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Photodiodes, phototransistors and solar cells behaviour in environment with gamma and neutron radiation: literature review and experiments

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Abstract – Due to its wide application areas, optoelectronic devices are exposed, in their work enviroment, to different types of radiation. Photodiodes, phototransistors and solar cells are most common used optoelectronic devices. Therefore, a number of experiments were performed on these devices in order to explain their behavior in the environment with pronounced gamma and neutron radiation. Especially when these two types of radiation appear successively. This paper presents review of these researches and scientific papers based on them. A number of PIN photodiodes, phototransistors and solar panels have been exposed to gamma radiation, neutron radiation and, especially, to their combination. Several types of photodiodes, phototransistors and solar panels were used in the experiment. *I-V* characteristics (current dependance on voltage) and other output parameters have been measured before and after irradiation. Some unusual behavior were observed.

Keywords **– Photodiodes; phototransistors; solar cells; gamma radiation; neutron radiation**

I. INTRODUCTION

Photovoltaic semiconductor detectors had enormous develop through the past decades. Devices based on these detectors have a number of applications in various fields such as electronic, medical, optical communication, military and also, they have relatively low cost because of miniaturization of electronic components and mass production. The possibility for semiconductor photovoltaic detectors to be exposed to enhanced radiation is pretty high. Thats why a number of researches have investigated this area. This work is limited to the presentation of experiments of effects of gamma and neutron irradiation on photodiodes, phototransistors and solar panels and results of these experiments.

II. METHODS

A number of optoelectronic devices have been studied through several experiments. Experimental measurement was carried out on a photovoltaic detectors by different manufacturer. Experiments were carried out on:

1. silicon PIN photodiodes by Vishay (BP104, BPW41N, BPW34) and by Osram (SFH203FA),
2. silicon NPN phototransistors by Telefunken electronic (BPW40) and by LITEON (LTR4206),
3. monocrystalline silicon solar panel (maximum power voltage 4.0 V, maximum power current 100.0 mA, dimension: 70 * 65 * 3.2 mm).

Devices were exposed to gamma radiation from Co^{60} source and 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 and 5000 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 (60keV and 14keV) with the activity of $3.7\text{x}10^{10}$Bq, the intensity of the neutron emission of $2.7\text{x}10^{6}$ neutrons s^{-1} and the mean energy of the neutrons E_{nav}=5.5MeV. The panels were at a distance of 5 cm from the source, so the photon equivalent dose rate is $\dot{H}_\gamma$=12mSv/hr, and the photon absorbed dose rate is $\dot{D}_\gamma$=12mGy/hr. Calculated neutron absorbed dose rate is $\dot{D}_n$=1.714mGy/hr and the equivalent dose rate of neutrons is $\dot{H}_n$=12mSv/hr with the quality factor Q_n=7. In this experiment, the semiconductor devices were placed at a distance of 5cm from the ^{241}Am-Be source, and the exposure period was 16.75hr. Since the total absorbed dose, for that distance, is $\dot{D}_{tot}$=13.714mGy/hr and the total equivalent dose is $\dot{H}_{tot}$=24mSv/hr, the total absorbed dose for material components is D_{tot}=229.71mGy and the total equivalent dose is H_{tot}=402mSv.

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% to 70%.

Before and after every step of irradiation spectral response and photocurrent have been measured. The measurement were performed on the photodiodes, phototransistors and solar panels, in highly controlled conditions at room temperature, which have previously been removed from the irradiation room. Measuremnts were performed immediately before the irradiation, immediately after the irradiation and 1 month after the irradiation (in order to give enough time for sample recovery). 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].

Five experiments were performed.

I experiment:

Photodiodes, phototransistors and solar panels were irradiated with Co^{60} gamma source with dose of 2000 Gy. *I-V* characteristics have been measured three times: first one immediately before gamma irradiation, second one immediately after gamma irradiation, and the third one 30 days after gamma irradiaton.

II experiment:

Photodiodes, phototransistors and solar panels were irradiated with ^{241}Am-Be neutron and gamma source. *I-V* characteristics have been measured three times: first one immediately before neutron irradiation, second one immediately after neutron irradiation, and the third one 30 days after neutron irradiaton.

III experiment:

Photodiodes, phototransistors and solar panels were irradiated with Co^{60} gamma source with dose of 2000 Gy and, 30 days later, with ^{241}Am-Be neutron and gamma source. Parameters of optoelectronic devices have been measured five times: first one just before gamma irradiation, second onejust after gamma irradiation, third one 30 days after gamma irradiaton (just before neutron irradiation), fourth one just after neutron irradiation fifth one 30 days after neutron irradiation.

IV experiment:

Photodiodes were irradiated with Co^{60} gamma source with dose of 2000 Gy and 15 days later with dose of 5000 Gy. *I-V* characteristics have been measured fourth times: first one just before gamma irradiation, second one just after gamma irradiation (2000 Gy), third one15 days after gamma irradiaton (just before second gamma irradiation – 5000 Gy) and fourth one just after second gamma irradiation.

III. RESULTS

I experiment:

Degradation of the main parameters (*I-V* characteristics) of the optoelectronic devices and their improvement, as a consequence of annealing, was observed for all used samples and published in *International Journal of Photoenergy* [3] and *FME Transactions* [4]. Nikolić *at all* [3, 4] confirm that gamma irradiation leads to degradation of the I-V characteristics and then annealing improves these characteristics (Fig. 1 to 3.).

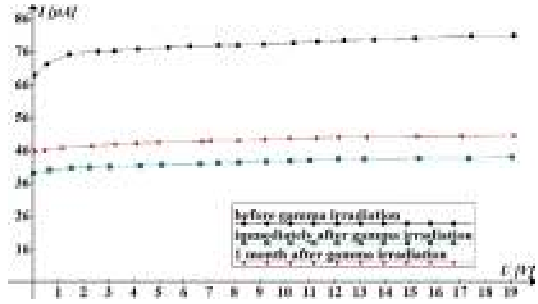

Fig. 1. Impact of gamma irradiation on *I-V* characteristics of BPW41N photodiode [3]

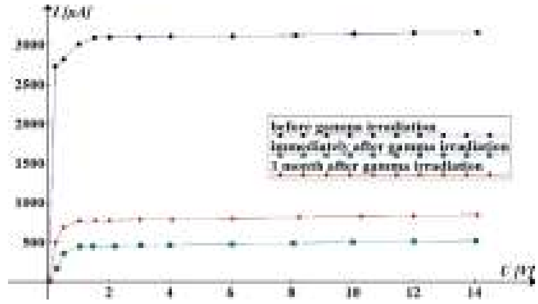

Fig. 2. Impact of gamma irradiation on *I-V* characteristics of BPW40 phototransistor [3]

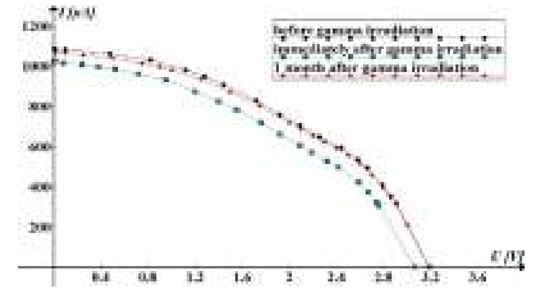

Fig. 3. Impact of gamma irradiation on *I-V* characteristics of solar panel [3]

Due to their amplifying action, the phototransistor are the most sensitive to radiation effects. Nikolić *at all* [3] said: "Vukić [5] show that the measured values of the forward emitter current gain decreased by 20-40% after the apsorption of a total dose of 500 Gy. The gain of the phototransistor is directly proportional to the minority carrier lifetime in the base region, and since this is strongly affected by radiation these devices are comparatively radiation sensitive. On the other hand, the solar panel are the least sensitive to gamma radiation. Its characteristics, in annealing process, were managed to recover to a value near the initial (the one before the irradiation). The combination of cells in the panel construction is a possible cause of this".

II experiment:

The effect of neutron radiation on optoelectronic devices, solar panels, photodiodes and phototransistors has been observed in this experiment and published in *International Journal of Photoenergy* [6] and *FME Transactions* [4]. Nikolić *at all* [4, 6] confirm that, according to current theories, neutron irradiation in all samples caused degradation of their structure and deterioration of the output characteristics (Fig. 4. to 6.).

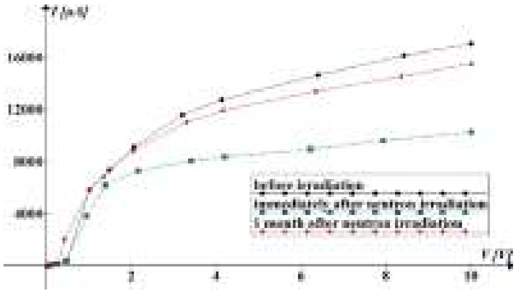

Fig. 4. Impact of neutron irradiation on *I-V* characteristics of LTR4206 phototransistor [6]

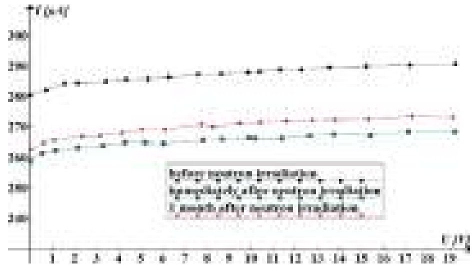

Fig. 5. Impact of neutron irradiation on *I-V* characteristics of BPW34 photodiode [6]

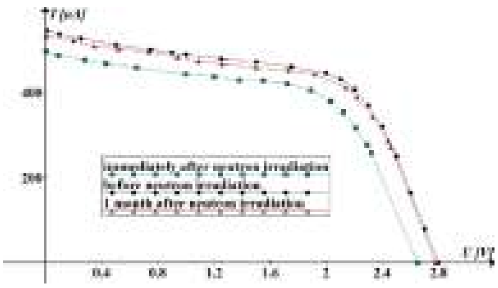

Fig. 6. Impact of neutron irradiation on *I-V* characteristics of solar panel [6]

Nikolić *at all* [6] said: „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 [7, 8]. Sporea *et al.* [9] 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 $1.2x10^{13}$ n/cm^2, occurs in the case of neutron irradiation (37.5 %) as compared to the gamma irradiation (7.2 %).

Solar panels have proved to be most resistant to the effects of neutrons (Fig. 6.). And their annealing process had the best effect. The reason for that could be the construction of a solar panel. To obtain the maximum power voltage of panels (4 V), a large number of individual cells are used in series and parallel combinations. According to the degree of recovery in the annealing process one can conclude that solar panels and phototransistors preferable for working in terms of increased neutron radiation than photodiodes.“

III experiment:

Degradation and improvement of the main photodiodes and phototransistors parameters, as a consequence of irradiation, was observed for all used samples and published in *Nuclear Technology & Radiation Protection* [10] and *InTech open science* [11]. Nikolić *at all* [10, 11] confirm that gamma irradiation leads to degradation of the I-V characteristics, and then neutron radiation improves these characteristics (Fig. 7. and 8.).

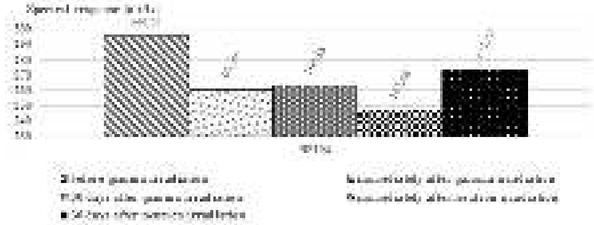

Fig. 7. Impact of gamma and neutron irradiation on spectral response of the reverse biased BP104 photodiode BP104 [11]

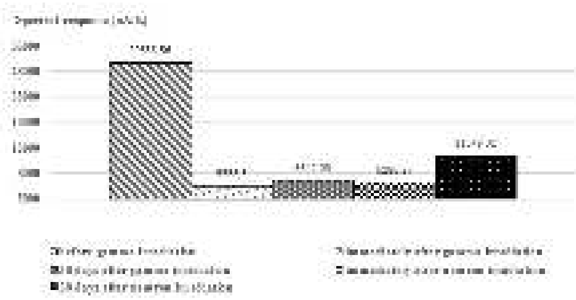

Fig. 8. Impact of gamma and neutron irradiation on spectral response of LTR4206 [11]

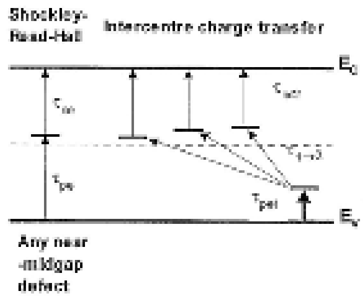

Fig. 9. Schematic diagram of Schokley-Read-Hall theory and intercenter charge transfer generation processess [18]

Enhanced generation through intercentre charge transfer explains the current enhancement after the neutron irradiation. Nikolić *at all* [11] said: "Standard 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 [12, 13].... Schokley-Read-Hall model assumes one level within a gap where electrons or holes can come, which dynamic is quasi-stationary [14, 15, 16].... One of the results of gamma radiation are interstitial (PKA – primary knock on atom), vacancies and their complexes. Vacancies are also one of the main products of neutron irradiation of the material [17]..... In some previous studies, increased generation [18] and increased recombination [19, 20] have been observed through the process of electron transfer directly between the defects located close to each other without passing through the conductive belt (Fig. 9.). This process can be very fast and therefore dominant compared to the Shockley-Read-Hall process. In order to occur the intercentre 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 enhancement of the fractional occupancy increases the number of electrons generated per unit of time from a defect state and hence increases the photocurrent [21].“ This mechanism will occur whenever high concentrations of defects are formed by previous gamma and then neutron irradiation. As the photodiodes and phototransistors, during their work, are often exposed to gamma radiation which causes 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.

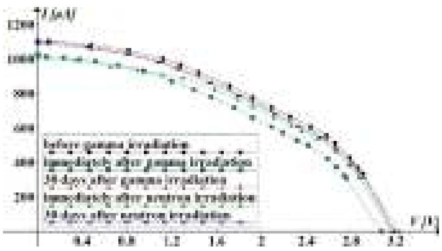

Fig. 10. Impact of gamma and neutron irradiation on *I-V* characteristics of the solar panels [22]

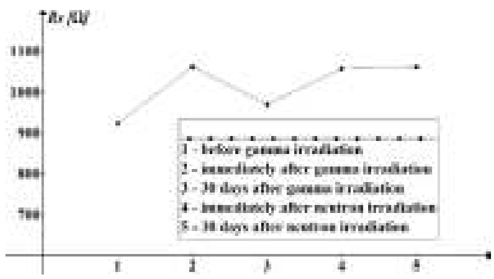

Fig. 11. Impact of gamma and neutron irradiation on series resistance of the solar panels [22]

Degradation of the main parameters of the solar cells and their improvement, as a consequence of annealing, was observed for all used samples nad published in *Journal of Optoelectronics and Advanced Materials* [22]. Nikolić *at all* [22] confirm that both gamma and neutron irradiation leads to degradation of the *I-V* characteristics and other parameters and then annealing improves these characteristics (Fig. 10. and 11.). Those characteristics, in annealing process, were managed to recover to a value near the initial (the one before the irradiation). The combination of cells in the panel construction is a possible cause of this.

IV experiment:

Degradation of the main parameters (*I-V* characteristics) of the PIN photodiodes and their improvement, as a consequence of annealing, in a term of double gamma irradiation (with the pause of 15 days) was observed for all used samples and published in *Scientific Publications of the State University of Novi Pazar* [23]. Nikolić *at all* [23] confirm that gamma irradiation leads to degradation of the I-V characteristics and then annealing improves these characteristics (Fig. 12.). After the second gamma irradiation (with the higher dose) the photocurrent drasticly decreased. This points to the further deterioration of the characteristics of photodiode, even in a long time after the irradiation. This means that such photodiodes after the irradiation are no longer reliable, even if their photocurrent immediately after the irradiation has not changed much.

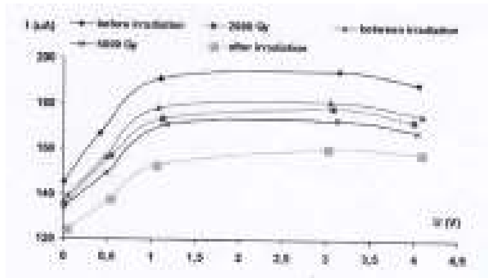

Fig. 12. Impact of double gamma irradiation on *I-V* characteristics of BPW34 photodiodes [23]

IV. CONCLUSION

This paper is a review of experiments with photovoltaic detectors in which one observed the influence of gamma and neutron radiation on the characteristics and operation of photovoltaic detectors, primarily fotodiodes, phototransistors and solar cells. As the effects which these types of radiation cause on various materials, including semiconductors, are well known and described in the literature, in these experiments, main goal was observing the behavior of photodiodes, phototransistors and solar panels immediately after exposure to radiation and 30 days afterwards. Since a couple of days are enough to stabilize the changes due to the long term recovery of the semiconductor after radiation, it can be highly assured that 30 days is a long enough time to complete all the processes in the semiconductor produced by radiation and recovery. Special attention is devoted to monitoring the behavior of photovoltaic detectors after the successive effect of two types of radiation over a two month time interval, with a 30 days pause between radiation.

Gamma and neutron radiation affect the semiconductor material by creating defects and changing the existing structure, resulting in a change in the output characteristics of the device and a decrease in their functionality. Gamma irradiation of a silicon semiconductor causes numerous defects of the crystal lattice, the atom displacement (PKA), Auger electrons, Compton scattering, photoelectric effect, the pair production. The influence of all these effects is manifested in the generation of energy levels in the energy gap of the crystal lattice material, which reduces the life of minor charge carriers, resulting in a reduction in photocurrent, spectral response and other parameters of photovoltaic detectors. A major change in the output characteristics of the phototransistor can be explained by the effect of radiation on the current gain. As the current gain is proportional to the minority carriers lifetime, this degradation of minority carriers lifetime directly affects the degradation of current gain. This degradation causes displacement of the atom in the bulk of the semiconductor, which affects the increase in the number of recombination centers as well as the oxidation in the passivation layer of the oxide and especially above the emitter-base compound.

The fact that solar panels are more resistant to the impact of both gamma and neutron radiation can be explained by their specific construction. Solar panels consist of a large number of solar cells, each of them suffers the same radiative damage as photodiode. As the solar cells in the panel are interconnected and closed in a common box that protects them from external influences, the total resulting impact of radiation on the entire panel is smaller.

Neutron irradiation of photovoltaic detectors causes damages such as displacement of silicon atoms from their positions in the grid and creation of vacancies. Besides, there are other effects: Augers electrons, Compton scattering, pair production and photoelectric effects. Combination of these defects creates complex of defects that act as recombination centers and reduce the minority charge carriers lifetime, which further leads to degradation of photovoltaic detectors electrical parameters.

When the semiconductor photovoltaic detectors are exposed first to gamma radiation, and after a month to neutron, there is an increased charge carriers generation due to the direct transfer (tunneling) of carriers through traps (recombination centers). A direct (inter-centre) charge transfer is a process in which the charge carrier spends some time trapped in the defect of the material (traps) before tunneling through the barrier. In order for the electron to become free it must have enough energy to skip the energy gap. However, if the traps, representing energy levels, are located near the edge of the conductive and valence zone and close to the Fermi level on both sides (according to the Dharival-Rajvanshi model) then the transfer of the electrons from the valentine zone into the trap requires less energy than for a direct transition to a conduction zone, which means that the traps actually facilitate the generation process of free carriers. And according to the Schokley-Read-Hall model, there is a quasi-stationary energy level within the process that the electron or cavity can come from. Pobability that the electron will fall into the trap and spend some time in it depends on density of defects in the energy gap. One way to increase the defect density in the energy gap is to create a large number of vacancies that will be physically close to each other in the semiconductor material. Gamma radiation leaves a large number of displaced atoms (vacancies). Since radiation damage caused by neutrons primarily relates to the displacement of atoms from their positions in the silicon semiconductor, i.e. formation of vacancies, this neutron irradiation of photovoltaic detectors applied after the gamma irradiation gives the possibility of creating enough divacancies for the inter-centre transfer and increasing of electrons generation, thus increasing the photocurrent and other parameters. The condition that neutron radiation generates divacancies is the existence of vacancies in a semiconductor formed due to the previous gamma radiation.

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