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Modelling the Influence of Low Energy Electrons Emitted from Pm-147 on the Performance of a Silicon PV Cell

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ABSTRACT: This paper investigated, using 1-D analysis, the effect of low energy electrons emitted from Promethium – 147 (Pm-147) on the performance of a silicon PV cell. The Pm-147 source is chosen due to the penetration depth of beta particles with the average kinetic energy of 62.5 KeV emitted from Pm-147, because at this depth the are able to generate charge carriers right down to the base. The continuity equation of excess minority carrier is solved respectively in the emitter for excess holes and in the base for excess electrons. The analytical expression of the density of electrons and holes for each part of the solar cell is derived and, in turn, the electrical parameters (J_{sc}, Voc, FF, η) of the PV cell are found. The influence of radiation flux on short-circuit current density (J_{sc}), Open circuit voltage (Voc), fill factor (FF) and conversion efficiency (η) are discussed. if we vary the flux of incident particles up to the value of 3.10^{10} cm^{-2}, we achieve a relative increase in the PV Cell conversion efficiency of the order of 0.2743 %.

KEYWORDS: Silicon solar cell, Beta electron, efficiency improvement, low energy electrons, Pm-147 source.

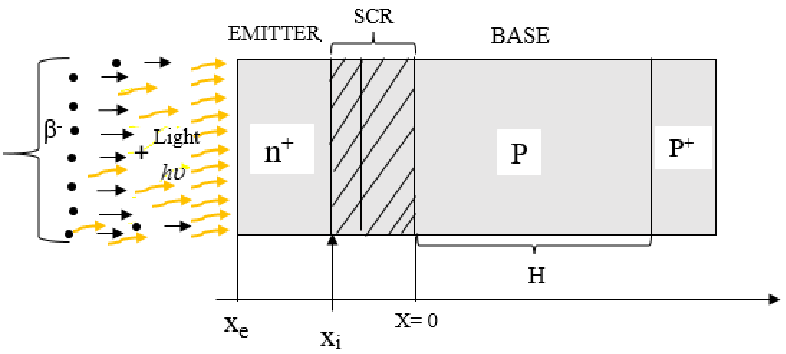
1 INTRODUCTION

The betavoltaic effects refers to the conversion of the energy of electrons from nuclear reactions into electric current through a p-n type semiconductor. A period of operation of up to decades, and also an ability to operate in a range of temperature from -50 to 150 °C, makes the betavoltaic effect an attractive phenomenon for many technological application possibilities such as the components used in the field of telecommunications, particle's detector sensor and implantable medical equipment [1]. Betavoltaic conversion has been intensely studied, whether experimentally or theoretically. The betavoltaic effect, just like several familiar photovoltaic effects are related and have several common characteristics. The energy conversion operation of betavoltaic cells is similar to that of photovoltaic ones. Electron-hole pairs (EHPs) are created by particles beta emitted from radioactive isotopes [2]. In recent years, betavoltaic batteries have become an ideal power source for micro electromechanical systems. Betavoltaic battery aims to use transducers to convert electrical energy, the decay energy of the particle's beta emitted by the radioisotope source.

These batteries have many advantages (long service life, high anti-interference capacity, small size, lightness, high energy density, easy miniaturization and integration) that make them research interest centers in the field of micro-energy [3]. Thus, considering the capacity of beta electrons to generate charge carriers, their low probability of creating defects in the material [4] and also their depth of penetration, we trend to find out their influence on the electrical parameters of the PV cell by carried out this theoretical study.

2 THEORETICAL BACKGROUND

This study focuses on a polycrystalline silicon solar cell under multispectral illumination and irradiated by beta electrons from a Pm-147 source. We present on Figure 1, the cross-section of an n^+-p-p^+ silicon solar cell, where β^- is beta particle emitted from radioactive isotopes (Pm-147). The n^+ doped region is emitter (Nd = 2.10^{18}cm^{-3}), p doped region is base (Na= 5.10^{16}cm^{-3}) and p^+ is the rear region in contact with the base which is responsible for the back surface field (BSF).



On this figure, Xi is junction position, Xe is the position of solar cell's front side and H is the base thickness. From the beta spectrum of Pm-147, we assume that the radiation of beta particles will generate charge carriers not only in the emitter, but also in the space charge region and as well as in the base.

Fig. 1. ***n^+-p-p^+ silicon solar cell simultaneously illuminated and irradiated***

As for solar illumination, it only generates the charge carriers in the base. Considering the small thicknesses of the emitter and space charge region (SCR), we will simply assume that the Voc of the entire cell is equal to that of the base of the cell. We also consider that only beta particles having an energy equal to that of the average energy to generate the charge carriers.

By solving the minority-carrier diffusion equation we can obtain the analytical expression of some electrical parameters like: short-circuit current Jsc), open circuit voltage (Voc), fill factor (FF) and PV cell conversion efficiency (η).

2.1 SHORT CIRCUIT CURRENT DENSITY OF THE PV CELL (JSC)

The total Jsc of the silicon PV cell under beta flux incidence is assumed to be the sum of short-circuit currents from three regions:

- **Short circuit current density of the emitter (J_{Esc})**

In the emitter, the minority charge carriers are holes and are essentially generated by the beta electrons. So, the diffusion of the minority carrier in the emitter is given by the equation (1) below:

$$\frac{d^2\delta_p(x)}{dx^2} - \frac{\delta_p(x)}{L_p{}^2} = -\frac{1}{D_p}G(x) \tag{1}$$

$\delta_p(x)$ is the hole's concentration with nuclear radiation, respectively, *Dp* refers to hole diffusion coefficient, and *G (x)* refers to the electron-hole generation rate. The expression of *G (x)* is derived from equation (2) [5]

$$G(x) = \frac{E}{\varepsilon}\alpha\phi(1-R)e^{-\alpha(x-x_e)} \tag{2}$$

Where *E* is the kinetic energy of beta particles, *α* is the absorption coefficient of silicon, *φ* is the incident beta flux, *R* is the reflection coefficient of silicon, and *ε* is the average energy necessary for the production of the pair of electron and hole.

The expression of *ε* is presented in equation (3) [6]:

$$\varepsilon = 2{,}8E_g + 0{,}5 \tag{3}$$

Eg is the bandgap of semiconductor (silicon). The boundaries conditions used to solve equation (1) are expressed in equations (4) and (5):

$$\left.\frac{d\delta_p(x,\phi)}{dx}\right|_{x=x_e} = S_p \frac{\delta_p(x_e,\phi)}{D_p} \tag{4}$$

$$\delta_p(x_i,\phi) = 0 \tag{5}$$

Sp is the surface recombination velocity. *Dp* is the hole diffusion coefficient and it value is *Dp = 2.66 cm²/s*. From these previous considerations we derived the expression of the J_{Esc} in the emitter from equation (6):

$$J_{Esc}(\phi) = \lim_{S_p \to \infty} J_E(S_p,\phi) \tag{6}$$

Where

$$J_E(S_p;\phi) = -qD_p \left.\frac{d\delta_p(x)}{dx}\right|_{x=x_i} \tag{7}$$

$$J_{Esc}(\phi) = -qD_p \left[\begin{array}{l} \lambda_p \dfrac{\alpha\left(\sinh(\lambda_p x_i)\dfrac{E\phi(1-R)}{D_p\varepsilon(\lambda_p{}^2-\alpha^2)} - \sinh(\lambda_p x_e)\dfrac{E\phi(1-R)e^{-\alpha(x_i-x_e)}}{D_p\varepsilon(\lambda_p{}^2-\alpha^2)}\right.}{\sinh(\lambda_p x_i)\left[-\cosh(\lambda_p x_e)\right] - \cosh(\lambda_p x_i)\left[-\sinh(\lambda_p x_e)\right]}\sinh(\lambda_p x_i) + \\ \lambda_p \dfrac{-\dfrac{\alpha E\phi(1-R)e^{-\alpha(x_i-x_e)}}{D_p\varepsilon(\lambda_p{}^2-\alpha^2)}\left[-\cosh(\lambda_p x_e)\right] - \cosh(\lambda_p x_i)\dfrac{\alpha\phi E(1-R)}{D_p\varepsilon(\lambda_p{}^2-\alpha^2)}}{\sinh(\lambda_p x_i)\left[-\cosh(\lambda_p x_e)\right] - \cosh(\lambda_p x_i)\left[-\sinh(\lambda_p x_e)\right]} \\ -\dfrac{\alpha^2 E}{D_p\varepsilon(\lambda_p{}^2-\alpha^2)}\phi(1-R)e^{-\alpha(x_i-x_e)} \end{array} \right] \tag{8}$$

- **Short circuit current density of the base (J_{Bsc})**

In the base, the minority charge carriers are electrons and are generated by both beta electrons and solar illumination. So, the equation (9) below characterize the minority-carrier diffusion:

$$\frac{d^2\delta_n(x)}{dx^2} - \frac{\delta_n(x)}{L_n{}^2} = -\frac{1}{D_n}G_2(x) \tag{9}$$

Where *G_2 (x),* the electrons generation rate:

$$G_2(x) = \frac{E}{\varepsilon}\alpha\phi(1-R)e^{-\alpha(x-x_e)} + \sum_{i=1}^{3} a_i e^{-b_i x} \tag{10}$$

The coefficients *ai* and *bi* are deducted from the modelling of the generation rate of the entire spectrum of solar radiation under *AM 1.5*. The boundaries conditions for solving equation (9) are expressed equations (11) and (12):

$$\left.\frac{d\delta_n(x,\phi)}{dx}\right|_{x=0} = S_f \frac{\delta_n(0,\phi)}{D_n} \tag{11}$$

$$\left.\frac{d\delta_n(x,\phi)}{dx}\right|_{x=H} = -S_b \frac{\delta_n(H,\phi)}{D_n} \tag{12}$$

Sf is the junction dynamic velocity and *Sb* characterize carriers losses at the rear side of the base. *Dn* refers to electron diffusion coefficient and its value is *Dn = 27 cm²/s*. The J_{Bsc} is derived from equation (13):

$$J_{Bsc}(\phi) = \lim_{S_f \to \infty} J_B(S_f,\phi) \tag{13}$$

where

$$J_B(S_f,\phi) = qD_n \left.\frac{d\delta_n(x)}{dx}\right|_{x=0} \tag{14}$$

$$J_{Bsc}(\phi) = qD_n \left[\lambda_n \left\{ \frac{\left[\sum_{i=1}^{3} \frac{a_i e^{-b_i H}}{D_n(\lambda_n^2 - b_i^2)}\left(-\frac{S_b}{D_n}+b_i\right) + \frac{E\phi(1-R)e^{-\alpha(H-x_e)}}{D_n\varepsilon(\lambda_n^2-\alpha^2)}\left(-\alpha\frac{S_b}{D_n}+\alpha^2\right)\right] - \left(\lambda_n \sinh(\lambda_n H) + \frac{S_b}{D_n}\cosh(\lambda_n H)\right)\left[\sum_{i=1}^{3}\frac{-a_i}{D_n(\lambda_n^2-b_i^2)} - \frac{E\phi e^{\alpha x_e}(1-R)}{D_n\varepsilon(\lambda_n^2-\alpha^2)}\alpha\right]}{\left[\lambda_n\cosh(\lambda_n H) + \frac{S_b}{D_n}\sinh(\lambda_n H)\right]} \right\} - \sum_{i=1}^{3}\frac{a_i b_i}{D_n(\lambda_n^2-b_i^2)} - \frac{\alpha^2 E\phi(1-R)}{D_n\varepsilon(\lambda_n^2-\alpha^2)} \right] \tag{15}$$

- **Short circuit current density of the space charge region (J_{Dsc})**

The charge carriers generated in depletion region are drawn out of this area very quickly due to the space charge region (SCR) electric field [7]. Thus, the equations (16) below gives the J_{Dsc} of this region.

$$J_{Dsc}(\phi) = \frac{qE}{\varepsilon}\phi(1-R)\left(e^{\alpha x_e} - e^{-\alpha(x_i - x_e)}\right) \tag{16}$$

- **Short circuit current density of the solar cell (Jsc)**

As mentioned previously, the total Jsc of the PV cell is the sum of short-circuit currents from the three regions ie emitter, base and junction and this current is expressed by the equation (17):

$$J_{sc}(\phi) = J_{Esc}(\phi) + J_{Dsc}(\phi) + J_{Bsc}(\phi) \tag{17}$$

2.2 OPEN CIRCUIT VOLTAGE OF THE SOLAR CELL (VOC)

From Boltzmann approximation the expression of voltage is derived and it is expressed by equation (18):

$$V(S_f,\phi)=\frac{k_B T}{q}\ln\left(\frac{\delta_n(0,\phi)}{n_0}+1\right) \tag{18}$$

The expression of equation (18) lead to the expression of the Voc through the relation 19:

$$V_{oc}=V(S_f,\phi) \text{ for } S_f=0\ cm.s^{-1} \tag{19}$$

Thus, equation (20) gives the expression of the Voc:

$$V_{oc}(\phi)=V_T\times\ln\left[1+\left\{\frac{\begin{array}{l}\left[\lambda_n\cosh(\lambda_n H)+\frac{S_b}{D_n}\sinh(\lambda_n H)\right]\times\left[\sum_{i=1}^{3}\frac{-a_i b_i}{D_n(\lambda_n^2-b_i^2)}-\frac{E\phi(1-R)\alpha^2}{D_n\varepsilon(\lambda_n^2-\alpha^2)}\right]\\+\lambda_n\left[\sum_{i=1}^{3}\frac{a_i e^{-b_i H}}{D_n(\lambda_n^2-b_i^2)}\left(-\frac{S_b}{D_n}+b_i\right)+\frac{E\phi(1-R)e^{-\alpha(H-x_e)}}{D_n\varepsilon(\lambda_n^2-\alpha^2)}\left(-\frac{\alpha S_b}{D_n}+\alpha^2\right)\right]\end{array}}{\frac{\lambda_n}{n_0}\left[\lambda_n\sinh(\lambda_n H)+\frac{S_b}{D_n}\cosh(\lambda_n H)\right]}+\sum_{i=1}^{3}\frac{a_i}{n_0 D_n(\lambda_n^2-b_i^2)}+\frac{E\phi\alpha(1-R)e^{\alpha x_e}}{n_0 D_n\varepsilon(\lambda_n^2-1)}\right\}\right] \tag{20}$$

2.3 Fill Factor (FF) and Conversion Efficiency (H)

The FF is a crucial data which makes it possible to evaluate for the degree of ideality of the curve of the J-V characteristic, i.e. the performance of the beta-photovoltaic generator. The equation (21) below gives its expression:

$$FF(\phi)=\frac{V_p(\phi)\cdot J_p(\phi)}{V_{oc}(\phi)\cdot J_{sc}(\phi)} \tag{21}$$

where V_p (φ) and J_p (φ) are respectively voltage and current at the maximum power point.

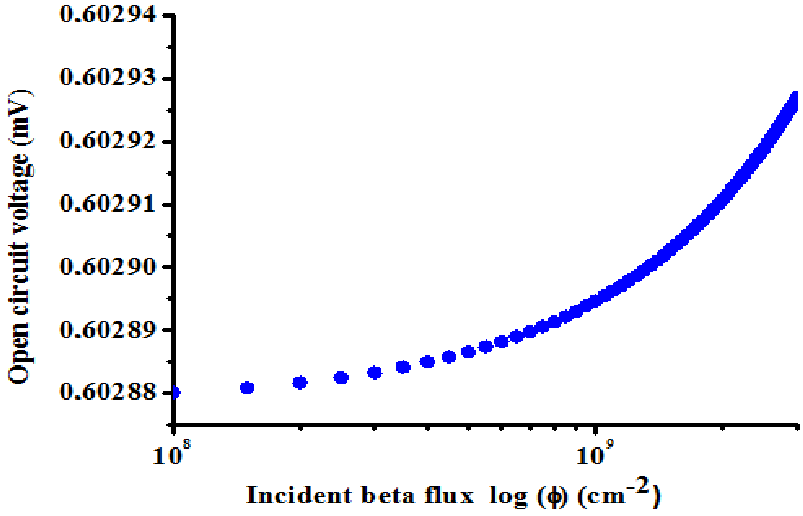
Equation (22) gives the expression of the η:

$$\eta(\phi)=\frac{P_{el\max}(\phi)}{Pinc} \tag{22}$$

In this expression, P_{elmax} (φ) is the maximum power that can be extracted from solar PV cell and Pinc characterize is the power of the incident light used for the illumination of the PV cell (Pinc=1000 W/m^2).

3 Results And Discussion

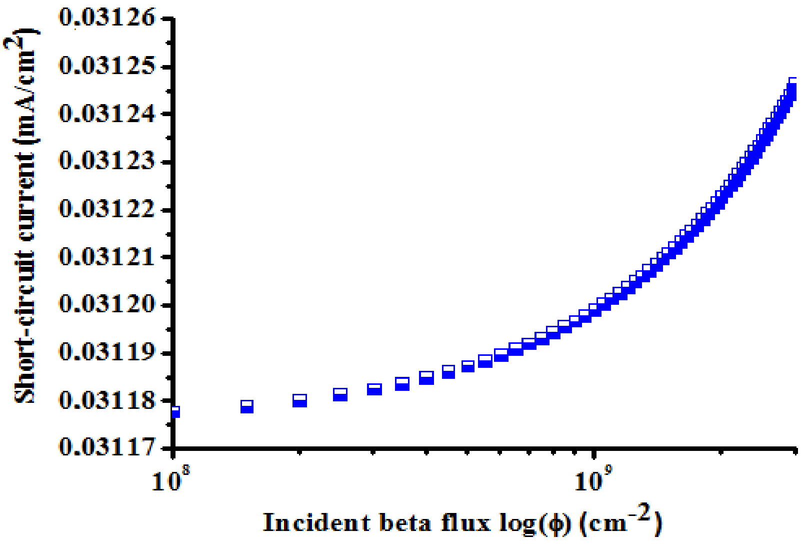
We observe through the equation (20) that the Voc is function of the incident beta flux. Figure 2 plots the Voc versus the flux of incident beta.



It appears on figure 2 that, the Voc increases when the incident beta flux increases. This behaviour means that, the concentration of the carriers in the bulk of the solar cell base increase with the increase of the beta flux incidence.
The increase of the concentration of the electrons in the base results of the extra supplementary electrons generated by the flux of beta particles on the PV cell.

Fig. 2. Voc versus incident beta flux

In the same way, through the expression of the Jsc expressed in equation (17), we present in figure 3, the influence of the incident beta particles flux on the Jsc.



We observe on this figure that the Jsc increases with the increase of incident beta flux. The increase of the Jsc means that the quantity of carriers that cross the junction of the PV cell increases. This situation is also in accordance with the increase of electrons concentration in the base induced by the increase of the flux of beta particles. If the concentration of the charge carriers in the base increase, the proportion of carriers that can cross the junction will also increase, and then will led to the increase of the Jsc.

Fig. 3. Jsc versus incident beta flux

The FF is a good indicator of the quality of the PV cell (junction quality, series and shunt resistances behaviour). To analyze the effect of the incident beta electrons flux on the PV cell quality, we present in figure 4, the curve of the FF in function of the flux of beta particles.

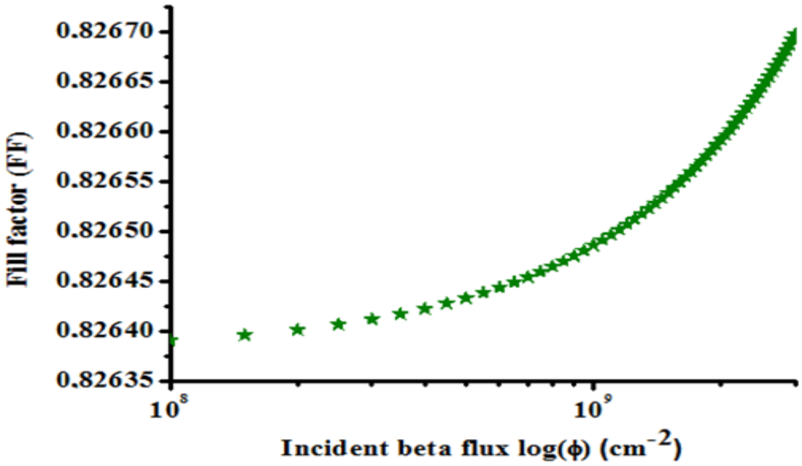


Fig. 4. 4 FF versus incident beta flux

We observe from the curve in figure 4 that the increase of beta electron flux leads to an increase of the PV cell's fill factor. This result suggests an improvement of the quality of the PV cell with the increase of beta electron flux. The η can be considered as one of the most important parameters to characterize the quality of a PV cell.

To verify the result related to the increase of the FF under the effect of beta electrons flux, we studied the effect of beta electrons flux on the η of the PV cell. Through equation (22), we plot in figure 5, the η of the solar cell as a function of beta particles flux.

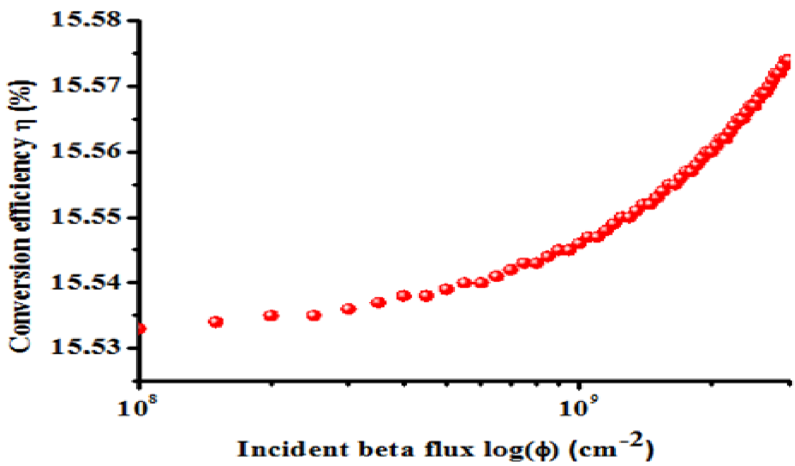


Fig. 5. η versus incident beta flux

It appears on the curve of figure 5 that the η increases when the flux of beta particles increases. This result is in accordance with those of figures 3 and 4 and confirm the improvement of the PV cell's quality with the increase of beta electron flux. The supplementary electrons generated by beta electrons contribute to increase the Jsc, the FF and the η.

4 Conclusion

In this study, the effect of beta electrons with energy of 62.5 KeV, on the performance of an illuminated silicon PV cell has been studied. The new expressions of electrical parameters (J_{sc}, Voc, FF, η) obtained through the resolution of continuity equation, are functions of the flux of beta electrons, and they increase with the increase of this one. The increase of the Voc means that the concentration of the carriers in the base of the PV cell increases with the increase of beta electrons flux. The increase in the J_{sc} is due to the increase of quantity of carriers that crosses the junction. According to the FF and the η, their increases means an improvement in the quality of the PV cell. For beta particles with kinetic energy of 62.5KeV, and for the flux values ranging from 0 to 3.10^{10} cm^{-2}, the η achieved a relative increase of about 0.2747 %. We can confirm that the low energy beta radiation has a positive influence on the performance of an illuminated solar cell.

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