# EFFICIENCY OF SOLAR CELLS IN THE CONDITIONS OF ELECTROMAGNETIC OR NEUTRON RADIATION

by

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**The paper discusses the influence of the dose of gamma or neutron radiation on a commercial silicon photovoltaic cell under operating conditions. Before the measurement, the cells were irradiated with electromagnetic gamma radiation or neutron radiation. The examination was carried out experimentally and theoretically. The experiments were performed under well-controlled laboratory conditions. Only licensed instruments were used. The measurement uncertainty of the experimental procedure was less than 5 %.**

*Key words: silicon solar cell, gamma and neutron radiation, cell efficiency*

## INTRODUCTION

Solar cells are *p-n* junctions that function based on the effect of incident photons. The condition for the functioning of solar cells is that the incident photons have an energy greater than the value of the energy gap (forbidden zone) of the material. If this condition is met, the conditions for photon absorption are created [1, 2]. Depending on the energy of the incident photon and the properties of the material of the *p-n* junction, photon absorption can take place in the *n*+ part of the space charge region or in the *n p* part (if working in an *n*+-*p* junction). If the surplus of minority carriers created in this way (cavities in the *n*+ part and electrons in the *p* part) can reach the boundary of the space charge area by diffusion. The voltage polarity of the diode is, then, identical to the direct polarization of an ordinary external diode but, the direction of the photo generated current is opposite to the direction of the current of the external diode in the case of direct polarization which, in the case of external cells, is called dark current and is a degrading factor [3, 4].

The voltage drop on the consumer, created by the flow of light-generated current, has the same effect as connecting the battery to a direct bias voltage of value RI. Therefore, when the incident light interacts with the solar cell, the following physical processes occur:

– Reflection of part of the energy from the cell surface,
– beneficial absorption with the creation of hole-electron pairs,
– separation of photo generated charge carrier,
– movement of charge carriers towards external contacts,
– dissipation of the photo generated current on the external consumer, and
– in relation to the mentioned phenomena, the requirements for obtaining efficient solar cells are as follows [5, 6]:
– absorption of photons and creation of electron-hole pairs,
– generated electron-hole pairs are separated in *n*-type and *p*-type *p-n* junctions,
– the building potential must be large enough because it determines the maximum output voltage of the cell. Ohmic voltage drop, as a consequence of parasitic resistances, must be reduced to the smallest possible extent, and
– all metal covers must be small, as they are not transparent to photons, [7, 8].

Efficiency as an output parameter is determined by a combination of three fundamental characteristics of a solar cell: the fill factor (a measure of squareness), short-circuit current density, and open-circuit voltage. From the perspective of evaluating solar cell quality, it is important to consider the interdependence of these parameters and their combined influence on efficiency. Specifically, the simultaneous interaction of the cell's physical parameters primarily contributes to reducing excessive current density and minimizing losses due to saturation of the contact grid.

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Regarding the physical aspects of loss analysis (*i. e*., the reduction in efficiency), special attention should be paid to the reflection of photons from the cell surface, which decreases the number of photons entering the semiconductor material, thereby reducing the photogeneration of electron-hole pairs. In this context, the aim of this paper is to determine the impact of electromagnetic and gamma radiation on the efficiency of solar cells.

It should be noted that this work continues the authors' interest in the impact of ionizing radiation on electronic components. Specifically, the increasing miniaturization of electronic components and the growing environmental contamination by ionizing radiation (especially near nuclear facilities and at high altitudes) have heightened the relevance of this issue.

## DEPENDENCE OF SHORT CIRCUIT CURRENT AND OPEN CIRCUIT VOLTAGE ON THE PHYSICAL PARAMETERS OF THE SOLAR CELL

The basic current-voltage (I-V) characteristics of solar cells are the surface short-circuit current density $J_{sc}$ and the open-circuit voltage $V_{oc}$. The values of those quantities are easily (directly) read from the I-V characteristic. They represent the two endpoints of the operation of the photovoltaic device. The open circuit voltage is determined by the infinite resistance of the short circuit when the voltage is equal to zero [9, 10].

The short-circuit current density is most justifiably defined by the superposition of the photo generated current and the dark current. This definition of the junction current is closest to ideal or near-ideal solar cells. The I-V characteristics of such cells can be represented by the equation

$$J = J_0\left[\exp\left(\frac{qV}{nkT}\right) - 1\right] - J_{\mathrm{L}} \tag{1}$$

or

$$J = J_{\mathrm{sc}} - J_0\left[\exp\left(\frac{qV}{nkT}\right) - 1\right] - J_{\mathrm{L}} \tag{2}$$

where $J_0$ is the saturation current density, $V$ – the applied voltage, $n$ – the ideality factor, $k$ – the Boltzmann constant, $q$ – the elementary charge, and $T$ – the temperature. This I-V characteristic is satisfactory for the case of small series and high parallel resistance. However, in real cases the I-V characteristic has the form

$$J = J_{01}\left[\exp\left(\frac{q(U - JR_{\mathrm{s}})}{nkT}\right) - 1\right] + J_{\mathrm{L}} + J_{0n}\left[\exp\left(\frac{q(U - JR_{\mathrm{s}})}{nkT}\right) - 1\right] + \left(\frac{(U - JR_{\mathrm{s}})}{R_{\mathrm{sh}}}\right) - J_{\mathrm{L}} \tag{3}$$

where $J_{01}$ and $J_{0n}$ are the saturation current densities of $n = 1$ and $n > 1$, respectively, and $R_{\mathrm{s}}$ and $R_{\mathrm{sh}}$ are the series and parallel resistances, respectively.

The existence of the current $J$ on the right side of the equation in the case when $R_{\mathrm{s}} \neq 0$ and $R_{\mathrm{sh}}$ is finite, prevents the direct superposition of the photo generated current and the dark current. In the case when the parallel resistance $R_{\mathrm{sh}}$ is extremely small, the short-circuit current is slightly smaller than the photo generated current $J_{\mathrm{L}}$, *i. e*.

$$J_{\mathrm{sc}} \approx \frac{J_{\mathrm{L}}}{1 + \dfrac{R_{\mathrm{s}}}{R_{\mathrm{sh}}}} \tag{4}$$

Since in most solar cells the parallel resistance has a large value, the approximation $J_{\mathrm{sc}} = -|J_{\mathrm{L}}|$ is considered satisfactorily accurate (except at higher illuminance values). The short-circuit current is primarily determined by the spectrum and intensity of the light source and the spectral response of the semiconductor material of the solar cell (the number of collected electron-hole pairs) to the incident photon, because

$$J_{\mathrm{L}} = q\int_0^{\infty} F(\lambda)SR(\lambda)\mathrm{d}\lambda \tag{5}$$

where $F(\lambda)$ is the number of incident photons per unit area per unit time (in the unit zone), and $SR(\lambda)$ – the spectral response, and $\lambda$ the wavelength. On the other hand, the spectral response depends on the absorption coefficient $\alpha$, the depth of the junction, the width of the depleted area [11-18].

The absorption coefficient $\alpha$ represents the ability of the material to absorb light of a given wavelength and depends on the size of the energy gap of the material as well as on the density of states in the breakdown and valence zone. For materials with an indirect energy gap (for example Si) the generation of charge carriers occurs deep below the surface (~10 μm) [19-24].

The analysis of the dependence of the open circuit voltage on the parameters of the solar cell is based on the expression that defines $V_{\mathrm{oc}}$ from the I-V characteristic

$$V_{\mathrm{oc}} = \frac{nkT}{q}\ln\left(\frac{J_{\mathrm{sc}}}{J_0} + 1\right) \tag{6}$$

Equation (6), obtained from eq. (2) when the output current is equal to zero (*i.e*. the resistance of the consumer is very high), can be written

$$V_{\mathrm{oc}} \approx \frac{nkT}{q}\ln\left(\frac{J_{\mathrm{sc}}}{J}\right) \tag{7}$$

## EXPERIMENT

The experiment is based on recording the *I-V* characteristic of a solar cell with a variation of measurement parameters: type of solar cell, type of lighting, intensity of lighting, type of radioactive radiation, energy and dose of radioactive radiation. During the experiment, silicon solar cells with dimensions of 55 mm × 22 mm, based on monocrystalline and polycrystalline silicon, were used, fig. 1. The *I-V* characteristics were recorded under white

**Figure 1. A sample of the tested commercial cell**

light. The samples were exposed to radioactive radiation in the form of a point neutron source (Pu-Be) and a gamma radiation source ($^{60}$Co).

In all the samples, the final value of the internal series resistance is $R_s$. The value of this resistance is obtained by numerical differential *I-V* characteristic

$$r = \frac{1}{\dfrac{d1}{\mathrm{d}V}}, \text{ for } I \to 0 \tag{8}$$

Since the solar cell is used as an electric generator, the internal series resistance is as small as possible during manufacturing. The series resistance of the solar cell depends on the depth of the junction, the concentration of impurities in the p and n regions, as well as the configuration of the contacts on the front surface [25, 26]. Typical series resistance values for solar cells with a standard front contact are between 0.4 Ω and 0.7 Ω [27]. For the purpose of analyzing the parameters of the solar cell depending on the applied radiation dose, this resistance was eliminated by introducing the $R_s$ value in the *I-V* equation of the solar cell. In this way, the corrected *I-V* characteristics are obtained, fig. 2.

The calculated initial resistance values $R_s$ of the sample before irradiation ranged between 0.64 Ω and 6.78 Ω. For each sample, it was observed that a lower value of $R_s$ corresponds to a higher illuminance. It was also observed that with the size of the irradiated samples, there is an increase in the resistance $R_s$, which is dependent on the applied radiation dose. The experiments were performed under well-controlled laboratory conditions. Only licensed instruments were used. The combined measurement uncertainty was less than 5 % [29-33].

## RESULTS

Figure 3 illustrates the variation of solar cell efficiency as a function of the absorbed gamma radiation

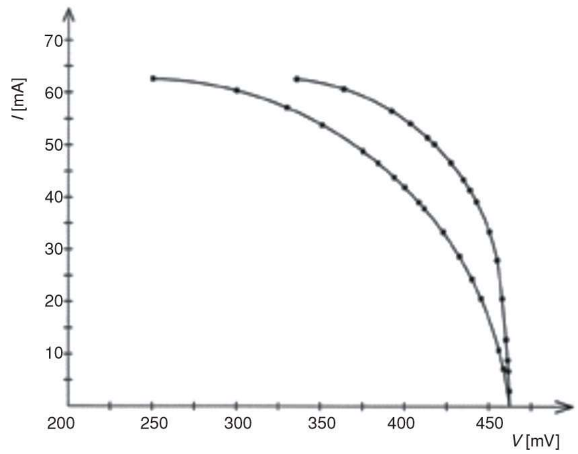


**Figure 2. Uncorrected and corrected *I-V* characteristic for sample $S_2$, white light, without correction, with correction**

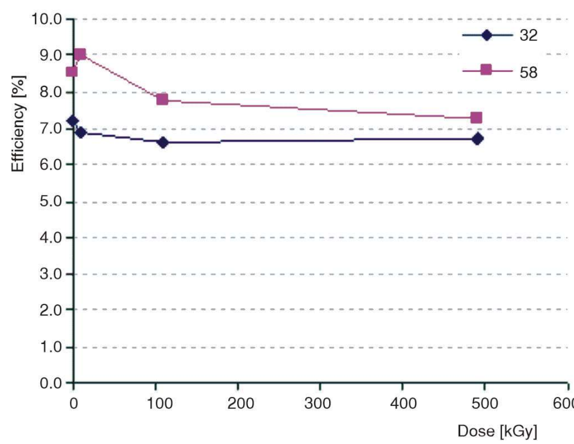


**Figure 3. Graph of dependence of efficiency on received dose of gamma radiation for sample $S_2$; white light, 32 $Wm^{-2}$, 58 $Wm^{-2}$**

dose at two distinct illumination levels. The observed fluctuations in efficiency lack a discernible physical pattern and cannot be reliably modeled mathematically. Moreover, these efficiency changes appear irregular and exhibit no consistent trend.

Figure 4 shows the dependence of the cell efficiency on the received two doses of gamma radiation with two levels of cell brightness. In this experiment, the cell received a slightly higher dose of radiation and it clearly shows a decrease in efficiency. The relative change is greater after the first step of irradiation, which is consistent with the change in $V_{OC}$ and $I_{SC}$ values as well as the fill factor.

Figures 5 and 6 show the dependences of cell efficiency on the received dose of gamma radiation for two samples at two levels of cell brightness. These samples received higher cumulative doses of radiation. In both samples, a sharp relative decrease in efficiency is noticeable after the first step of irradiation and a slightly less pronounced decrease in efficiency after the second step of irradiation.

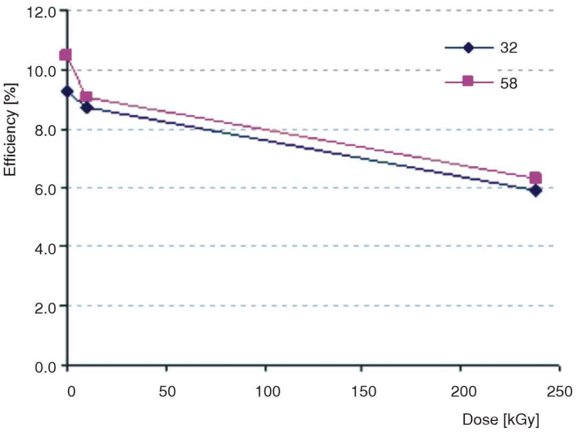


**Figure 4. Graph of dependence of efficiency on received dose of gamma radiation for sample $S_5$; white light, 32 $Wm^{-2}$, 58 $Wm^{-2}$**

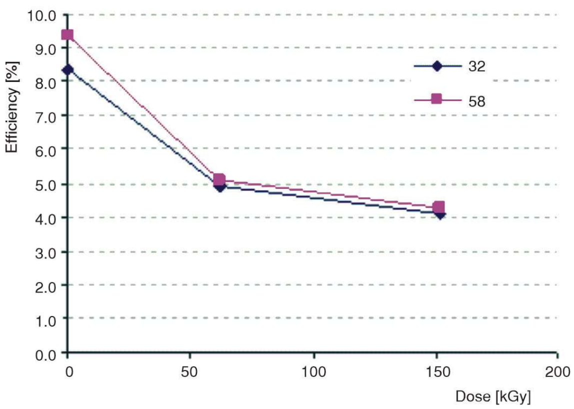


**Figure 5. Graph of dependence of efficiency on received dose of gamma radiation for sample $S_1$; white light, 32 $Wm^{-2}$, 58 $Wm^{-2}$**

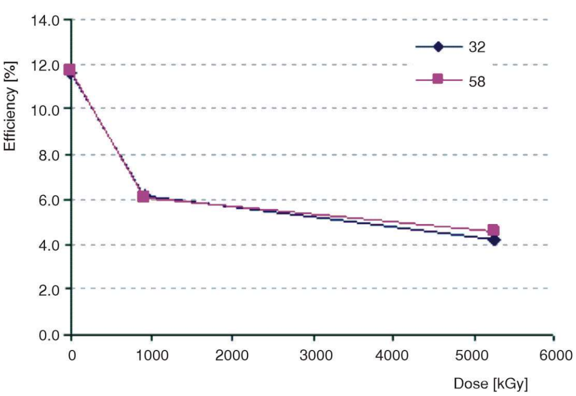


**Figure 6. Graph of dependence of efficiency on received dose of gamma radiation for sample $S_6$; white light, 32 $Wm^{-2}$, 58 $Wm^{-2}$**

Figure 7 shows the dependence of the cell efficiency on the received dose of gamma radiation for the sample for the initial level of cell illumination. As in the previous two cases, a sharp drop in efficiency is noticeable after the first step of irradiation and a smaller drop in efficiency after the second step of irradiation.

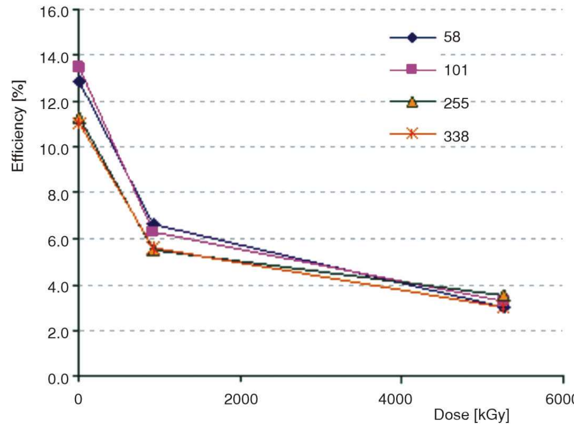


**Figure 7. Graph of dependence of efficiency on received dose of neutron radiation for sample $S_6$, white light, 32 $Wm^{-2}$, 101 $Wm^{-2}$, 255 $Wm^{-2}$, 338 $Wm^{-2}$**

Figures 8 and 9 show the dependences of cell efficiency on the received dose of gamma radiation of samples $S_7$ and $S_3$ at two levels of cell brightness. A sharp initial decrease in efficiency after the first step of irradiation and a significantly less pronounced decrease after the second step of irradiation are also noticeable in these samples.

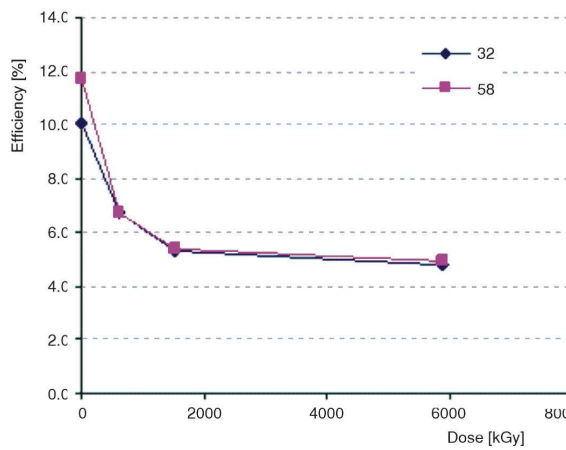


**Figure 8. Graph of dependence of efficiency on received dose of neutron radiation for sample $S_7$ white light, 32 $Wm^{-2}$, 58 $Wm^{-2}$**

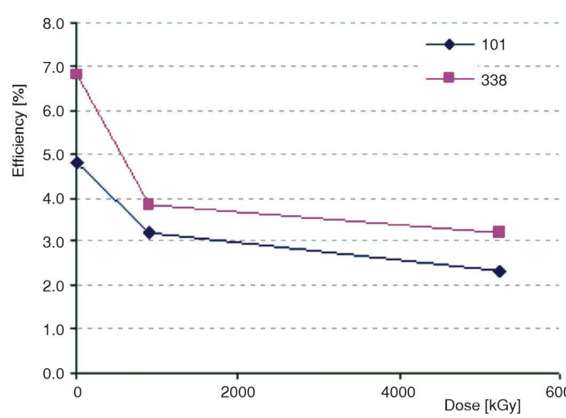


**Figure 9. Graph of dependence of efficiency on received dose of neutron radiation for sample $S_3$ white light, 101 $Wm^{-2}$, 338 $Wm^{-2}$**

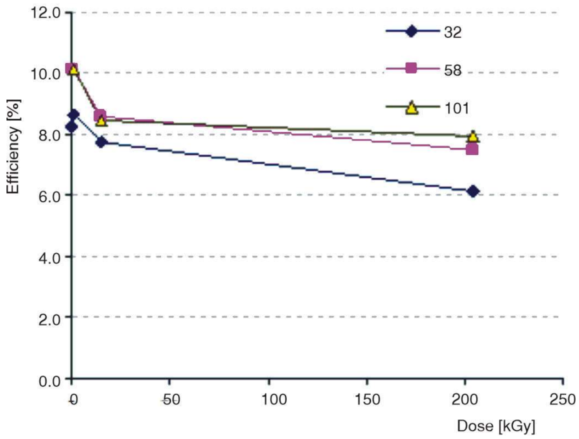


**Figure 10. Graph of dependence of efficiency on received dose of neutron radiation for sample $S_4$, monochromatic light, 32 $Wm^{-2}$, 58 $Wm^{-2}$, 101 $Wm^{-2}$**

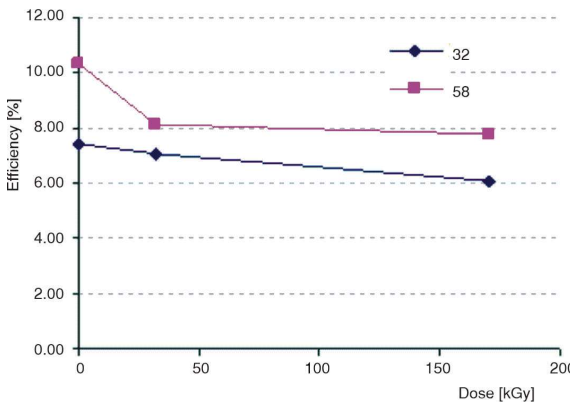


**Figure 11. Graph of dependence of efficiency on received dose of neutron radiation for sample $S_8$, monochromatic light, 32 $Wm^{-2}$, 58 $Wm^{-2}$**

Figures 10 and 11 show the dependences of cell efficiency on the received dose of neutron radiation for the sample at three (respectively two) levels of illumination. In the case of samples $S_4$ and $S_8$, a repetition of the trend from most previous cases of efficiency reduction is noticeable, which is less pronounced in the last step of irradiation.

Based on the presented results, it can be concluded that the efficiency of the photovoltaic cell decreases faster if it receives a dose of neutron radiation before the test than if it receives a dose of gamma radiation. The decrease in photocell efficiency is even greater if the received dose of gamma or neutron radiation is higher. The efficiency drop itself does not depend significantly on the type of light with which the measurement is made. It can be assumed that the effects of radiation on the efficiency of the solar a cell would increase significantly if the solar cell received a dose of charged ions.

## CONCLUSION

In a theoretical loss analysis for a silicon solar cell with an ideality factor equal to 1, it is estimated that reflection as a loss mechanism reduces the total input power by 2 %, and shading caused by the overhead catenary reduces it by 4 %. If photon absorption occurs in the self-reflective layer or at defects, those photons do not contribute to the generation of charge carriers, resulting in power losses of less than 1 %. Photons that reach the interior of the solar cell may have energy greater than the bandgap of the material (E_photon > Eg). The excess energy above the bandgap cannot be used in photovoltaic conversion, representing a loss of up to 30 %. On the other hand, photons with energy less than the bandgap (E_photon < Eg) pass through the solar cell without generating electron-hole pairs, which also causes losses.

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## AUTHORS' CONTRIBUTIONS

N. M. Kartalović conceived the research idea, supervised the experimental work, participated in the interpretation of results, and drafted the manuscript. A. R. Jusić contributed to the experimental planning, data processing and analysis, and participated in writing and technical editing of the manuscript. U. D. Kovačević was involved in conducting the experiments under controlled laboratory conditions and was responsible for instrumentation and measurement accuracy. A. I. Vasić assisted in the preparation of the experimental setup, data processing, and preparation of graphical materials for the manuscript.

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## ЕФИКАСНОСТ СОЛАРНИХ ЋЕЛИЈА У УСЛОВИМА ДЕЈСТВА ЕЛЕКТРОМАГНЕТНОГ ИЛИ НЕУТРОНСКОГ ЗРАЧЕЊА

У раду се разматра утицај дозе гама или неутронског зрачења на комерцијалну силицијумску фотонапонску ћелију у условима експлоатације. Ћелије су пре мерења биле озрачене електромагнетним гама зрачењем или неутронским зрачењем. Испитивање је вршено експериментално и теоријски. Експерименти су вршени под добро контролисаним лабораторијским условима. Коришћени су искључиво лиценцирани инструменти. Мерна несигурност експерименталног поступка била је мања од 5 %.

*Кључне речи: силицијумска соларна ћелија, гама и неутронско зрачење, ефикасност ћелије*