

Research Article

Comparative Study of Gamma Radiation Effects on Solar Cells, Photodiodes, and Phototransistors

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This paper presents the behavior of various optoelectronic devices after gamma irradiation. A number of PIN photodiodes, phototransistors, and solar panels have been exposed to gamma irradiation. Several types of photodiodes and phototransistors were used in the experiment. *I-V* characteristics (current dependence on voltage) of these devices have been measured before and after irradiation. The process of annealing has also been observed. A comparative analysis of measurement results has been performed in order to determine the reliability of optoelectronic devices in radiation environments.

1. Introduction

Optoelectronics is an interesting branch of electronics that combines both electronics and optics. Optoelectronic devices find varied applications in telecommunications, military services, medical field, and automatic control systems. These devices produce electrical energy when exposed to incident light energy. In this paper, solar cells, photodiodes, and phototransistors have been observed.

Photoelectric transducers generate electric current when exposed to light. A photovoltaic cell consists of many p-n junctions connected in series. One of the junctions is very thin, so light can easily pass through it. When light passes, charge carriers such as holes and electrons are produced proportional to the incident light. Photovoltaic cells are used in various applications to generate electricity where main power is not available. Examples include solar cells and solar batteries, which are used in satellites. The solar energy incident on the p-n junction of the solar cell collides with the valence electrons. This causes the formation of electron-hole pairs, which cross the p-n junction in an opposing manner and create a voltage across the p-n junction. The voltage generated per cell is approximately 0.6 V. Large arrays of solar

cells are used in series and parallel combinations to produce a large voltage.

Photodiodes are high-impedance devices that are usually reverse biased for improved performance. These are high-speed sensors which generate a tiny current (in μA) proportional to the amount of incident light. The photodiode consists of a relatively large silicon p-n junction, which is illuminated by the incident light. Light photons impinging on the junction have sufficient energy to rupture a number of covalent bonds in the junction, thereby producing electron-hole pairs. This causes the flow of current in the diodes. As the illumination increases, additional electron-hole pairs are released and the diode current increases.

Phototransistors employ the principle of photodiodes, but the amplifying action of the transistor makes these devices more sensitive. Phototransistors are duo diodes having two junctions in the same device separated by a wide base region, thus forming an n-p-n junction. The n-p junction is slightly forward biased and the p-n junction is reverse biased. Light energy striking the n-p junction liberates electron-hole pairs. The released electrons diffuse out of the p region towards the junction. The holes, however, are trapped in the p region and

form a positive surface charge. This causes an increase in forward bias of n-p junction, increasing the current flow. Phototransistor is usually connected in common-emitter configuration with an open base. Photons are focused to the junction through a lens system. Only two leads (collector and emitter) of the phototransistor are usually used in circuit connections. The base current is created by the photons falling on the base-collector junction. The current in the phototransistor depends on the intensity of incident light and is less affected by the voltage in the circuit.

During the previous decades many researchers tested various optoelectronic devices and published the results of their researches [1–7]. Two types of radiation damage effects occur in solid-state electronic products: displacement damage and ionization effects. Displacement damage is the movement of atoms from their normal position in the lattice to another placement, causing a defect in the lattice material. Ionization effect is the generation of electron-hole pairs within the material that causes radiation effects.

When gamma rays interact with material, they create two effects. The first effect is ionization. Photoelectric effect, Compton scattering, and pair production eject electrons from the atoms of the material. These ejected electrons can create secondary reactions. The result is a track of ionized atoms in the bulk of the material. The second effect is atomic displacement. Sometimes the atom receives so much kinetic energy at the site of interaction that it leaves its initial location in the material. This displacement creates additional atomic movement on its track that may result in a cluster of defects into the atomic lattice. The immediate and long-term results of ionization and atomic displacement strongly depend on the material. After electron-hole generations, electrons and holes travel in the bulk under the influence of the local electric field. The mobility of electrons is much higher than the mobility of holes, but both charge carriers may get into defects of the lattice called traps. Charge carriers accumulate around traps and create a local charge build-up. These traps can be single point defects or a mismatch of interface surfaces [8, 9].

High-energy photons give rise to clusters of defects and low-energy photons only produce single point defects. The interstitial atoms are not such electrically active as a complex of defects. Defects introduce intermediate energy levels in the gap between the conducting band and the valence band. These band-gap defects disturb the transport of electrical charges by several reactions [10]. First, generation and recombination of electron-hole pairs degrade the minority carrier lifetime. Second, the trapping and compensation effects change the majority carrier density and decrease the carrier mobility [11]. The results show that, under the influence of these effects, the reduction of photocurrent is significant.

This work describes a series of measurements undertaken to try to identify the similarities and differences in behavior of solar cells, photodiodes, and phototransistors in situation when these have previously been damaged by gamma radiation and have had enough time to recover. The aim of this paper is to provide readers with a comparative overview of the processes that occur in solar cells, photodiodes, and phototransistors after gamma irradiation and to give a critical review of the effectiveness of these devices.

2. Materials and Methods

Experimental measurement in this paper was carried out on the commercially available optoelectronic devices. In this experiment the following were used:

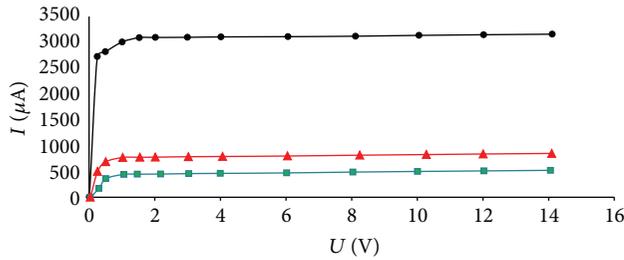
- (1) four types of silicon PIN photodiodes (BP104, BPW41N0, BPW34 all manufactured by Vishay, and SFH203FA by Osram),
- (2) two types of silicon NPN phototransistors (BPW40 manufactured by Telefunken electronic and LTR4206 by LITEON),
- (3) monocrystalline silicon solar panel (maximum power voltage 4.0 V, maximum power current 100.0 mA, dimension: 70 * 65 * 3.2 mm).

Devices were irradiated with Co^{60} 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 controlled 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%. Irradiation was performed in professional laboratory at the Department of Radiation and Environmental Protection of the Vinča Institute of Nuclear Sciences in Belgrade, Serbia.

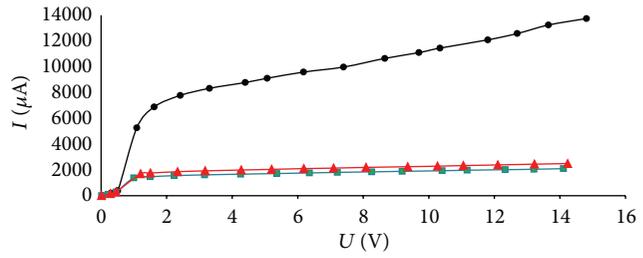
Before and after the irradiation, current-voltage (I - V) characteristics of all optoelectronic devices were measured in highly controlled conditions at room temperature. During the measurement, the samples were removed from the experimental room after absorption of the anticipated dose of radiation. Three measurements of the I - V characteristics have been undertaken:

- (1) first measurement: immediately before gamma irradiation,
- (2) second measurement: immediately after gamma irradiation,
- (3) third measurement: 1 month after gamma irradiation.

The third measurement has been undertaken one month after the irradiation, in order to give enough time for sample recovery. For this reason, the changes occurring in the samples can be considered as 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% [12–16]. Measurements of I - V characteristics have been performed for illumination levels of 10 W/m² (for phototransistors BPW40), 4.32 W/m² (for solar panels), and 0.45 W/m² (for phototransistor LTR4206 and all photodiodes: BP104, BPW41N, BPW34, and SFH203FA).



(a) Phototransistor BPW40



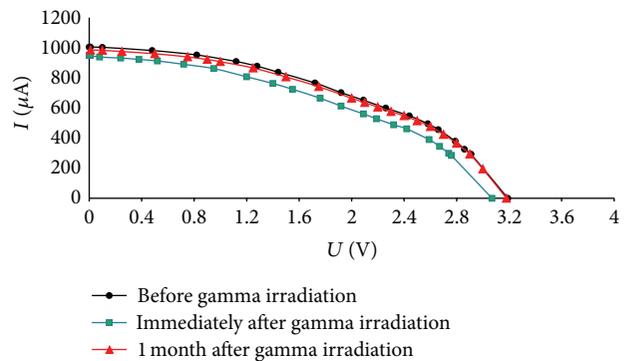
(b) Phototransistor LTR4206

FIGURE 1: I - V characteristics of the phototransistors before and after gamma irradiation.

3. Results and Discussion

Gamma rays lightly ionize and penetrate deeply into the matter. For low-energy photons (<0.5 MeV) the photoelectric effect is the dominant interaction. Photon scattering is by definition the scattering of an incoming photon by an electron. This scattering can be coherent (the photon energy is conserved) or incoherent (the photon energy is partially transferred to the electron). In both cases the photon has its trajectory modified and the electron is ejected from the atom. The most common scattering is Compton scattering. Pair production is dominant interaction at high energy and occurs only if the photon energy is greater than 1.022 MeV. In the electric field of a nucleus or an electron, a photon is spontaneously annihilated and converted into an electron-positron pair. The positron and the electron have a total kinetic energy equal to the difference of the initial photon energy and 1.022 MeV. Since the energy of the photon in this experiment is 1.25 MeV, the dominant effect that occurs is pair production. All three types of optoelectronic devices used in this experiment consist of p-n junction. Because of that, after gamma irradiation they all behaved in a similar way (Figures 1 to 3). Gamma radiation decreased their photocurrent and, after that, the process of annealing increased it. Figures 1 to 3 show that gamma radiation caused the greatest damages in phototransistors and the smallest in solar panels.

Vukić [17] shows that the measured values of the forward emitter current gain decreased by 20–40% after the absorption 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. Gain degradation and leakage are the most striking and common effects of radiation on bipolar transistors. One cause of gain degradation is atomic displacement in the bulk of a semiconductor. This bulk damage produces an increase in the number of recombination centers and therefore reduces minority carrier lifetime. The other main cause of gain degradation is ionization in the oxide passivation layer, particularly that part covering the emitter-base junction region [1]. Mechanisms of hole injection into the emitter and surface electron depletion

FIGURE 2: I - V characteristics of the solar panels before and after gamma irradiation.

would have significant influence on the serial transistor's forward emitter current gain. Enhanced hole injection into the emitter is manifested through the accumulation of the surface of the base, caused by the negative oxide charge trapped in the oxide over the emitter-base junction. Forward bias of the base junction would cause many holes to be injected into the emitter, thus increasing the base current [17]. The collector current changes significantly with the total dose. Since the base current increases, reduction of a collector current (Figure 1) has a strong impact on the current gain degradation. Vukić and Osmokrović [18] show that two effects cause the decrease of collector current in the heavily doped emitter devices: the recombination in the neutral base region and the reduction of the emitter injection efficiency.

The permanent damage in solar cell materials is caused by the collisions of incident radiation particles with atoms in the crystalline lattice, which are displaced from their positions. These defects degrade the transport properties of the material and particularly the minority carrier lifetime. The interaction between vacancies, self-interstitials, impurities, and dopants in Si leads to the formation of undesirable point defects such as recombination and compensator centers which affect performance of solar cells, especially in space. The introduction of radiation-induced recombination centers reduces the minority carrier lifetime in the base layer of the p-n junction

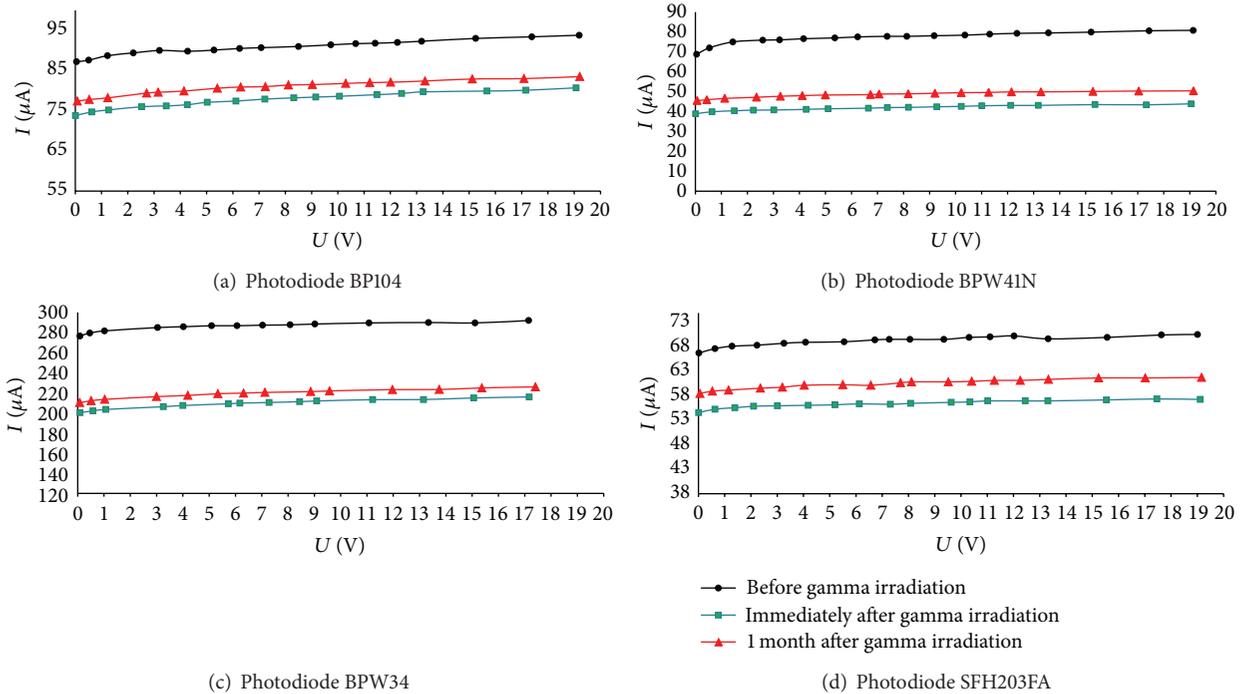


FIGURE 3: I - V characteristics of the reverse-biased photodiodes before and after gamma irradiation.

increasing series resistance [19]. Radosavljević and Vasić [20] show that the generation of electron-hole pairs due to ionization effects usually results in the generation and increase of noise and the minimum signal that can be detected. All of these effects lead to the decrease of the output current, as can be seen in Figure 2.

PIN photodiodes interpose a lightly doped i -region between the P and N layers. The PIN detector operates with a sufficiently high reverse bias to completely deplete the central region. Consequently, all of the charge is collected by drift. Although light collection efficiency in PIN diodes is less affected by radiation damage, leakage current in the lightly doped intrinsic region is sensitive to displacement damage [21]. Displacement damage within the silicon material results from incident radiation, causing crystal lattice defects. These defects (vacancies, divacancies, interstitials, and defect clusters) generate energy levels in the forbidden bandgap of the material lattice, causing the reduction of the minority carrier lifetime. The final result is the decreasing of the photocurrent (Figure 3).

For this research, the long-term isothermal annealing at room temperature was used. The vacancies and interstitials are quite mobile in silicon at room temperature and hence are referred to as 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 [22–24]. Moll [25] describes the enhancement of the effective doping concentration for the longer annealing times. This phenomenon Feick [26]

observed at room temperature. During the process of annealing defects cluster and some electrical inactive defects become active in a cluster. The best results annealing process has achieved are in the solar panels and the worst are in phototransistors (Figures 1 to 3). The rate of damage recovery from annealing in solar panels is almost the same as the rate of damage creation (Figure 2), so it is possible to use annealing as a part of a hardening method [8, 9]. Probable cause is the construction of solar panels. To obtain the maximum power voltage of panels (4 V), a large number of individual cells are used in series and parallel combinations. The effect of gamma irradiation on the single cell is similar to the effect on photodiode but a combination of a number of cells that affected the panel would be more resistant to the influence of gamma radiation and the process of annealing would be more efficient.

In recent papers the efficiency and properties of solar cells in terms of various conditions have been observed [27–30]. Those researches show that development, innovation, and new devices concepts in silicon solar cells are taking place to bring down the cost of solar technologies and make them even more effective and competitive with conventional optoelectronic devices. Experimental measurements applied in this paper also confirm that solar cells, even in the area of reliability in gamma radiation environments, are superior to conventional optoelectronic devices such as phototransistors and photodiodes.

4. Conclusion

Degradation of the main parameters of the optoelectronic devices and their improvement, as a consequence of

annealing, were observed for all used samples. The results confirm that gamma irradiation leads to degradation of the I - V characteristics and then annealing improves these characteristics. Due to their amplifying action, the phototransistors are the most sensitive to radiation effects. On the other hand, the solar panels are the least sensitive to gamma radiation. Its characteristics, in annealing process, 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.

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