

EFFECTS OF RADIATION ON SOLAR CELLS AS PHOTOVOLTAIC GENERATORS

by

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The growing need for obtaining electrical energy through renewable energy sources such as solar energy have lead to significant technological developments in the production of the basic element of PV conversion, the solar cell. Basically, a solar cell is a p-n junction whose characteristics have a great influence on its output parameters, primarily efficiency. Defects and impurities in the basic material, especially if located within the energy gap, may be activated during its lifetime, becoming traps for optically produced electron-hole pairs and, thus, decreasing the output power of the cell. All of the said effects could be induced in many ways over a lifetime of a solar cell and are consistent with the effects that radiation produces in semiconductor devices. The aim of this paper is to investigate changes in the main characteristics of solar cells, such as efficiency, output current and power, due to the exposure of solar systems to different (hostile) radiation environments.

Key words: output power, solar cell, radiation environment, dose, efficiency

INTRODUCTION

The fundamental “structural” element of solar (PV) systems, the solar cell, is usually based on the p-n junction device that, exposed to solar radiation, gives power as its output characteristic. Due to the unavoidable market competitiveness with conventional energy sources, PV technology is oriented towards the production of high efficiency solar cells that could produce more energy and, thus, serve as a feasible renewable energy source of the future. Ongoing research is focused on the effects of the defects and impurities that influence the main parameters, such as the lifetime of charge carriers, better understanding of transport processes, the creation of electron-hole pairs, *etc.* [1-4]. Analytical connections between fundamental and output characteristics of solar cells are a matter of theoretical analysis, but experimentally obtained results are more complex than theoretical suppositions. Both in the production of solar cells and their performance, the distribution of dopants, impurities, and especially, defects, is usually not uniform and predictable and could, thus, directly influence the processes taking place in the cells themselves. The empirically obtained influence of funda-

mental parameters is usually mathematically defined by the formal introduction of the ideality factor, n , in the exponent of the current – voltage characteristics of solar cells. The said ideality factor combines all the variations of the current flow of the ideal case, induced by various internal and external influences of physical parameters of the manufacturing process, or those which are a consequence of aging. It has already been established [5, 6] that an increase in the ideality factor has a substantial negative influence on the output characteristics of solar cells, primarily on the fill factor and efficiency. The main characteristics of a solar cell are its efficiency, η , open circuit voltage, V_{oc} , short circuit current, J_{sc} , maximum power, P_m , and fill factor, ff . These parameters strongly depend on the fundamental parameters of a real solar cell (or, on a real p-n junction in general), such as the series and parallel (shunt) resistance (R_s and R_{sh}), ideality factor (n) and saturation current density (J_0). The changes in these solar cell parameters caused by the process of aging are consistent with radiation induced effects in semiconductor devices.

Due to their wide area of application, solar cells are often exposed to a variety of radiation effects (natural space environment, atmospheric environment, military and civil nuclear environment). Since spent nuclear fuels, in addition, simultaneously emit gamma rays, several neutrons, semiconductor devices such as

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solar cells, when placed in the vicinity of these fuels, sustain different kinds of radiation damage, both from gamma and neutron irradiation. Therefore, extensive studies on the development of semiconductor devices that could operate normally in a radiation environment have been carried out. The conclusion reached was that radiation induced defects significantly degrade the performance of photo detectors and solar cells [7-10]. From a technological point of view, it is important to study the variations induced by the irradiation of semiconductor junction characteristic parameters (reverse saturation current, ideality factor *etc.*) that affect the performance of the solar cells.

The aim of this paper is to investigate changes in the main characteristics of solar cells, such as efficiency, output current and power, due to the exposure of solar systems to different (hostile) radiation environments.

THEORETICAL ANALYSIS

Output characteristics of all semiconductor devices are primarily defined by fundamental parameters (resistance, lifetime and mobility of charge carriers, diffusion length, *etc.*), and processes in them. In polycrystalline and monocrystalline solar cells, the inherent presence of defects and impurities in the basic material could, over time, produce certain negative effects. This is especially emphasized if those states are located within the energy gap and are activated during use. In such a case, they become traps for optically produced electron-hole pairs and thus decrease the number of collected charge carriers. Macroscopically, this effect may be observed as a decrease in the output current and voltage and, might, ultimately, lead to the decrease of the efficiency of the solar cell. Lower values of the short-circuit current indicate the existence of recombination centers that decrease the mobility and diffusion length of charge carriers, making recombination in the depletion region a dominant mode of transport in such solar cells. Also, voltage decrease in the maximum power point (P_m) has a great influence on efficiency. One of the main reasons for this decrease is the increase of the ideality factor, so it can be said that the influence of the ideality factor on solar cell efficiency is through voltage. A set of experimentally obtained $\eta = f(n)$ dependencies for different solar cells is shown in fig. 1.

All of these effects could be induced in many ways over a lifetime of a solar cell (optically, by temperature changes in the environment, *etc.*), and are consistent with the effects that radiation produces in the semiconductor devices. Many experiments have shown that the short-circuit current and output power decrease gradually with the increase in the radiation dose [10-14], while the open circuit voltage can be se-

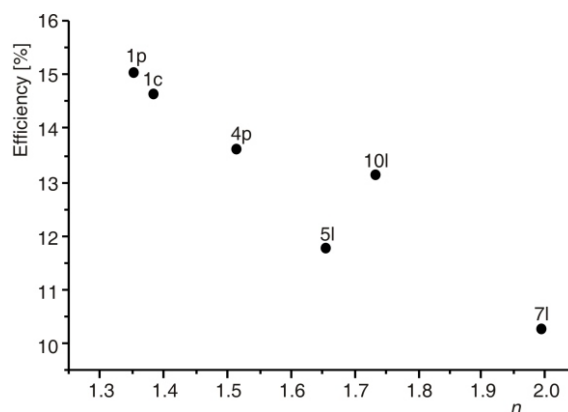


Figure 1. Dependence of efficiency on the ideality factor

verely degraded even at low doses [14]. The change in the short-circuit current was mainly related to the lifetime of minority carriers, the change in the open circuit voltage, to the damage of p-n junctions. The presence of impurity atoms that are either added to the base material as donors or during the manufacturing process, has indicated the possibility that some of the produced electrons might be trapped by those atoms between the valence and conduction band [15-17]. Therefore, the power output of the solar cells exposed to γ radiation is also reduced.

EXPERIMENTAL PROCEDURE

All experimental measurements were performed on monocrystalline, non-encapsulated Si solar cells manufactured by Siemens. Current-voltage data were used for the characterization of their properties. Standard measurement equipment was used to measure the I - V curve under two different illumination levels (32 W/m² and 58 W/m²). A reflective lamp was used as a solar simulator. From the obtained curves, all relevant parameters were obtained.

Two types of radiation (gamma and neutron) were used for the measurements. Before and after each step of the irradiation, current-voltage characteristics of the diodes were measured in highly controlled conditions, at room temperature, with combined measurement uncertainty less than 5% [18-21]. One group of solar cells were irradiated with a ⁶⁰Co gamma source with different doses. The irradiation was performed through glass, in a controlled environment. Another group of solar cells were irradiated with a Pu-Be point neutron source. This point source is a mixture of ²³⁸Pu, with beryllium as a good source of neutrons (through a nuclear reaction in which Be absorbs an alpha particle from Pu and forms ¹²C, with the emission of a neutron). A direct contact of the samples and the source was established, and the maximum dose rate was established as $dD/dt = 0.36$ mGy/h.

RESULTS AND DISCUSSION

As is known, depending on the energy of gamma rays, their interaction with the material is through the photoelectric and Compton effects that may produce ionization induced changes in the material. These changes usually result in an increase of the surface recombination velocity and the density of surface states. If those states correspond to deep energy levels in the silicon energy gap, they act as efficient surface recombination centers for charge carriers. 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. 2, for the current at the maximum power point (J_m).

Similar behaviour could be observed in the dependence of maximum power (P_m) on doses for the two illumination levels (fig. 3).

Besides the expected decrease of the output characteristics with an increase in doses, a slight increase of J_m and

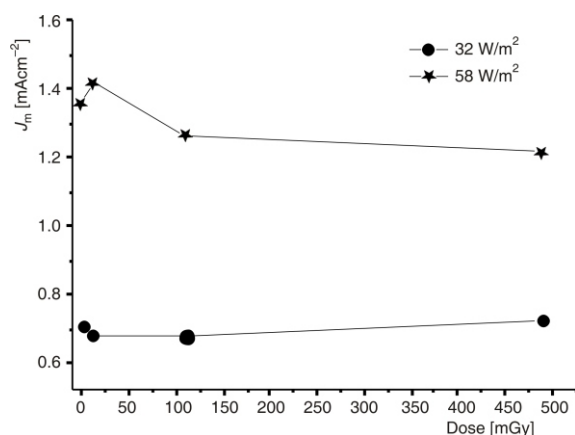


Figure 2. Dependence of the current at the maximum power point on doses (gamma irradiation)

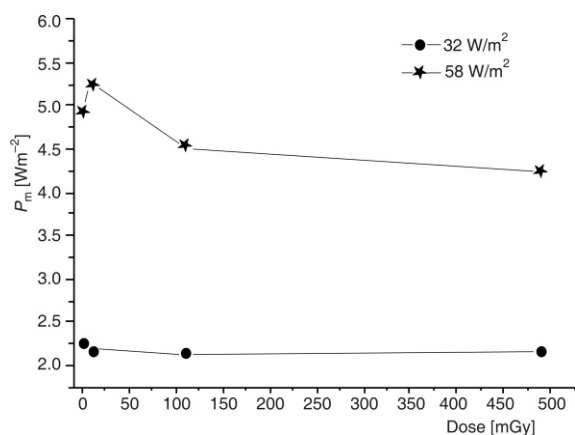


Figure 3. Dependence of the maximum power on doses (gamma irradiation)

P_m was detected at the higher illumination level. This increase is very significant from the standpoint of solar cells as power generators, because it indicates a possible beneficial influence of low doses of irradiation.

A possible explanation could be the fact that during the fabrication processes, unavoidable structural defects and impurities produce tension in the crystal lattice. The interaction of irradiation with such a material could act similarly to annealing, relaxing the lattice structure and decreasing the series resistance, ultimately leading to a increase in efficiency (fig. 4).

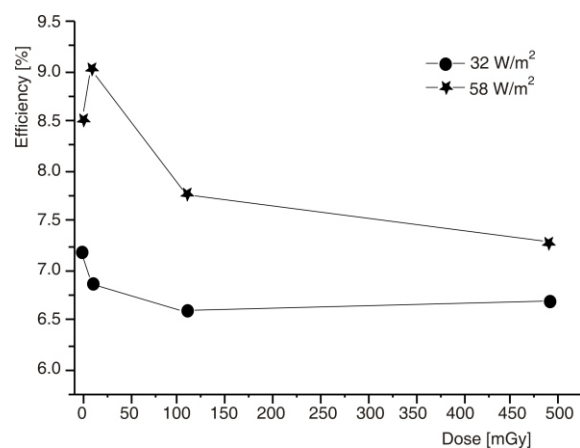


Figure 4. Dependence of efficiency on doses (gamma irradiation)

Charge carrier lifetime decreases due to radiation damage induced by neutrons, causes the degradation of electrical parameters of the cell such as series resistance (R_s), output power and, finally, efficiency (η). A high level of series resistance usually indicates the presence of impurity atoms and defects localized in the depletion region, acting as traps for recombination or tunneling effects, increasing the dark current of the cell. Moreover, shallow recombination centers in the vicinity of the conducting zone enhance the tunneling effect, further degrading the output characteristics of the cell by increasing the noise level (especially that of burst noise, connected to the presence of an excess current).

Such a negative impact of neutron radiation was observed at a higher illumination level, as can be seen in fig. 5

But, an interesting phenomenon – an increase of the maximum power – was observed for lower values of illumination. (Different behaviors for different illumination levels are due to the presence of finite series and parallel resistance in the cell.)

A possible explanation for the observed effect could be similar to that of gamma irradiation, namely: small doses of radiation may produce a decrease in series resistance. Subsequently, this will lead to a lower-

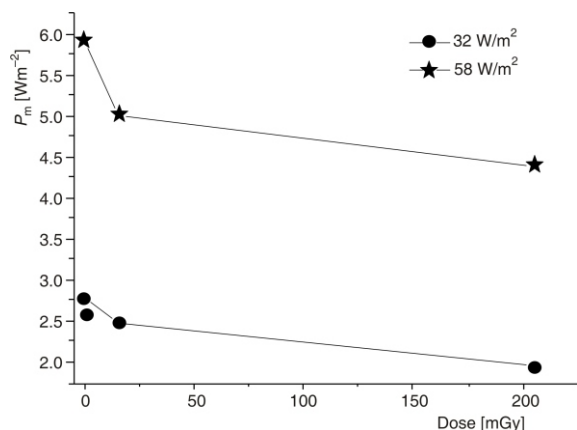


Figure 5. Dependence of the maximum power on doses (neutrons)

ing of the noise level and an increase in the output current since, as is well known, high series resistance of a solar cell is one of the main limiting factors of its efficiency.

Finally, the improvement of output characteristics after the first irradiation step at the low illumination level has also been registered for efficiency, fig. 6. Although higher doses of neutron radiation undoubtedly have a negative impact on the performance of solar cells, observed phenomena offer possibilities for the use of radiation as a means in improving solar cell characteristics.

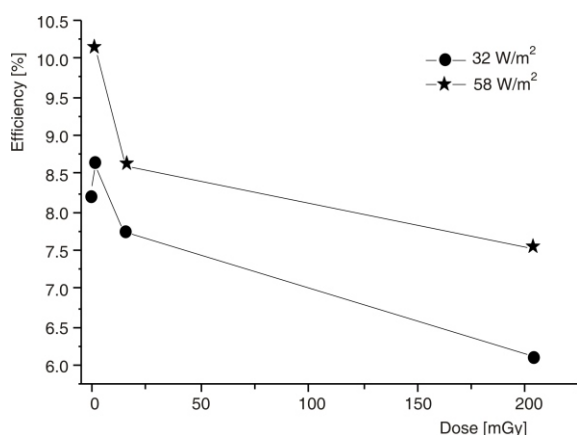


Figure 6. Dependence of efficiency on doses (neutrons)

CONCLUSIONS

Solar cells, the basic elements of the photovoltaic conversion of solar energy, are especially susceptible to radiation damage, primarily due to their large surface. Permanent damage in solar cell material is caused by the collision of incident radiation particles with the atoms in the crystalline lattice. The resulting defects degrade the transport properties of the material

and, in particular, the lifetime of the minority carrier. This decrease in the lifetime enhances further degradation of the cell's parameters. Many experiments have shown that output power and efficiency decrease gradually with the increase of the radiation dose. However, though commonly referred to as a source of noise in semiconducting devices, radiation induced effects could, in some cases, have a positive effect on the main electrical characteristics (J_m , P_m , η). Initial improvement of such characteristics observed at small doses of neutron radiation and low illumination levels, indicates that there is a possibility of using irradiation for the enhancement of solar cell quality.

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REFERENCES

- [1] Sze, S. M., Physics of Semiconductor Devices, 2nd ed., John Wiley & Sons, New York, USA, 1981
- [2] Fahrenbruck, A. L., Bube, R. H., Fundamentals of Solar Cells, Academic Press, New York, USA, 1983
- [3] Hovel, J., Semiconductors and Semimetals, Academic Press, New York, USA, 1975
- [4] Vujisić, M., *et al.*, Radiation Hardness of COTS EPROMs and EEPROMs, Radiation Effects and Defects in Solids: *Incorporating Plasma Science and Plasma Technology*, 165 (2010), 5, pp. 362-369
- [5] Vasić, A., Stojanović, M., Osmokrović, P., Stojanović, N., The Influence of Ideality Factor on Fill Factor and Efficiency of Solar Cells, *Materials Science Forum*, 352 (2000), 1, pp. 241-246
- [6] Zdravković, M., *et al.*, Influence of Radiation on the Properties of Solar Cells, *Nucl Technol Radiat*, 26 (2011), 2, pp.158-163
- [7] Marjanović, N., *et al.*, Effects of Heavy Ion Bombardment on TiO₂ Memristor Operation, Radiation Effects and Defects in Solids: *Incorporating Plasma Science and Plasma Technology*, 166 (2011), 1, pp. 1-7
- [8] Marjanović, N., *et al.*, Simulated Exposure of Titanium Dioxide Memristors to Ion Beams, *Nucl Technol Radiat*, 25 (2010), 2, pp. 120-125
- [9] Vujisić, M., *et al.*, Simulated Effects of Proton and Ion Beam Irradiation on Titanium Dioxide Memristors, *IEEE Transactions on Nuclear Science*, 57 (2010), 4, pp. 1798-1804
- [10] Alurralde, M., *et al.*, Experimental and Theoretical Radiation Damage Studies on Crystalline Silicon Solar Cells, *Solar Energy Materials & Solar Cells*, 82 (2004), 4, pp. 531-542
- [11] Osmokrović, P., *et al.*, Validity of the Space-Time Enlargement Law for Vacuum Breakdown, *Vacuum*, 85 (2010), 2, pp. 221-230
- [12] Osmokrović, P., *et al.*, Conditions for the Applicability of the Geometrical Similarity Law to Gas Pulse Breakdown, *IEEE Transactions on Dielectrics and Electrical Insulation*, 17 (2010), 4, pp. 1185-1195
- [13] Stanković, K., *et al.*, Time Enlargement Law for Gas Pulse Breakdown, *Plasma Sources Science and Technology*, 18 (2009), 025028

- [14] Hu, Z., He, S., Yang, D., Effects of <200 keV Proton Radiation on Electric Properties of Silicon Solar Cells at 77 K, *NIM B, Beam Interaction with Materials & Atoms*, 217 (2004), 2, pp. 321-326
- [15] Horiuchi, N., Nozaki, T., Chiba, A., Improvement in Electrical Performance of Radiation-Damaged Silicon Solar Cells by Annealing, *NIM A, Accelerators, Spectrometers, Detectors, and Associated Equipment*, 443 (2000), 1, pp. 186-193
- [16] Khan, A., et al., Strategies for Improving Radiation Tolerance of Si Space Solar Cells, *Solar Energy Materials & Solar Cells*, 75 (2003), 1-2, pp. 271-276
- [17] Alexander, D. R., Transient Ionizing Radiation Effects in Devices and Circuits, *IEEE Transaction on Nuclear Sciences*, 50 (2003), 3, pp. 565-582
- [18] Vujisić, M., Stanković, K., Osmokrović, P., A Statistical Analysis of Measurement Results Obtained from Nonlinear Physical Laws, *Applied Mathematical Modeling*, 35 (2011), 7, pp. 3128-3135
- [19] Stanković, K., et al., Statistical Analysis of the Characteristics of Some Basic Mass-Produced Passive Electrical Circuits Used in Measurements, *Measurement*, 44 (2011), 9, pp. 1713-1722
- [20] Stanković, K., Influence of the Plain-Parallel Electrode Surface Dimensions on the Type A Measurement Uncertainty of GM Counter, *Nucl Technol Radiat*, 26 (2011), 1, pp. 39-44
- [21] Stanković, K., Vujisić, M., Delić, Lj., Influence of Tube Volume on Measurement Uncertainty of GM Counters, *Nucl Technol Radiat*, 25 (2010), 1, pp. 46-50

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Радован Љ. РАДОСАВЉЕВИЋ, Александра И. ВАСИЋ**УТИЦАЈ ЗРАЧЕЊА НА СОЛАРНЕ ЋЕЛИЈЕ КАО
ФОТОНАПОНСКЕ ГЕНЕРАТОРЕ**

Растућа потреба за добијањем електричне енергије из обновљивих извора енергије као што је сунчева енергија, довела је до значајног технолошког развоја у производњи основног елемента фотонапонске конверзије, соларне ћелије. Соларна ћелија је у основи р-п спој чије карактеристике имају велики утицај на излазне параметре, првенствено на ефикасност. Дефекти и нечистоће у основном материјалу, посебно ако се налазе унутар енергетског процепа, могу током рада да се активирају, постајући замке за оптички генерисане парове електрон-шупљина и на тај начин смањујући излазну снагу ћелија. Сви наведени ефекти могу бити проузроковани на различите начине током рада соларних ћелија и у складу су са ефектима које производи зрачење у полупроводничким уређајима. Циљ овог рада је да се истраже промене главних излазних карактеристика соларних ћелија, као што је ефикасност, излазна струја и снага, настале услед излагања соларних система различитим радијационим окружењима.

Кључне речи: излазна снага, соларна ћелија, радијационо окружење, доза, ефикасност