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Effects of successive gamma and neutron irradiation on solar cells

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This paper presents the behavior of solar cells after successive gamma and neutron irradiation. Commercial solar panels have been exposed to gamma radiation and then, after 30 days of recovery, to neutron radiation. I-V characteristics, series and parallel resistance, open-circuit voltage, short-circuit current and fill factor have been measured before and after every step of 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 solar cells in radiation environments.

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1. Introduction

Solar energy and other clean energies are emerging and growing rapidly in the globe nowadays. Solar energy with less carbon emission is renewable and clean energy for our living environment. Solar energy can be converted to electricity in photovoltaic (PV) devices, solar cells, or solar thermal/electric power plants.

Photovoltaic (PV) conversion of solar energy is one of the most up-to-date semiconductor technologies that enables application of PV systems for various purposes. The wider substitution of conventional energies by solar energy lies in the rate of developing solar cell technology. Silicon is still the mostly used element for solar cell production, so efforts are directed to the improvement of physical properties of silicon structures. Silicon solar cells belong to a wide group of semiconductor detector devises. One of the most specific field of application of solar cells is the space. Possibilities of application of solar cells in this area are countless (photonic communications, photonic signal processing, photonic sensing, special applications etc.). A complete evaluation of the solar cells technology has to be performed in advance in order to select the best components and to reduce the risk of using devices that have not been designed to work in space environmental conditions. Experience shows that the evaluation of the most critical aspects reveals that not all the commercial devices that are available in the market are suitable for space use [1].

A number of researchers and institutions working hard to produce new and improve existing solar cells to be reliable and effective in specific circumstances such as space. In the space environment solar cells are exposed to different types of radiation, such as protons, alpha particles, heavy ions, neutrons, gamma rays, electrons, positrons, etc. In previous papers the behavior of various optoelectronic devices in terms of nuclear radiation has been observed [2-9].

Spent nuclear fuels emit simultaneously, in addition to γ-rays, several neutrons also, so semiconducting device (e.g., solar cell) placed in the vicinity of these fuels sustains different kind of radiation damage both from γ-rays and from neutrons. The lifetime of the solar cell is restricted by the degree of radiation damage that the cell receives. This is an important factor that affects the performance of the solar cell in practical applications. The main effect of the radiation is an increase of the saturation current generated within or at the surface of the depletion region. The permanent damage in the solar cells materials is caused by collisions of the incident radiation particles with the 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 [10]. 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 affects performance of the solar cells, especially in space. Introduction of radiation-induced recombination centers reduce the minority carrier lifetime in the base layer of the p-n junction increasing series resistance. After very high doses of radiation series resistance of the base layer could be so high that most of the power generated by the device is dissipated by its own internal resistance. However, small doses of radiation carefully introduced and monitored, could have some beneficial effects on device performance due to possible relaxation of crystal lattice, leading to lowering of series resistance [11].

During the previous decades many researchers tested various optoelectronic devices and published the results of their researches [3-9]. 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 [12-13].

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 [14]. 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 [15]. The results show that, under the influence of these effects, the reduction of photocurrent is significant.

The fundamental “structural” element of solar (PV - photovoltaic) systems, the solar cell, is usually based on the p-n junction device that, exposed to solar radiation, gives power as its output characteristic. Radiation damage due to neutrons is primarily connected to the displacement of silicon atoms from their lattice sites in the crystalline silicon solar cells, leading to the destruction and distortion of local lattice structure and formation of defects. If, under the influence of neutrons, stable defects are made, they could, together with impurity atoms, donors and for example implanted atoms, form complex defects acting as recombination sites or traps, significantly decreasing minority carrier lifetime. This lifetime decrease produces the degradation of the electrical parameters of the cell, such as series resistance (*Rs*), output current and finally efficiency (μ) [16]. 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 life time in the base layer of the p-n junction increasing series resistance. Factors that influence the internal parameters of solar cells such as series and parallel resistance lead to changes in efficiency and maximum generated power in a solar cell [17, 18].

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

2. Experimental

Experimental measurement in this paper was carried out on the commercially available monocrystalline silicon solar panels (maximum power voltage 4.0V, maximum power current 100.0mA, dimension: 70*65*3.2mm).

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.

One month after gamma irradiation solar panels have been exposed to neutron and gamma radiation from ^{241}Am-Be source, which is housed in the SSDL (Secondary Standard Dosimetry Laboratory) Institute of Nuclear Sciences "Vinča", Belgrade. ^{241}Am-Be source emits gamma photons of low energy (60 keV and 14 keV), so that for the activity of 1 Ci, calculated 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 at a distance of 5 cm from the source. The intensity of the neutron emission from this source is 2.7×10^6 neutrons s^{-1}, and the mean energy of the neutrons E_{nav} = 5.5 MeV. Based on measurements of the quality factor for this neutron spectrum Q_n = 7, calculated the neutron absorbed dose rate $\dot{D}_n$ = 1.714 mGy/hr and the equivalent dose rate of neutrons $\dot{H}_n$ = 12 mSv/hr. This means that at 5 cm distance from the ^{241}Am-Be source with a total absorbed dose rate is $\dot{D}_{tot}$ = 13.714 mGy/hr, while the total equivalent dose is $\dot{H}_{tot}$ = 24 mSv/hr. 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. In this interval, the material components received of the total absorbed dose in the amount of D_{tot} = 229.71 mGy, and respectively, the total equivalent dose H_{tot} = 402 mSv. The components were irradiated in the air at a temperature of 21° C and relative humidity of 40% to 70%.

Before and after every step of irradiation, I-V characteristics, series and parallel resistance, open-circuit voltage, short-circuit current and fill factor have been 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 solar cells parameters:

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

The third and fifth measurement have 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 a permanent. Standard measurement equipment was used for measurement. The professional digital multimeter AMPROBE 33XR was used for the current measurement. Combined measurement uncertainty for all measurements was less than 1.2% [19-21].

3. Results and discussion

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 life time. 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 life time in the base layer of the p-n junction increasing series resistance [17, 22]. Radosavljević *et al.* [23] 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 Fig. 1. [24, 25].

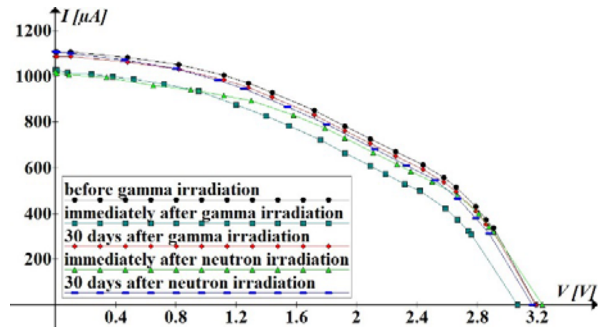

Fig. 1. I-V characteristics of the solar panels before and after gamma and neutron irradiation.

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 a 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. Gamma radiation decreased solar cells photocurrent and, after that, the process of annealing increased it (Fig. 1.).

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 [12, 13]. As a result, there has been the reduction of the photocurrent after neutron irradiation (Fig. 1.).

Fig. 2 shows sequential changes in resistance upon irradiation with different types of radiation. After both gamma and neutron irradiation increasing in resistance has been observed. This increase can be explained by increasing of surface states density. The relative increase of resistance values after neutron radiation is lower than after gamma radiation, which means that there is a saturation of surface states density, due to neutron irradiation is applied after gamma radiation.

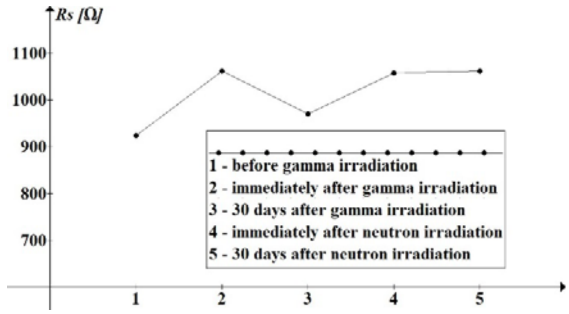

Fig. 2. Series resistance of the solar panels before and after gamma and neutron irradiation

The parallel resistance behavior is in contrast to the series resistance, when the series resistance increases parallel decreases and vice-versa (Fig. 3.).

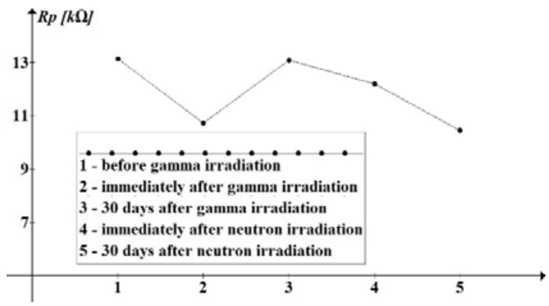

Fig. 3. Parallel resistance of the solar panels before and after gamma and neutron irradiation

Short-circuit current is determined primarily by the spectrum and intensity of the light source and the spectral response of the solar cell semiconductor material (number of collected electron-hole pairs per incident photon), because:

$$J_{sc} = q\int_{0}^{\infty} F(\lambda)SR(\lambda)d\lambda \qquad (1)$$

where *F(λ)* is number of incident photons per unit area in unit time and in a unit zone width, and *SR(λ)* is spectral response. On the other hand, spectral response depends on the absorption coefficient *α*, the depth of the compound, the width of the depletion area, life time and mobility (diffusion length) of minority carriers on both sides of the junction, the presence or absence of an electric field on both sides of the junction and speed of the surface recombination. Rate of the minority carriers photogeneration and their ability to diffuse to the junction and output contacts are basically determined by the value of the short-circuit current density (Fig. 4.).

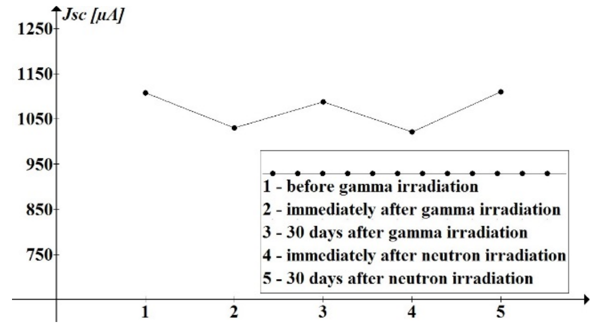

Fig. 4. Short-circuit current of the solar panels before and after gamma and neutron irradiation

The I-V characteristics define the open-circuit voltage as:

$$V_{oc} = \frac{nkT}{q}\ln\left(\frac{J_{sc}}{J_o}+1\right) \qquad (2)$$

where J_o is the saturation current density. After gamma irradiation, due to decreasing of short-circuit current, the open-circuit voltage have also been decreased. After neutron irradiation, a saturation of surface states density occur and open-circuit voltage have been increased, although there is a short-circuit current decreasing (Fig. 5.).

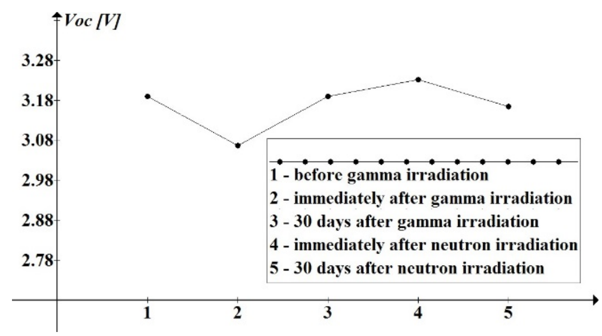

Fig. 5. Open-circuit voltage of the solar panels before and after gamma and neutron irradiation

A detailed analysis of definition expression for fill factor leads to an important conclusion that the fill factor depends mainly on the open-circuit voltage V_{oc} ie factor qV_{oc}/nkT. Thus, the characteristics of the fill factor resembles the characteristics of the open-circuit voltage (Figs. 5. and 6.).

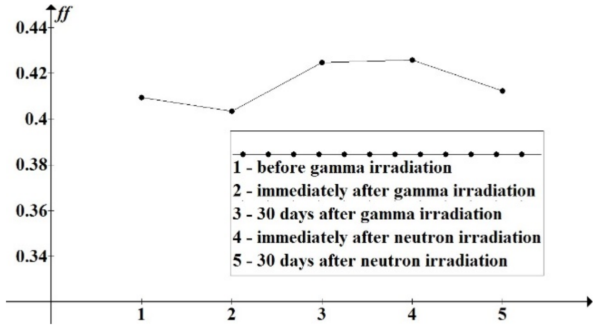

Fig. 6. Fill factor of the solar panels before and after gamma and neutron irradiation

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 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 [26, 27, 28]. Moll [29] describes the enhancement of the effective doping concentration for the longer annealing times. This phenomenon Feick [30] observed at room temperature. During the process of annealing defects clusterize and some electrical inactive defects become active in a cluster. The rate of damage recovery from annealing in solar panels is almost the same as the rate of damage creation (Fig. 1.), so it is possible to use annealing as a part of a hardening method [12, 13]. 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 affected that the panel would be more resistant to the influence of gamma radiation and the process of annealing would be more efficient [31].

In recent papers the efficiency and properties of solar cells in terms of various conditions has been observed [32-34]. 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 confirms that solar cells, even in the area of reliability in successive gamma and neutron irradiation environments, are very reliable.

4. Conclusion

Degradation of the main parameters of the solar cells and their improvement, as a consequence of annealing, was observed for all used samples. The results confirm that both gamma and neutron irradiation leads to degradation of the I-V characteristics and other parameters and then annealing improves these characteristics. 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.

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