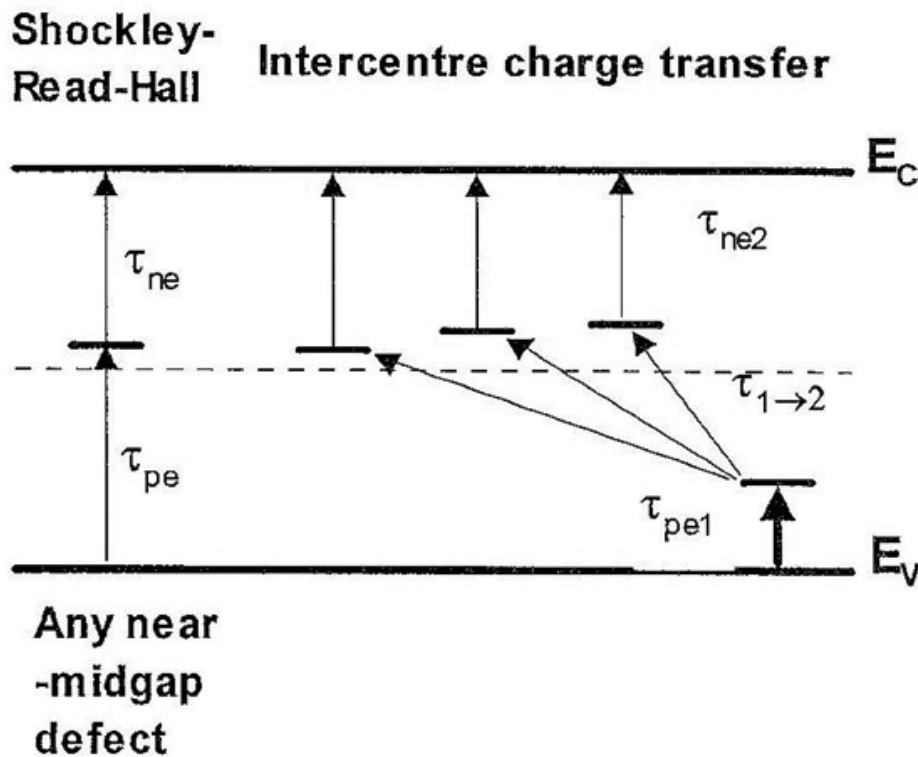


Figure 12. Schematic diagram of Shockley–Read–Hall theory and intercenter charge transfer generation processes [12].

The enhancement of the fractional occupancy increases the number of electrons generated per unit of time from a defect state and hence increases the photocurrent [33].

3.3. Monte Carlo simulation of radiation transfer through photovoltaic detectors

In order to understand the state of the semiconductor after irradiation, Monte Carlo simulations of radiation particles transfer through the material were performed. Monte Carlo simulation gets the answers by simulation of each individual particle and memorizing of certain aspects of their middle behavior. For simulation, FOTELP-2K10 and MCNP programs were used. FOTELP-2K10 is a program that gives the Monte Carlo simulation of the transport of photons, electrons, and positrons [39], while the MCNP (*Monte Carlo N-Particle*) is a general purpose software that can simulate the transport of neutrons, photons, electrons, or a combination of neutron/photon/electron through arbitrary geometric configurations [40].

For this experiment, two Monte Carlo simulation were made, γ -photon transfer through the PIN photodiode and through the phototransistor. The simulations were done with the aim of

understanding the processes occurring in the photodiode and phototransistor between gamma and neutron irradiation, i.e. to provide a review process, which is gamma radiation caused in a semiconductor since the final result of these processes represents the initial conditions for neutron irradiation that followed.

3.3.1. Monte Carlo simulation of gamma photon transport through a pin photodiode

Figure 13 presents a cross-section of a PIN photodiode used for the simulation.

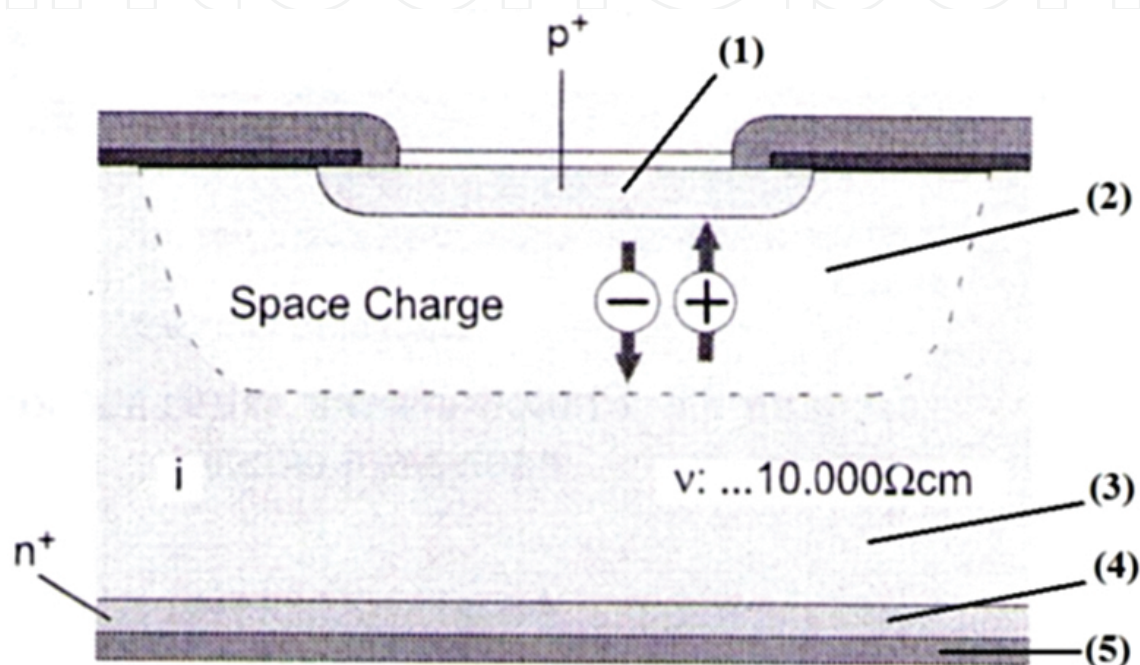


Figure 13. Cross-section of a PIN photodiode [41].

The results of Monte Carlo simulations are shown in **Tables 1–5** and in **Figure 14**. **Table 1** shows the deposited energy per input particle in each zone of photodiode, where the zones are semiconductors area: p^+ (zone 1), p (zone 2), and n^+ (zone 4), and the pure semiconductor (zone 3). **Figure 14** shows the ratio of energy absorbed during each interaction in different layers per depth of semiconductors, i.e. each zone.

Zone	Deposited energy (eV)	Relative error (%)
1	556.77	0.165
2	257.78	0.255
3	293.31	0.239
4	1386.9	0.112

Table 1. Deposited energy per input particle obtained by Monte Carlo simulation using FOTELP-2K10.

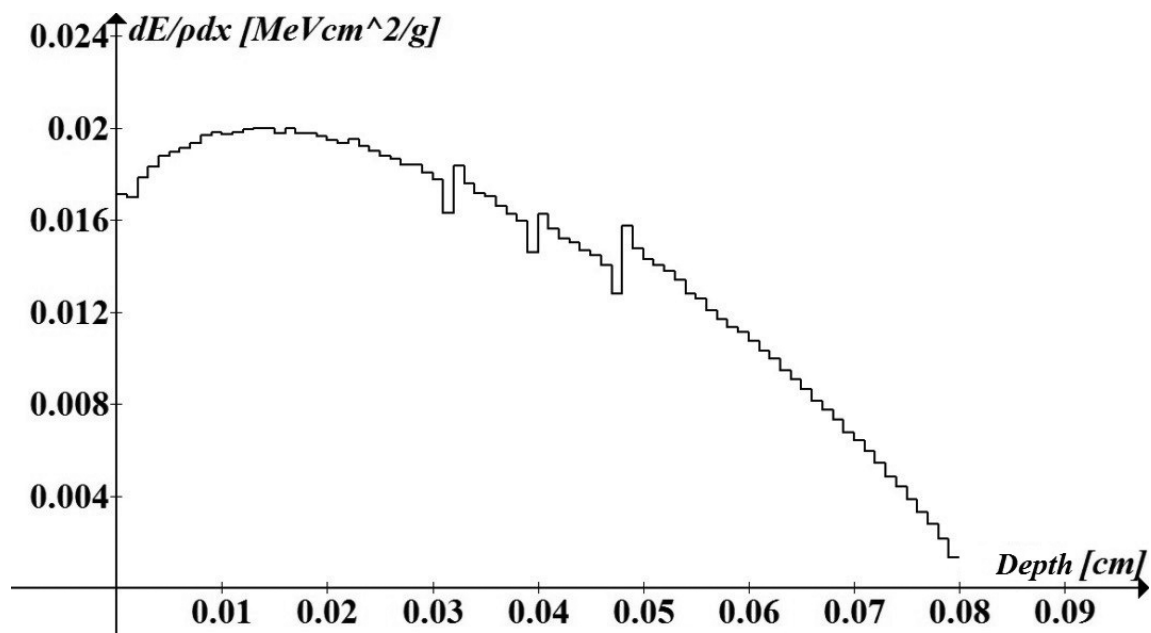


Figure 14. Depth dose distribution in PIN photodiode obtained using FOTELP-2K10.

In order for a lattice atom to be displaced, a minimum amount of energy must be transferred to the target atom. This threshold energy is called the displacement energy E_d (*threshold displacement energy—TDE*) [42, 43]. By using molecular dynamics (MD) simulations, Perlado *et al.* [44] predicted TDE values, at 300 K, ranging from 42 to 112 eV for Si. Average TDE values of 93 eV for Si are suggested by El-Azab and Ghoniem from MD simulations [45].

In each zone of photodiode (Table 1), and in almost every layer (Figure 14) deposited energy per incident particle is high enough to move the atom, i.e. to create vacancy.

Tables 2 and 3 show the probability of creating new photons and electrons per incident particle (photon) through individual interactions.

Probability of creating new photons	Interaction that creates photons
8.4333E-06	Bremsstrahlung
1.0000E-06	Positron-electron annihilation
4.0000E-07	Electron x-rays

Table 2. Probability of creating new photons per incident particle (photon) obtained using MCNP.

Probability of creating new electrons	Interaction that creates electrons
1.3333E-06	Pair production
2.1085E-06	Compton effect
3.3667E-07	Photoelectric effect

Probability of creating new electrons	Interaction that creates electrons
3.3333E-06	Auger photons
4.1667E-06	Auger electrons
5.3281E-07	Electrons knocked out in a collision with impact electrons

Table 3. Probability of creating new electrons per incident particle (photon) obtained using MCNP.

Bremsstrahlung is the interaction that has the highest probability to generate new photons (Table 2), while the highest probability for creation have Auger electrons (Table 3).

Tables 4 and 5 show the number of physical interactions in which are created or disappeared photons and electrons per input particle (per cell).

Physical interaction	Area 1— p^+	Area 2— p	Area 3— i (intrinsic)	Area 4— n^+	Area 5—Al contact
From neutrons	0	0	0	0	0
Bremsstrahlung	9.3333E-07	7.3333E-07	6.3333E-07	2.1333E-06	4.0000E-07
Capture of photons	-2.233E-06	-1.433E-06	-1.867E-06	-1.500E-06	-1.133E-06
P-annihilation	6.6667E-08	0	0	6.6667E-08	0
Pair production	-3.333E-08	0	0	-3.333E-08	0
Photonuclear effect	0	0	0	0	0
Electron x-rays	1.4333E-06	9.0000E-07	1.4667E-06	0	9.6667E-07
Total	1.6667E-07	2.0000E-07	2.3333E-07	6.6667E-07	2.3333E-07

Table 4. Number of physical interactions in which are created or disappeared photons per incident particle (per cell) obtained using MCNP.

Physical interaction	Area 1— p^+	Area 2— p	Area 3— i (intrinsic)	Area 4— n^+	Area 5—Al contact
Pair production	6.6667E-08	0	0	6.6667E-08	0
Compton recoil	1.7967E-05	9.1000E-06	9.1667E-06	2.3833E-05	7.7333E-06
Photoelectric effect	2.2333E-06	1.4333E-06	1.8667E-06	1.5000E-06	1.1333E-06
Photon Auger	0	3.3333E-08	3.3333E-08	1.3333E-07	0
Electron Auger	4.7667E-05	3.4133E-05	3.7300E-05	0	5.5800E-05
PKA	2.5647E-04	1.8663E-04	2.0543E-04	7.2073E-04	2.1520E-04
p-annihilation	-3.333E-08	0	0	-3.333E-08	0
Total	3.2437E-04	2.3133E-04	2.5380E-04	7.4623E-04	2.7987E-04

Table 5. Number of physical interactions in which are created or disappeared electrons per incident particle (per cell) obtained using MCNP.

Simulation results show that the number of interactions that result in a vacancy i.e. PKA (*primary knock-on atom*) are 10 to 1000 times higher than all other possible types of interaction (**Table 5**—shaded part). Among the total number of electrons caused by gamma radiation in all areas of photodiode, 78–80% is produced by PKA (in area 4 even up to 97%). This is an unequivocal sign that the gamma radiation caused a very large number of vacancies.

In order for neutron irradiation of photodiodes (applied after gamma radiation) to cause intercenter charge transfer and tunneling supported by traps, as already mentioned, it is necessary for neutron radiation to form defects in a semiconductor (vacancies), which are close to each other, and to create a sufficient number of divacancies. As a relatively heavy and uncharged particles, neutrons, in a collision with the atoms of the crystal lattice, lead to the displacement of entire atoms from the lattice. This naturally causes the breaking and destruction of the local lattice structure by displacing atoms and creating vacancies. Displaced atom is called interstitial because it takes place in the space between knots, and a pair of interstitial atom and vacancy is called Frenkel defect. If the energy of incident neutron is high enough, it can give sufficient energy to displaced atom, which can displace other atoms in the lattice. In the case of high-energy incident neutrons, this process has a cascade (avalanche) character. This requires quick energy neutrons from 10 keV to 10 MeV. At the end, all displaced atoms lose their excess energy and the heat balance in the grid established. Some of the atoms return to vacancies and reconstruct the structure of the local grid. Some of these atoms come together with dopants or impurity atoms and form stable electrically inactive defects, which do not contain recombination centers and trap. On the other hand, moving vacancies associate with impurity atoms, vacancies, and other donors forming temperature stable defects (complex defects) that represent recombination centers and trap centers. Since the mean energy of neutrons from a source in the experiment was 5.5 MeV, it follows that neutrons have sufficient energy to cause a cascading process of creating vacancies. Previously, gamma irradiation created a large number of vacancies, increasing the probability for vacancies, created by neutron irradiation, to be physically close to the preformed vacancy. Divacancies, formed like this, facilitate intercenter charge transfer supported by traps and provide increased generation of charge carriers and this, as already mentioned in Section 3.1., leads to partial reparation of semiconductor structure and increase the spectral response and the photocurrent of the photodiode.

3.3.2. Monte Carlo simulation of gamma photon transport through a phototransistor

Figure 15 presents a cross-section of a phototransistor used for the simulation.

The results of Monte Carlo simulations are given in **Tables 6–8**. **Tables 6** and **7** show the probability of creating new photons and electrons per incident particle (photon) through individual interactions.

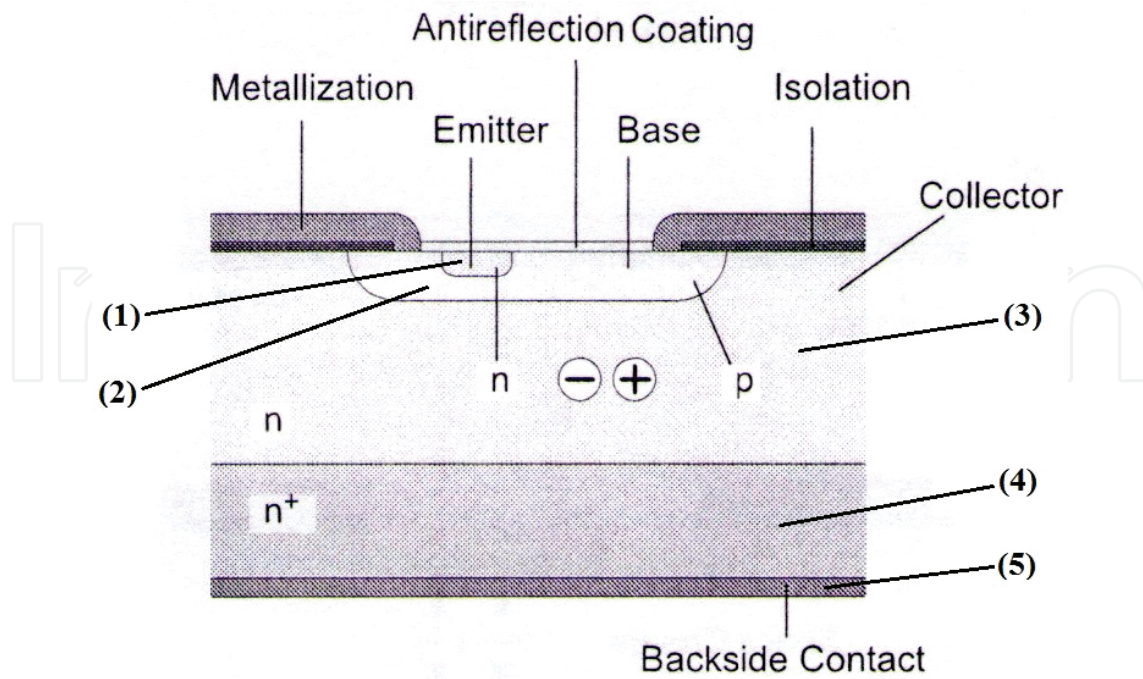


Figure 15. Cross-section of a phototransistor [41].

Probability of creating new photons	Interaction that creates photons
1.3333E-05	Bremsstrahlung
1.1333E-06	Positron-electron annihilation
5.1667E-06	Electron x-rays

Table 6. Probability of creating new photons per incident particle (photon).

Probability of creating new electrons	Interaction that creates electrons
1.4667E-06	Pair production
2.1764E-03	Compton effect
1.1633E-05	Photoelectric effect
2.3333E-07	Auger photons
1.7910E-04	Auger electrons
7.0135E-03	Electrons knocked out in a collision with impact electrons

Table 7. Probability of creating new electrons per incident particle (photon).

According to the simulation results in any semiconductor field within the phototransistor, there was no interaction in which are created or disappeared photons. Table 8 show the

number of physical interactions in which are created or disappeared electrons per input particle (per cell).

Physical interaction	Area 1—emitter <i>n</i>	Area 2—base <i>p</i>	Area 3—colector <i>n</i>	Area 4— <i>n</i> ⁺	Area 5—Al contact
Pair production	0	0	0	0	0
Compton recoil	0	3.3333E-08	1.6667E-07	1.6667E-07	0
Photoelectric effect	0	0	0	0	0
Photon Auger	0	0	0	0	0
Electron Auger	0	3.3333E-08	0	0	0
PKA	0	0	4.3333E-07	7.0000E-07	6.6667E-08
p-annihilation	0	0	0	0	0
Total	0	6.6667E-08	6.0000E-07	8.6667E-07	6.6667E-08

Table 8. Number of physical interactions in which are created or disappeared electrons per incident particle (per cell).

In phototransistor, as in the photodiode, the largest number of integration caused by gamma radiation are vacancies (PKA) (**Table 8**—shaded part). When the semiconductor material, with structure like this, is exposed to neutron radiation, due to the nature of radiation, a number of new vacancies will be created together with those previously formed. The final result of both types of radiation action are divacancies. As already mentioned in Section 3.2, divacancies cause the increased generation of charge carriers through the two dominant effects [19]:

1. divacancies strain homopolar bond and break it, causing a release of one or two electrons;
2. divacancies allow direct transfer of electrons between the defects located close to each other without passing through the conduction band (intercentre charge transfer) [12].

According to the results in **Table 8** the largest number of divacancies have creating in collector and the *n*⁺ area of phototransistor, increasing the concentration of electrons in these areas. On the other hand, due to Compton scattering and Auger electron and increases the concentration of electrons in the base. The final result of these effects is increasing the transistors photocurrent after neutron irradiation (compared to its value after gamma irradiation), which is consistent with the results of the experiment presented in chapter 3.2.

4. Conclusion

Gamma and neutron radiation, applied individually, affect the semiconductor material creating defects and changing the existing structure, which results in a change in the output characteristics of the device and reducing their functionality.

Gamma irradiation of silicon semiconductor causing numerous defects of the crystal lattice. Monte Carlo simulations showed that in this experiment were represented almost all of the

effects described in the literature: displacement of atoms (PKA), Auger electrons, Compton scattering, photoelectric effect, pair production. The impact of all these effects are manifested in the generation of energy levels in the energy gap of crystal lattice which decreases the minority charge carriers lifetime resulting in a decrease in the photocurrent and spectral response. The big change of phototransistors output characteristics can be explained by the influence of radiation on the current gain. The current gain is proportional to the minority charge carriers lifetime so the degradation of their lifetime directly affects the degradation of current gain. This degradation is caused by a displacement of atoms in the semiconductor bulk which affects the increase in the number of recombination centers and also oxidation of the oxide passivation layer especially over the emitter-base junction.

Neutron irradiation causes damage in the photovoltaic detector which is primarily related to the displacement of silicon atoms from their positions in a grid and creating vacancies. Together with the vacancies, other effects appeared. Monte Carlo simulations showed that after the vacancies, the most frequent are Auger electrons, Compton scattering, pair production, and the photoelectric effect. Because of the combination of complex defects, defects that act as recombination centers are created and reduce the minority charge carriers' lifetime which can lead to the degradation of electrical parameters of photovoltaic detectors.

When the semiconductor photovoltaic detectors are first exposed to gamma radiation and after a month to neutron, one can see that neutron radiation, applied after gamma radiation, partially corrects the characteristics of semiconductor devices which are exacerbated by gamma radiation, and that is manifested through increased spectral response and output photocurrent. This behavior of photodiodes and phototransistors can be explained by the increased generation of charge carriers as a result of direct transfer (tunneling) of the charge through the traps (recombination centers). Direct (intercenter) charge transfer is a process where charge carriers spend some time trapped in the defect of material (traps) before tunneling through the barrier. To become free (transferred from the valence to the conductive band), an electron must have enough energy to overcome the energy gap. However, if the traps, that represent energy levels, are located near the edge of the conduction and valence band and near the Fermi level on both sides (according to Dharival-Rajvanshi model), then moving electrons from the valence band into the trap require notably less energy than for direct transit to the conductive band, which means that the traps actually facilitate the process of generation of free carriers. Also, according to the Shockley–Read–Hall model, there is one quasi-stationary energy level within the gap where the electron or hole could come. The probability that an electron will fall into the trap and spend some time in it depends, among other causes, on the density of defects in the energy gap. One of the ways to increase the density of defects in the energy gap is creating a large number of vacancies located physically close to each other in semiconductor material. Monte Carlo simulation of γ -photons transfer through the photovoltaic detectors showed that gamma radiation leaves behind itself a number of displaced atoms (vacancies). Since the radiation damage caused by neutrons primarily related to the displacement of atoms from their positions in the lattice of silicon semiconductor, i.e. forming of vacancies, so neutron irradiation of photovoltaic detectors applied after gamma irradiation gives a possibility for the creation of a sufficient number of divacancies which can

cause intercenter transfer and increased generation of charges and thereby increasing the photocurrent and other parameters. The requirement for creation of divacancies by neutron irradiation is the existence of vacancies in a semiconductor caused by previous gamma radiation.

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