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Polycrystalline Silicon Solar Cell p-n Junction Capacitance Behavior Modelling under an Integrated External Electrical Field Source in Solar Cell System

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Abstract

The state of the p-n junction is very important to explain the performances of a solar cell. Some works give the influence of the electric field on the junction capacitance. However, these works do not relate the quality of the p-n junction under the electic field. The present manuscript is about a theoretical modelling of the p-n junction capacitance behavior of the polycrystalline silicon solar cell under an integration of the external electrical field source. An external electrical source is integrated in a solar cell system. The electronic carriers charge generated in the solar cell crossed mainly the junction with the great strength external electrical field. In open circuit, this crossing of the electronic charge carriers causes the thermal heating of the p-n junction by Joule effect. The p-n junction capacitance plotted versus the junction dynamic velocity and the photo-voltage for different external electrical fields. The electric field causes the decrease of the photo-voltage mainly the open-circuit photo-voltage. The decrease of the photo-voltage translates the narrowing of the Space Charge Region (SCR). The average value of the external electric field used in this study is not sufficient to cause the breakdown of the p-n junction of the solar cell system under integration of the external electrical field production source. The increase of the electrical field causes rather the narrowing of the SCR. That can provide an improvement of the solar cell's electrical outputs.

Keywords

Polycrystalline Silicon Solar Cell, Space Charge Region, Photo-Current, Photo-Voltage, Conversion Efficiency, p-n Junction Capacitance, External Electrical Field

1. Introduction

The electricity accessibility is a real difficulty for many developing countries. Today, the photovoltaic (PV) solar energy presents a better opportunity for the providing of the energy for these countries. But, the conversion efficiency being around 26% [1] of the PV solar cell which is the fundamental component of the PV system is weak compared to the needs. However, many researches about the improvement of the performance of the outputs electrical parameters of the PV solar cell exist. In previous paper, we have analyzed the behavior of a single-crystalline silicon solar module versus the external load variation [2]. It has been observed that an increase of the external load resistance caused an increase of the voltage while the current decreases. This study proposes that for the real operation condition of a domestical PV installation, it is better to use the external load resistance smaller than the real supported capability of the PV module. The integration of an additional electric field source in the solar cell has presented an improvement under monochromatic illumination [3] and under sun light illumination [4]. These studies have shown the possibility to increase the fill factor, the conversion efficiency and others outputs of a crystalline silicon solar cell by addition of an external electrical field. This improvement observed is caused by the increase of the crossing of the carrier's charge through the p-n junction. Zerbo *et al.* [5] has shown an influence of the junction dynamic velocity on the p-n junction. Note that the junction dynamic velocity translates the flow of the carriers' charge which can cross through the p-n junction. Barro *et al.* [6] have shown that the increase of the doping level causing the decrease of the junction capacitance because of the increase of the recombination effect caused by the high doping. It is presented in this work an analytical model for the quasi-static capacitance of the space-charge region of p-n junction devices to provide an understanding of the physics related to storage of mobile holes and electrons in the junction space-charge region. The behavior under solar illumination and under gamma radiation of a single-crystalline silicon solar PV module had been studied by Ouedraogo *et al.* [7]. In this study, under the extremely low values of the radiation dose, the solar PV module shown some improvements of the photo-current and the electric power while the photo-voltage is being constant. The great values of the radiation dose can cause the recombination of the electron-hole in the PV module. Electric field and electromagnetic field have caused the increase of the p-n junction crossing by the carrier charge [8]. There is in this case an addition of the external electrical field to the p-n junction electric field [9]. It has been also proved that the space-charge region reduces with the increase of the electric field [6]. A need exists then to provide a better explanation about electrical field effect on the p-n junction capacitance to meet the better requirements for polycrystalline silicon solar cell efficiency after an integration of an electrical field source in the PV system. This paper is about a theoretical modelling of the capacitance of a polycrystalline silicon PV solar cell after an integration of an electrical field source in the PV solar cell system. Section 2 gives the theoretical background and the description of integration of the external electrical field. The results and discussion is presented in Section 3. The conclusions are in the last section of this work.

2. Methods and Theories

2.1. Assessment of the External Electrical Field

The $n^+ - p - p^+$ polycrystalline silicon solar cell structure has been chosen for this work. This work is carried out in the theory of quasi-neutral base (QNB) which is given by Fossum *et al.* [10], assumes that the intrinsic electric field in the base's region can be neglected. The emitter contribution will be neglected and the base of the solar cell is assumed to be the real center of all the generation phenomenon's and the recombination phenomenon's. The integration of electrical field source in PV system is presented on **Figure 1** [3]. The integration of the external electrical field is the addition of other solar cells to generate the open circuit voltage. The other solar cells will be connected to the aluminum planar frames which will be considered as armatures (anode and cathode). In the next, a solar cell will be introduced in the region where there is a created electric field. The variation of the gap between the two armatures makes it possible to vary the external electric field. The electrical field can be gotten following the number of the solar cells used to create the open-circuit photo-voltage. The external electrical field will be added to the electric field of the space charge region [9]. But for the present model, the slop angle of the external electrical field is a real challenge of this assumption. The inequality of the height between the two armatures can allow to put a tilt angle between both armatures as shows **Figure 2**.

The electric field of the space charge region $\vec{E}_{SCR}$ is given by the different doping level between the emitter (*n*-type) and the base (*p*-type). It will not be

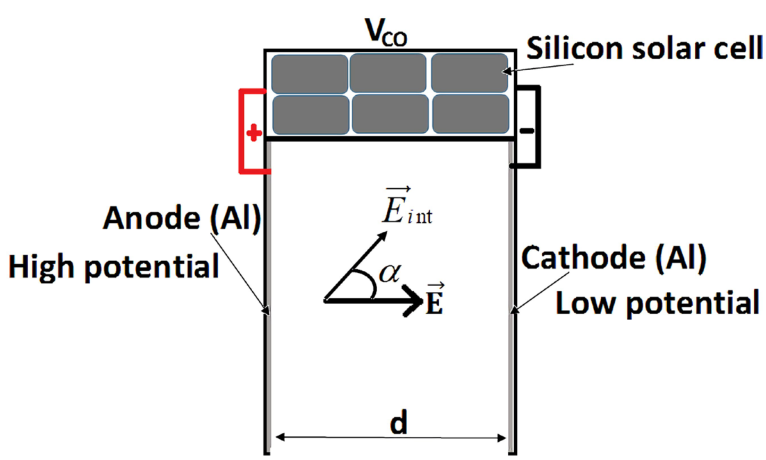

Figure 1. Integration of the electrical field source into solar cell or solar module [3] [4].

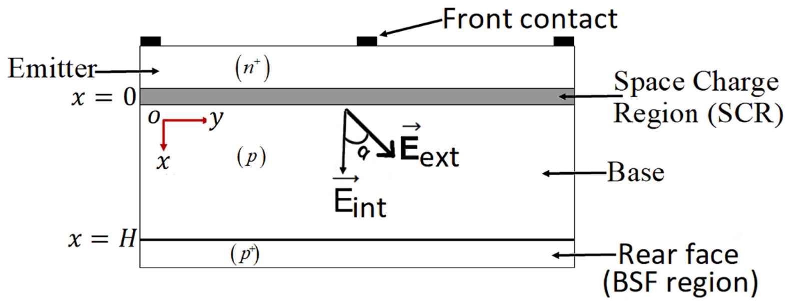

Figure 2. Representation of the space charge region and external electrical fields coupling on a PV solar cell.

discussed in this paper how the $\vec{E}_{SCR}$ is determinated. The external electrical field is given as following:

$$\vec{E}_{ext} = E_{ext}\cos(\alpha)\vec{e}_x \quad (1)$$

where $\alpha \in \left[0, \frac{\pi}{2}\right[$. The maximum strength of the external electrical field is obtained for $\alpha = 0\,\text{rad}$. But, for this angle value, the external electrical field can deflect the generated electrons. In fact, $\vec{E}_{SCR}$ and $\vec{E}_{ext}$ will be perpendicular. However, when we take into account the orientation and inclination in the northern hemisphere, we have in Burkina Faso an average angle of 15˚ which is used for the PV system installation. Then, $\cos(15^\circ) = 0.965 \approx 1$. For instant, this study will be carried out when $\cos(15^\circ) \approx 1$, the experimental studies will allow to deepen the investigations. The external electric field strength is then provided by [2] [4]:

$$E(L_n, n, d) = \frac{nV_{ph_{CO}}(L_n)}{d} \quad (2)$$

where d and n give respectively the distance between the two armatures and the number of the solar cells used to create the $V_{ph_{CO}}(L_n)$. Table 1 provides some values of the electrical field for $V_{ph_{CO}}(L_n)$ given by one solar cell *i.e.* $n = 1$.

Table 1 presents a diminution of the electrical field with the increase of the distance between the two armatures of the production source of this electric field. The next subsection will give the different theories and calculations about p-n junction capacitance.

2.2. Assessment of the p-n Junction Capacitance

The rebalancing of the charges is due to the fact that if a space-charge is produced locally, the resulting electrostatic potential generates at each space-charge a potential energy much higher than the average thermal energy. This space-charge then quickly attracts a charge of opposite sign and restores electronic neutrality in the space-charge region [11]. This study will be limited to the case of the abrupt junction [12], with a partition surface of the conductive areas P and N which are planar. We can say that the Space-charge region (SCR) in p-n junction region

Table 1. External electrical field for different distances between the planar armatures ($L_n = 150\ \mu\text{m}$, $D_n = 26\ \text{cm}^2 \cdot \text{s}^{-1}$, $\mu_n = 1000\ \text{cm}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$, $H = 300\ \mu\text{m}$, $S_b = 5 \times 10^4\ \text{cm} \cdot \text{s}^{-1}$).

Distance d (m)	E ($\text{V} \cdot \text{m}^{-1}$)
1	55.2
2	27.6
3	18.4
4	13.8
5	11.0
$d \to +\infty$	0.0

can be assumed as a dielectric between the both conductive areas [13]. The two sites from emitter to base of p-n junction will be so considered as a capacity. The reverse biased p-n junction therefore behaves as a capacity [12]. In this capacity, there is an electrical field which is created in the SCR. The field lines will be parallel to $\boldsymbol{E}_{SCR}$ and perpendicular to two conductive areas [14]. The capacitance will be so expressed as following equation [6] [9] [12] [15] [16].

$$C = \frac{\text{d}Q}{\text{d}V_{ph}} \tag{3}$$

where Q and V_{ph} are respectively the total quantity charge of each armature of the capacity and the photo-voltage. $\text{d}Q$ can be written:

$$\text{d}Q = q\text{d}\delta(0) \tag{4}$$

And V_{ph} is given by Equation (5) [6] [9] [12] [15] [16]

$$\text{d}V_{ph} = \frac{V_T \text{d}\delta(0)}{n_0 + \delta(0)} \tag{5}$$

where $n_0 = \frac{n_i^2}{N_B}$ and $V_T = \frac{k_B T}{q}$ is the thermal voltage with q, T and k_B respectively being the electronic charge, absolute temperature, and Boltzmann's constant. At 300K, $V_T = 26\ \text{mV}$. $\delta(0)$ gives the excess minority carriers (electrons) density photogenerated in the base region at $x = 0$. The different assumptions about 1D model and the calculations of $\delta(0)$ are provided by Ouedraogo *et al.* [3] [4]. In the next section, it will be presented the results and the discussions about the evolution of the capacitance versus external electrical field.

3. Results and Discussions

This section is about the density of the carrier's charge in open-circuit and the short-circuit situations. It is about also the capacitance versus the junction dynamic velocity and the photo-voltage.

3.1. Influence of the External Electrical Field on Electrons Flow

Figure 3 presents the evolution of the carrier's charge density in function of the base depth in open-circuit state.

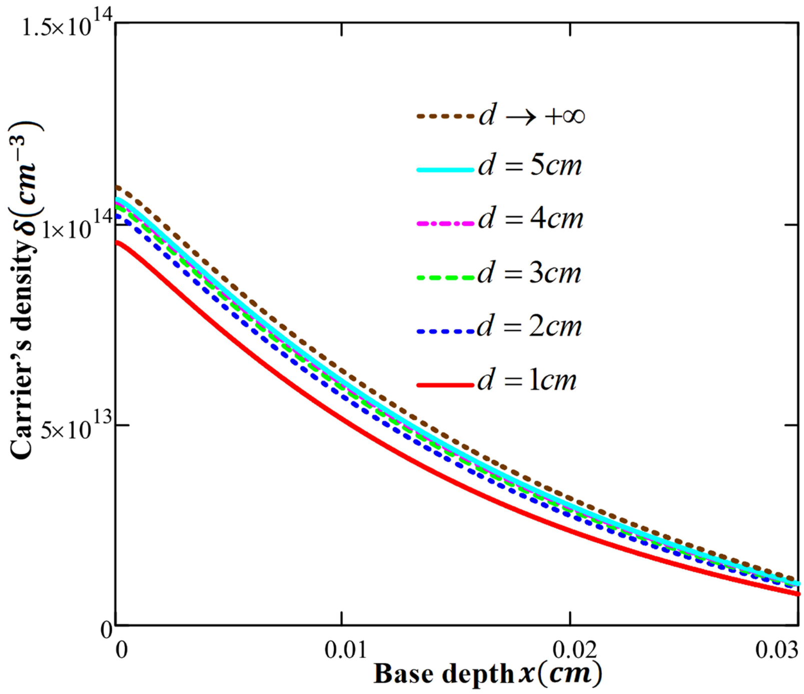

Figure 3. Excess minority carriers (electrons) density photogenerated in the base region in open-circuit versus base depth for different distances ($L_n = 150\ \mu\text{m}$, $D_n = 26\ \text{cm}^2 \cdot \text{s}^{-1}$, $\mu_n = 1000\ \text{cm}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$, $H = 300\ \mu\text{m}$, $S_b = 5 \times 10^4\ \text{cm} \cdot \text{s}^{-1}$, $S_f = 0\ \text{cm} \cdot \text{s}^{-1}$).

The increase of the electric field *i.e.* the decrease of the distance causes the decrease of the carrier's charge density. That translates the crossing of the p-n junction by the carrier's charge especially the flux of electrons. This important crossing of the p-n junction by the electrons can be explained by the kinetic energy provided to the electrons by the electric field. However, in open-circuit state, there is no collection of the electrons in outside of the solar cell. The p-n junction crossing can be explained as a loss due to the Joule effect in p-n junction [3] [4]. The direct consequence is to reduce the photo-voltage mainly the open-circuit photo-voltage. **Figure 4** shows the evolution of the carrier's charge density in short-circuit situation.

Figure 4 presents three levels of evolution. The first level, is the most interesting zone because it provides the quantity of the carrier's charge which can cross the p-n junction and to participate to the external photo-current. The two last levels give the quantity of the carrier's charge which can be stocked in p-n junction or can be recombined in surface or in volume. The increase of the crossing of the p-n junction by the excess minority carrier's charge which is in reality electrons observed in **Figure 4** is caused by the increase of the electric field *i.e.* the decrease of the distance. The analysis of the external electrical field effects on the carriers' charge density allows to understand the importance of the crossing of the flow of the electrons in p-n junction in presence of the external electrical field. It will be studied in the following subsection, the behavior of the p-n junction capacitance versus the external electrical field.

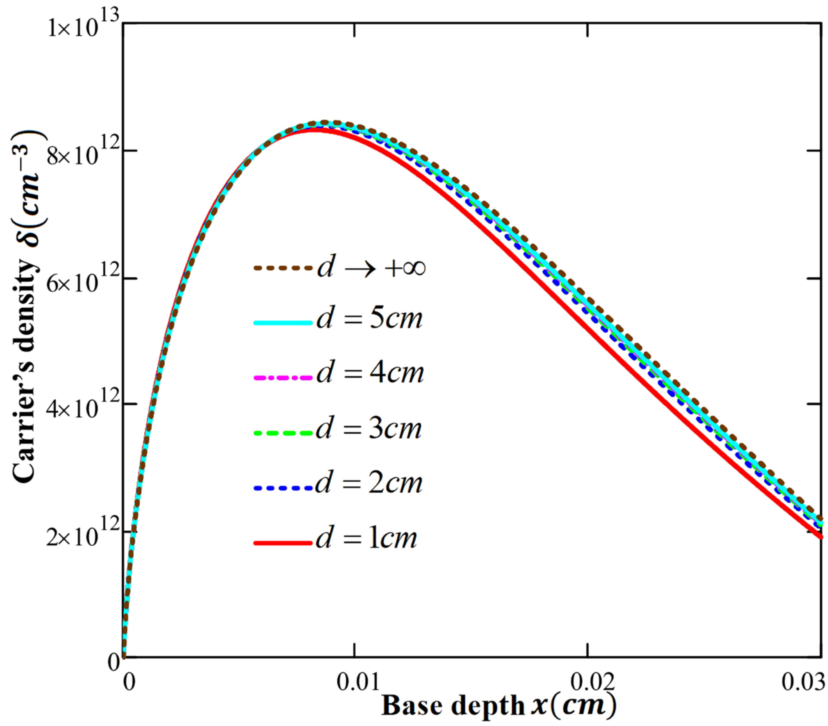

Figure 4. Excess minority carriers (electrons) density photo-generated in the base region in short-circuit versus base depth for different distances ($L_n = 150\ \mu\text{m}$, $D_n = 26\ \text{cm}^2\cdot\text{s}^{-1}$, $\mu_n = 1000\ \text{cm}^2\cdot\text{V}^{-1}\cdot\text{s}^{-1}$, $H = 300\ \mu\text{m}$, $S_b = 5\times10^4\ \text{cm}\cdot\text{s}^{-1}$, $S_f = 8\times10^8\ \text{cm}\cdot\text{s}^{-1}$).

3.2. Study of the Capacitance versus the External Electrical Field

Figure 5 presents the capacitance versus junction dynamic velocity for different distances.

The great values of the capacitance are obtained in open-circuit state *i.e.* in low values of the junction dynamic velocity. The great capacity is got with the increase of the electrical field. In fact, the increase of the electrical field causes the increase of the crossing of the p-n junction by the excess minority carrier's charge. The increase of the junction dynamic velocity results in increase of the extension of the space charge region and decrease of the density of the minority charge carriers and the value capacity of the solar cell [17]. But, when the electrical field increase, the capacitance increases also. That can be explained by the reduction of the denominator of the fraction of Equation (3). When C is great, the capacitor accumulates more carriers charge. On the other hand, if C is small, the capacitor accumulates less carriers charge. However, in this case, it is not an accumulation. It is in reality a crossing of the p-n junction by the electrons because of the electrical field. The charge current through a p-n junction is an electron current only in the n region. The C-V characteristic for different distances is plotted in the next **Figure 6**.

The C-V characteristics of **Figure 6** present the exponential progression. It progresses speedy for the shortest distances. The carrier's charge concentration deduced from the C-V profiles is a measure of trapped charge [18]. When the

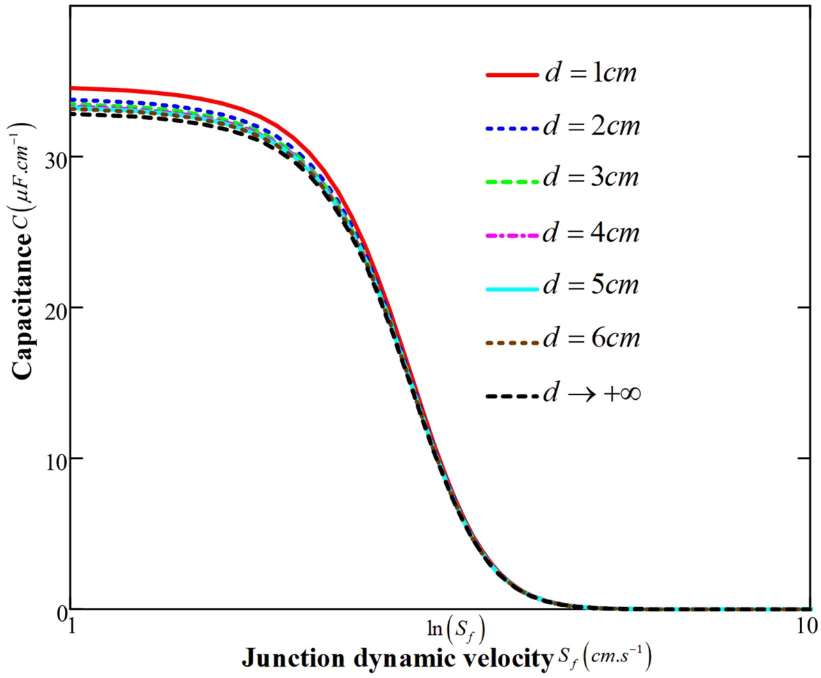

Figure 5. Capacitance versus Junction dynamic velocity for different distances ($L_n = 150\ \mu m$, $D_n = 26\ cm^2 \cdot s^{-1}$, $\mu_n = 1000\ cm^2 \cdot V^{-1} \cdot s^{-1}$, $H = 300\ \mu m$, $S_b = 5\times10^4\ cm \cdot s^{-1}$).

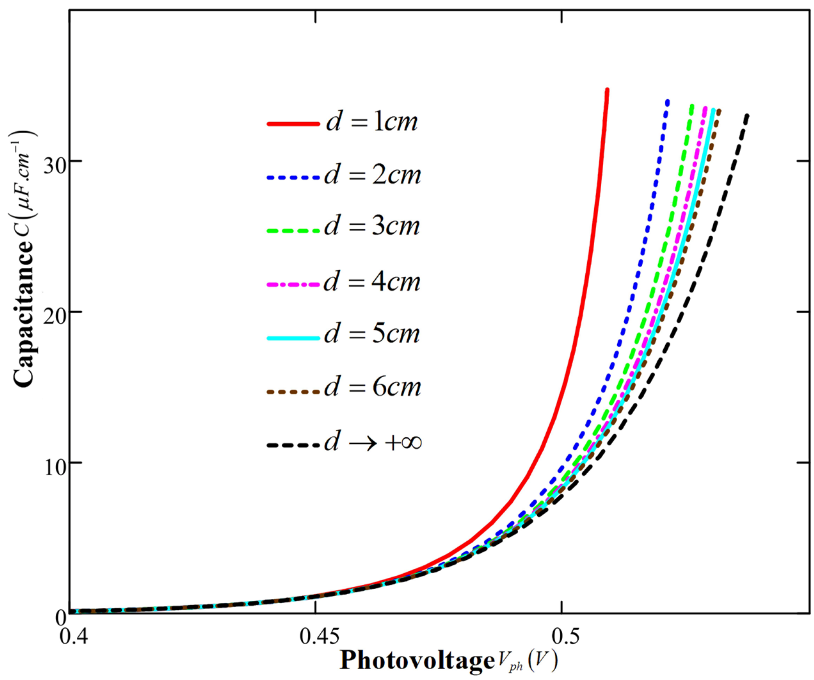

Figure 6. *C*-*V* characteristics for different distances ($L_n = 150\ \mu m$, $D_n = 26\ cm^2 \cdot s^{-1}$, $\mu_n = 1000\ cm^2 \cdot V^{-1} \cdot s^{-1}$, $H = 300\ \mu m$, $S_b = 5\times10^4\ cm \cdot s^{-1}$).

electrical field increases there is a decrease of the electrical voltage because of the important crossing of the junction by the carrier's charge. That can explain the increase of the capacitance causing then its fast exponential progression with the increase of the photo-voltage *i.e.* when the solar cell brings closer to the open-circuit situation. The electrical field of a p-n junction is driving force for the currents flowing during illumination [19]. The addition of the external electrical field causes an amplification of this effect. For the high electrical field values, the shunt resistance decreases. However, in the range of the average electrical field value used in the present study the increase of the external electrical field can cause a narrowing of the SCR like the interest is to reduce the SCR in p-n junction. The evolutions observed in **Figure 6** show excellent agreement with the results presented by Liou *et al.* [20] and Jean Zaraket *et al.* [21]. It can be deducted here that the average of the external electrical field used for this simulation cannot cause the breakdown of the p-n junction of the solar cell under integration of the electrical field production source.

4. Conclusions

The behavior of the junction SCR capacitance has been studied in this paper. The external electrical field has been evaluated. It increases with the decrease of the distance between the armature of the planar capacity created. The expression of the p-n junction capacitance has been also evaluated.

The electronic carrier's charge crosses mainly the junction with the shortest distances *i.e.* with the great strength of the external electrical field. In open-circuit this main crossing of the electronic carriers charge causes the thermal heating of the p-n junction by Joule effect. However, the important crossing of electronic carrier's charge translates the increase of the external photo-current.

The p-n junction capacitance plotted versus the junction dynamic velocity has presented a main value in open-circuit. It has been observed an increase when the external electrical field is great. That can be explained by the decrease of the photo-voltage translating then the narrowing of the SCR. The C-V characteristic has shown the same observations.

After this study, it can be deducted that the average value of the external electric field is not sufficient to cause the breakdown of the p-n junction of the solar cell under integration of the external electrical field production source. The increase of the electrical field causes rather the narrowing of the SCR. That can provide an improvement of the solar cell's electrical outputs. This work can be extended on the study of the behavior of the shunting and the series resistances when the solar cell is under the integration of the electric field.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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