IMPROVEMENT POSSIBILITIES OF THE I-V CHARACTERISTICS OF PIN PHOTODIODES DAMAGED BY GAMMA IRRADIATION

by

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This paper presents the behavior of PIN photodiodes after combined gamma and neutron irradiation. Different types of PIN photodiodes have been exposed first to gamma and then to neutron irradiation. I-V characteristics (current dependence on voltage) of photodiodes have been measured after each of these irradiations. It has been noted that the photocurrent level after the neutron irradiation is higher than before it, which is not consistent with the current theories about the effects of neutron radiation on semiconductors. In order to explain this behavior of the photodiodes, the Monte Carlo simulation of photon transport through the material has been used. It is proposed that a possible cause for current enhancement are defects in semiconductor created by gamma irradiation and effects of neutron irradiation on these defects. The results can be explained by an intercentre transfer of charge between defects in close proximity to each other. The aim of this paper is to investigate the improvement possibilities of the I-V characteristics of PIN photodiodes, and photodetectors in general, damaged by gamma irradiation.

Key words: PIN photodiode, gamma irradiation, neutron irradiation, I-V characteristic, Monte Carlo simulation

INTRODUCTION

Modern measurements are mainly based on the conversion of physical quantities to electrical signals. The basic measuring devices which enable the receiving of information in the automatic control system are sensors.

The main reason why optoelectronic sensors attract the attention of many researchers and users is the phenomenon of change of the optical signal parameters by changing of measured physical quantity as the basic functioning principle of optoelectronic sensors. In functional terms, optical sensors are more flexible, more reliable and more universal than conventional sensors, because of the possibility of use in all conditions with strong magnetic fields, electrical noise, chemical corrosion, *etc*.

On the other hand, nowadays, due to the high technological development, one is under the constant influence of the entire spectrum of electromagnetic radiation, which comes from natural sources and the devices that man has created himself. The trend of miniaturization and the higher degree of electronic components integration has resulted in increased sensitivity of these components to the effects of ionizing radiation. The technological process of large scale integration circuits often includes bombardment with high-energy ions or photons, which can lead to significant radiation damage.

In recent papers the behavior of various optoelectronic devices in terms of gamma and neutron radiation has been observed [1-6]. Photodiodes, as one of the most used and the simplest types of optical sensors, have been analyzed in most papers. The influence of gamma and neutron irradiation on semiconductors in general (and especially on the photodiodes) is very well known and described in several papers and textbooks.

This work describes a series of measurements undertaken in order to try to identify the PIN photodiodes behavior model after the neutron irradiation in a situation when these have previously been damaged by gamma radiation and have had enough

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time to recover. Though the effect of gamma radiation follows the well-known theoretical model (which is manifested in the reduction of photocurrent), the subsequent neutron irradiation on the photodiodes causes the opposite effect from the theoretical model, so the photocurrent increases.

The aim of this paper is to explain the processes that occur in the photodiode after gamma and neutron radiation and to try to find the way of improving the characteristics of photodiodes, and photodetectors in general, damaged by gamma irradiation.

THEORETICAL ANALYSIS

There are several interaction mechanisms of electromagnetic radiation with the material (the elastic incoherent Thomson scattering, the elastic coherent Rayleigh scattering, the inelastic Compton scattering, the photoelectric effect, the nuclear photoeffect, the production of electron-positron pairs).

Gamma ray (high energy photons) interacts with orbital electrons via photoelectric and Compton effects. If the energy of gamma ray is high enough (above several hundred keV) the pair generation occurs. The energy spectrum of the energetic electrons is called "slowing spectrum". The energetic electron interacts with a lattice atom. As a result, the lattice atom is displaced from the lattice site. This is so called primary knock on atom (PKA) [7, 8]. Interstitial PKA, vacancy, and complex of them form a deep level in bandgap (so-called the generation-recombination centre). The recombination centers in bulk region cause the reduction of carrier lifetime. In addition the deep levels compensate the donor or acceptor levels resulting in the reduction of effective carrier concentration carrier removal (CR) effect. It affects the depletion layer width by becoming wider.

On the other hand, as relatively heavy and uncharged particles, neutrons colliding with atoms in the crystal lattice cause displacement of atoms from the lattice. A pair of interstitial atom and vacancy are called the Frencel defect. If the incident neutron energy is high enough, it can deliver enough energy to the displaced atom which can displace other atoms in the lattice. This requires fast neutrons with energies from 10 keV to 10 MeV. Shifting vacancies connect with the impurity atoms, donors and other vacancies forming temperature stable defects (complex defects) which represent recombination centers and trap centers, significantly reducing the minority carrier lifetime [8, 9].

The final result of both gamma and neutron radiation on photodiodes is increasing of recombination centers concentration, which, according to the Shockley-Read formula [9], directly resulted in decreasing the minority carrier lifetime

$$\tau \quad \frac{1}{c_n N_t}\frac{n_o \quad \delta n \quad n_1}{n_o \quad p_o \quad \delta n} \quad \frac{1}{c_n N_t}\frac{n_o \quad \delta p \quad p_1}{n_o \quad p_o \quad \delta p} \tag{1}$$

where $\tau = \tau_p = \tau_n$ is the lifetime of electrons and holes and N_t concentration of R-centres (recombination centres 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 some electromagnetic radiation such as gamma radiation, the effects of neutron irradiation will be different. In that case the damage structure from neutron irradiation leads to clusters of intrinstic defects such as divacancies.

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} or τ_{pe}. If several defect levels exist, they are regarded as the sum of the individual components. In coupled defect generation, illustrated in fig. 1, an electron is first captured by the donor state in the bottom half of the bandgap. This is an efficient process with 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 via the conduction band. The time constant for this step is denoted $\tau_{1 \quad 2}$. 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 [1, 10].

The enhancement of the fractional occupancy increases the number of electrons generated per unit of

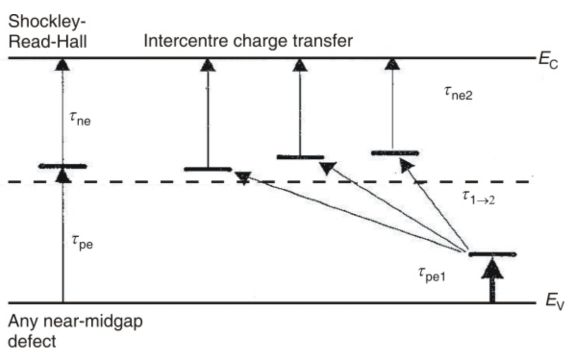

Figure 1. Schematic diagram of Schokley-Read-Hall theory and intercentre charge transfer generation processes [1, 9]

time from a defect state and hence increases the photocurrent [9].

EXPERIMENTAL PROCEDURE

Experimental measurement in this paper was carried out on the commercially available silicon PIN photodiode manufactured by Vishay and Osram. Four types of photodiodes were used in this experiment (BP104, BPW41N, and BPW34 by Vishay and SFH203FA by Osram).

Photodiodes were irradiated with the ^{60}Co gamma source with dose of 2000 Gy, the energy of 1.25 MeV, and half-life time of 5.27 years (this energy is sufficient for the creation of electron-hole pairs). The dose rate was 100 Gy/h at a distance of 150 mm away from the radioactive source. Irradiation was performed through glass in controled environment. The dose rate was measured by electrometer UNIDOS with ionization chamber TW 30012-0172, produced by PTW, Germany. Measurement uncertainty of the system is less than 1.2%. The components were irradiated in the air at a temperature of 21 °C and relative humidity of 40% to 70%.

One month after that the photodiodes were exposed to the neutron irradiation of Pu-Be point neutron source with dose of 4.32 mGy and a half-life time of 87.7 years. The dose rate was measured by DINEUTRON Portable Unit for Neutron Dosimetry, developed by the CEA (French Atomic Energy Commission). A mixture of the ^{238}Pu with beryllium is a good source of neutrons, through a nuclear reaction in which the ^{9}Be absorbs an alpha particle from ^{238}Pu and forms ^{12}C with the emission of a neutron. This neutron source provides a broad beam of emitted neutrons up to about 11 MeV with an intensity maximum of about 5 MeV. The advantage of the ^{238}Pu-Be source is its higher neutron fluence for the same source mass, allowing a more compact design of the source and the significantly smaller contribution of photons to the radiation field. Samples were in direct contact with the source. The dose rate was 0.36 mGy/h at a distance of 60 mm away from the radioactive source. The components were also irradiated in the air at the temperature of 21 °C and with the relative humidity of 40% to 70%.

Both gamma and neutron irradiation was performed in professional laboratory at the Department of Radiation and Environmental Protection of the Vinča Institute of Nuclear Sciences in Belgrade, Serbia.

Before and after every step of the irradiation, current-voltage (I-V) characteristics of the reverse biased photodiodes were measured in highly controlled conditions at room temperature. During the measurement, the samples were removed from the experimental room after absorption of the anticipated dose of radiation. There have been undertaken five measurements of the photodiodes' reverse-bias characteristics:

– first measurement: immediately before gamma irradiation,
– second measurement: immediately after gamma irradiation,
– third measurement: 1 month after gamma irradiation (immediately before neutron irradiation),
– fourth measurement: immediately after neutron irradiation, and
– fifth measurement: 1 month after neutron irradiation.

The third and the fifth measurement have been undertaken one month after the irradiation, in order to give enough time for diode recovery. For this reason, the changes occurring in the diodes can be considered as a permanent. Standard measurement equipment was used to measure I-V curve. The professional digital multimeter AMPROBE 33XR was used for the current measurement. Combined measurement uncertainty for all measurements was less than 1.2% [11-14].

In order to better understand the state of photodiode structure after gamma and before neutron irradiation (the initial conditions for neutron irradiation), the Monte Carlo simulation of gamma photon transport through a PIN photodiode has been performed.

Also, a number of new unirradiated photodiodes of all four types (BPW34, BPW41N, BP104, and SFH203FA) has been exposed only to neutron radiation in order to confirm the theory that explains the influence of neutron irradiation on semiconductors.

RESULTS

I-V characteristics of the reverse biased photodiodes before and after every step of the irradiation are shown in fig. 2. The important fact is that all four types of photodiodes (BP104, BPW41N, BPW34, SFH203FA) behaved in a similar way. The gamma radiation decreased their photocurrent and, after that, the neutron irradiation increased it.

Due to the effects that are well known, after the recovery period, gamma radiation decreased the photocurrent (compared to the photocurrent before the irradiation) by:

– approximately 13% for BP104,
– approximately 22% for BPW41N,
– approximately 23% for BPW34, and
– approximately 13% for SFH203FA.

The effects that cause photocurrent increasing by a 5% for all four types of photodiodes (compared to the photocurrent after the first irradiation – gamma) appeared after the exposure to neutron radiation and one month of diode recovery.

Tables 1 and 2 and fig. 3 present the results of Monte Carlo simulation of gamma photon transport through a PIN photodiode [15]. Table 1 shows the de-

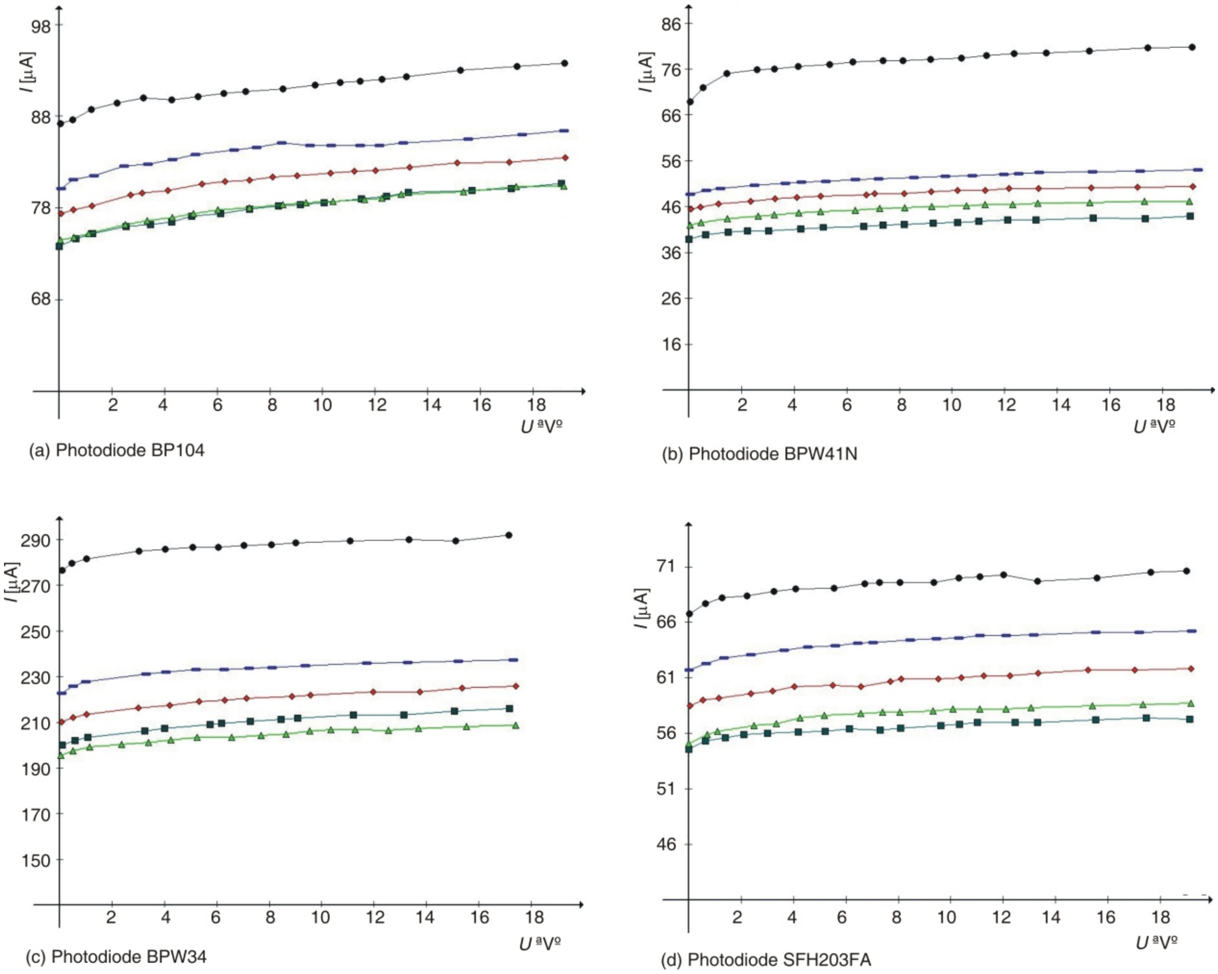

Figure 2. I-V characteristics of the reverse biased photodiodes before and after every step of the irradiation
*– **before gamma irradiation**, ■ – immediately after gamma irradiation ◆ – 1 month after gamma irradiation ▲ – immediately after neutron irradiation ▬ – 1 month after neutron irradiation*

Table 1. Deposited energy per input particle obtained by Monte Carlo simulation

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

posited energy per input particle in each zone of the photodiode, where the zones are areas (regions) of p^+, p, n^+ type and pure semiconductor. Figure 3 shows the ratio of the energy absorbed in each interaction and the thickness of the layer in the material zone.

Neutron radiation, applied to new, undamaged photodiodes, causes the reduction of photocurrent by:

– approximately 7% for BP104,
– approximately 11% for BPW41N,
– approximately 8% for BPW34, and

Table 2. Statistics of collisions obtained by Monte Carlo simulation

Statistics of collisions	
Photoeffects	802
Compton	106909
Pair	57
Coherent	292
Annihilations	57
Ionizations	9956068
Total electrons	161449
Total positrons	57
Delta e electrons	56327
Delta p electrons	0
Bremstrahlung	8444
Relaxed X-rays	0
Auger electrons	0

– approximately 14% for SFH203FA, compared to the photocurrent before the irradiation, as it is shown in fig. 4.

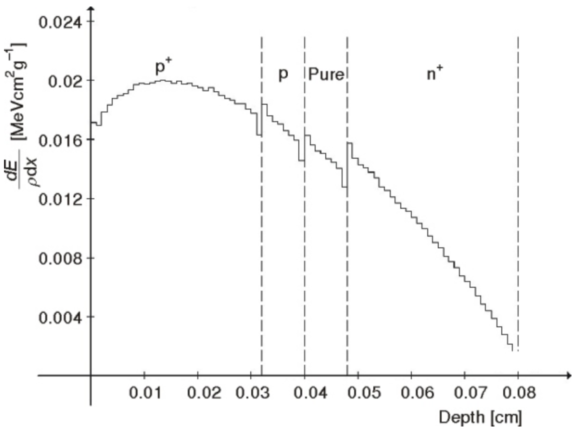

Figure 3. Depth dose distribution in semiconductor (PIN photodiode)

DISCUSSION

When high energy neutron particles influence inside a semiconductor crystal network like silicon, there are several mechanisms to move atoms. Elastic scattering is an example. Some of the particles can transfer energy to the silicon core in this phenomenon. If enough energy transfers (almost 25 eV) the core exits of its location [16]. The released silicon atom, can lose its energy by ionization changing location by the other atoms. Korde *et al*. [17] show that neutron exposure increases the static and dynamic resistance of the diode. The increase in these resistances was found to be a function of the resistivity and the type of the starting silicon wafers used to fabricate the photodiodes. Also, the increase in these resistances affect the diode photocurrent and decrease it (fig. 4).

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 vacancies are mobile and combine with other vacancies or with impurities of the semiconductor [18, 19]. Sporea *et al*. [20] have (been) 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/cm^2, occurs in

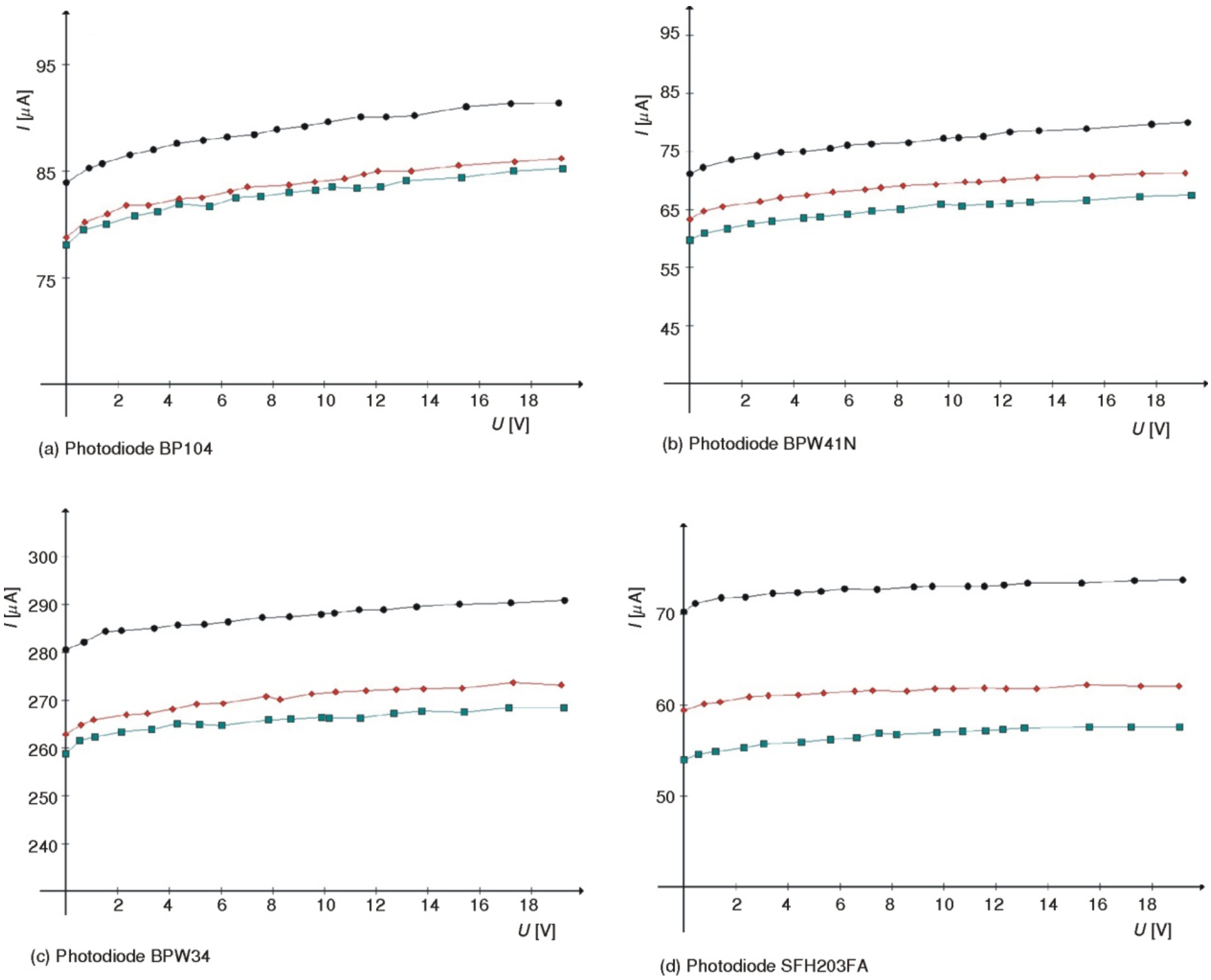

Figure 4. I-V characteristics of the new photodiodes (reverse biased) before and after the neutron irradiation
● – ***before gamma irradiation***, ■ – *immediately after gamma irradiation* ◆ – *1 month after gamma irradiation*

the case of neutron irradiation (37.5%) as compared to the gamma irradiation (7.2%).

The neutron irradiation, by itself, affect the creation of displacement damage in photodiodes which lead to a degradation of their electrical characteristics (figs. 2 and 4). However, the neutron irradiation, applied after gamma radiation, causes such changes in the photodiodes that make the process of annealing more efficient and as a result we have improved electrical characteristics. One of the possible causes are divacancies and enhanced generation.

One of the results of gamma irradiation is the interstitial PKA, vacancy and the complex of them. Vacancies are also one of the main products of neutron irradiation effects on material. In a material that already contains a number of vacancies, the neutron radiation creates new vacancies and, in that case, there is a great probability for vacancies to be physically close to one another. Two vacancies, standing side by side within the lattice, form a defect complex called divacancies complex. This complex can capture the electrons and, also, can stress the homopolar connection which may lead to the breaking of chemical connection. Stressing of homopolar connection and its termination can lead to the release of one or two electrons from the defect complex in the conduction band, which results in the enhanced generation. In some previous papers the enhanced generation [1] and the enhanced recombination [21, 22] have been observed via the process where the electron is transferred directly between defects located near (to) one another without passing through the conduction band. This transfer can be very rapid and therefore dominate over the standard Shockley--Read-Hall process. For the intercentre charge transfer to occur, defects must be physically near to one another. Two irradiations of the same material, such as gamma and neutron irradiation, allows for some defects to be close to one another. The condition for creating divacancies by neutron radiation is creation of vacancies in the photodiode PKA by the previous gamma irradiation. 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 [23, 24]. By using molecular dynamics (MD) simulations, threshold displacement energy (TDE) values for Si have been predicted, at 300 K, ranging from 42-112 eV [25] and also average threshold displacement energy values of 93 eV [26].

In order to understand the effects of the gamma radiation on the photodiode and the amount of deposited energy, the Monte Carlo simulation of photon transport through a PIN photodiode has been used (tabs. 1 and 2, and fig. 3). In each zone of photodiode (tab. 1) and in almost every layer (fig. 3), deposited energy per input particle is high enough to displace the lattice atom *i. e.* to create the vacancy. Table 2 shows statistics of collisions in photodiode during gamma radiation. Each effect separately (photoeffect, Compton, pair, PKA, vacancy, *etc.*) causes the ionization of the atoms. Number of all individual effects is negligible compared to the number of ionizations (tab. 2) so it could be assumed that the most of ionizations has been created by vacancies *i. e.* the number of vacancies created by gamma irradiation is significant. Because of these vacancies and the vacancies created by the neutron, the radiation (divacancies) are causing the photocurrent increasing after neutron irradiation and annealing that follows it [1].

For this research, the long-term isothermal annealing at the room temperature was used. The vacancies and the interstitials are quite mobile in silicon at the room temperature and hence are referred to as an unstable defects. After vacancy introduction by irradiation, vacancies move through the lattice and form more stable defects, such as divacancies and vacancy-impurity complexes. When electrical properties are monitored during this defect rearrangement (or annealing) process, a decrease in the effectiveness of the damage with increasing time is typically observed [27-30]. Moll [31] describes the enhancement of the effective doping concentration for the longer annealing times. This phenomenon Feick [32] observed at room temperature. During the process of annealing defects clusterize and some electrical inactive defects become active in a cluster.

So, during the combined gamma and neutron radiation a higher concentration of divacanacies occurs. Because of that, the annealing process can partially improve the electrical characteristics of the photodiode disturbed by gamma radiation. This effect was not evident in the cases of single gamma or neutron radiation. If there were not vacancies and other effects caused by gamma radiation, neutron radiation would not be able to cause the photocurrent enhancement. Only neutron irradiation applied after gamma radiation, causes the photocurrent enhancement *i. e.* partially improves the characteristics of photodiodes damaged by gamma radiation.

CONCLUSIONS

The degradation and the improvement of the main photodiodes parameters, as a consequence of irradiation, was observed for all used samples. The results showed that gamma irradiation leads to degradation of the I-V characteristics, and then neutron radiation improves these characteristics. Enhanced generation through intercentre charge transfer and the mobility of the divacancies explains our observation of current enhancement after the neutron irradiation. This mechanism will occur whenever high concentrations of defects are formed by previous gamma and then neutron irradiation. As the photodiodes and photodetectors in general, during their work, are often exposed to gamma radiation which causes the deterioration of their characteristics, this may be one way for a partial repair of damage and improvement of the characteristics. This is specially important for detectors working in hostile conditions, both from the financial and technological point of view, since it could enhance their working lifetime in such environment.

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AUTHOR CONTRIBUTIONS

Theoretical analysis as carried out by D S. Nikolić and A. I. Vasić. Experiments were carried out by D. S. Nikolić, A. I. Vasić, Dj. R. Lazarević, and M. D. Obrenović. All of the authors have analyzed and discussed the results. The manuscript was written by D. S. Nikolić and A. I. Vasić. The figures were prepared by D. S. Nikolić.

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МОГУЋНОСТИ ПОБОЉШАЊА I-U КАРАКТЕРИСТИКЕ PIN ФОТОДИОДА ОШТЕЋЕНИХ ГАМА ЗРАЧЕЊЕМ

У овом раду се приказује понашање PIN фотодиода након озрачивања гама зрацима и неутронима. Различити типови PIN фотодиода експонирани су прво гама зрацима, а онда неутронима. Примећено је да је фотострује након озрачивања неутронима виша, него пре озрачивања, што није у складу са теоријом о ефектима неутронског зрачења на полупроводнике. Да би се објаснило ово понашање фотодиода, коришћена је Монте Карло симулација транспорта фотона кроз материјал. Претпоставка је да су могући узроци повећања струје дефекти у полупроводнику, изазвани гама озрачивањем и утицајем неутронског зрачења на ове дефекте. Ови резултати могу се објаснити међупросторним кретањем наелектрисања између дефеката који су у непосредној близини једни другима. Циљ овог рада је да се истраже могућа побољшања I-U карактеристика PIN фотодиода, односно фотодетектора, оштећених гама зрацима.

Кључне речи: PIN фотодиода, гама озрачивање, неутронско озрачивање, I-U карактеристика, Монте Карло симулација