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Investigation of the Contribution of the Widening of the SCR in the Study of 1 MeV Electrons Damage on the Performances of a Polycrystalline Silicon Solar Cell

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ABSTRACT

When solar cells are used for space applications, there are exposed to different types of energetic particles such as protons and electrons. Those energetic particles create defects in the base of the solar cell and lead to the degradation of the performances of the solar cell. Three mainly phenomenon observed in silicon solar cells exposed to 1 MeV electron irradiation are decrease in diffusion length, removal of majority charge careers and enlargement of Space Charge Region (SCR). These three phenomenon lead to the type conversion of the base of solar cell and an anomalous behavior of the short-circuit current for a certain value of the fluences. In the present study, theoretical approach is used to investigate the impact of decrease in diffusion length, removal of majority charge careers and enlargement of SCR on the anomalous behavior of the short-circuit current and type conversion of the base.The electric parameters are studied under AM 1.5 for different fluences of 1 MeV electrons.It was found that, defects responsible for the anomalous behavior of the short-circuit current could appear for different values of the fluences and that, the type conversion of the base is caused by the removal of the majority charged carriers and decrease in diffusion length while the anomaly observed in the evolution of the short-circuit current is caused by the widening of the SCR.

Introduction

Solar cells are widely used as the power supply in space vehicles. In such applications the solar cells are continuously exposed to a variety of radiation types such as α, β, γ-rays, X-rays, neutrons etc., which may have an adverse effect on the performance of the cells [1]. The defects produced by irradiation at room temperature can be of different nature depending on the material. In Si, they are secondary defects resulting from the interaction of the primary defects with impurities or with each other's, because the primary defects are mobile well below 300 K [2]. 1 MeV electron irradiation induces structural defects in the Si lattice, particularly in the Van Allen radiation belt, lattice defects are induced in semiconductors due to high- energy electron and proton irradiations, and these cause a decrease in the output power of solar cells [3, 4]. These defects introduce energy levels in the Si forbidden energy gap and which act as recombination centers and/or traps of free carriers. The solar cell performance suffers a sever deterioration as a result. [5, 6]. Further improvements in conversion efficiency and radiation resistance of space cells are necessary for widespread applications of space missions. Since radiation in space is severe. Therefore solar cells for space use are required to have radiation-resistant characteristics [3].

Ongoing research is focused on the effects of the defects and impurities that influence the main parameters, such as the life time of charge carriers, better understanding of trans port processes, the creation of electron-hole pairs [7].

In this work we have focused on those which play the role of recombination centers and of compensating centers [3]. Therefore, the impact of decrease in diffusion length, removal of majority charged carriers and widening of the SCR on the performances of a solar cell illuminated under AM 1.5 and irradiated with different fluences of 1 MeV electrons have been studied.

Theoretical Background

1. Theoretical assumptions

This sections defines the continuity equation, neutrality equation and the expressions of some diffusion parameters such as diffusion length, diffusion coefficient, and variation of the SCR widening for the polysilicon solar cell exposed to 1 MeV electron irradiation and under multispectral illumination. From these equation and these previously mentioned parameters we then derives the expressions of the electrical parameters such as open circuit voltage, short-circuit current, and the efficiency (η) of the PV cell.

In the figure 1, we present a schematic representation of interaction between light, 1 MeV beta particles and solar cell.

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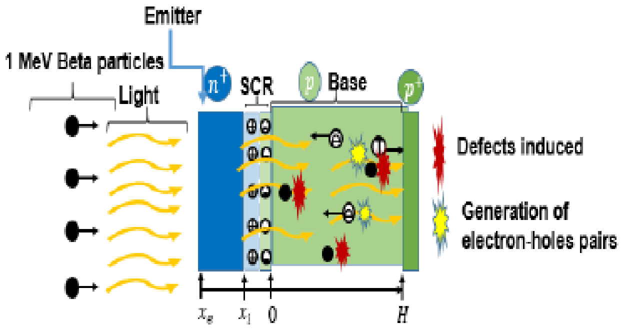

Figure 1. Illuminated polysilicon cell under 1 MeV Electronsirradiation

This work is conducted in the base of a ∂n^+pp^+ polysilicon PV cell using these following assumptions:

- Light generate electron-hole pairs into the base
- 1 MeV electrons irradiation induce defects responsible of decrease of the of the minority charged carriers diffusion length (recombination
- 1 MeV electrons irradiation causes enlargement of the SCR Removal of majority charged carriers is taken into account through the influence of irradiation on the diffusion coefficient
- The enlargement of the SCR leads to a reduction in the thickness of the base, i.e; a displacement of the position.

$$x = 0\left(\Delta x_1 = x_1(\emptyset)\right)$$

Figure 2, present an illustration of the enlargement of the SCR which correspond to the decrease in the thickness of the base.

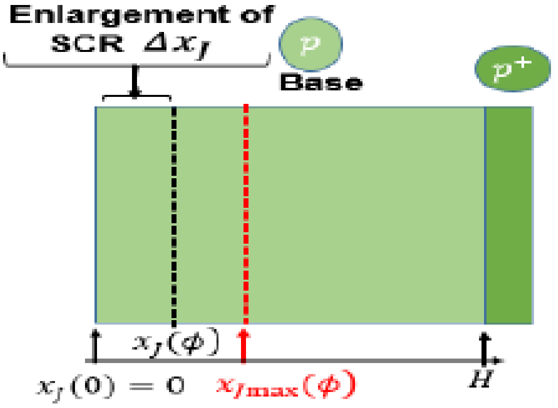

Figure 2. Illustration of the enlargement of the SCR

The expression of the diffusion length of the minority charged carriers under high energy particles is derive from the following equation [8]:

$$\Delta\left(\frac{1}{L(\emptyset)}\right) = \frac{1}{L^2(\emptyset)} - \frac{1}{L_0^2} = \text{Kl}.\emptyset \qquad (1)$$

From this previous equation, we derive the diffusion length of the minority charged carriers as:

$$L(\emptyset) = \frac{1}{\sqrt{L_0^2}}\text{Kl}.\emptyset \qquad (2)$$

$L(\emptyset)$ and L_0 are respectively the diffusion lengths after and before irradiation

$(\emptyset)$; is the flux of the incident particles

Kl: is the damage coefficient

Kl = 8.10^{-11}. **[9]**

For the determination of the expression of the diffusion coefficient, we first of all determine the relationship between acceptor atoms concentration and majority charged carriers concentration by solving the following neutrality equation

$$N_A + \frac{n_i^2}{P(\emptyset)} \qquad (3)$$

Where N_A and $P(\emptyset)$ are respectively acceptor atoms concentration and majority charged carriers concentration after irradiation. From the equation (3), we derives the expression of N_A :

$$N_A = \frac{(P(\emptyset))^2 + n_i^2}{P(\emptyset)} \qquad (4)$$

The expression of $P(\emptyset)$ is given by the following equation[8]:

$$P(\emptyset) = P(0)e^{\frac{R_c\emptyset}{P(\emptyset)}} \qquad (5)$$

$P(\emptyset)$ is the majority charged carriers concentration before irradiation and R_c is the removal rate of majority charged carriers.

The relationship between diffusion coefficient and majority charged carriers concentration is given by the following equation [10]:

$$D_n = \frac{1350.V_T}{\sqrt{1 + \frac{81N_A}{N_A + 3.2.10^{18}}}} \qquad (6)$$

From the equations (6) we obtain the expression of the diffusion coefficient as a function of the flux of incident particles given by:

$$D_n(\emptyset)\frac{1350.V_T}{\sqrt{1 + \frac{81\left[\frac{(P(\emptyset))^2 - n_i^2}{P(\emptyset)}\right]}{\left[\frac{(P(\emptyset))^2 + n_i^2}{P(\emptyset)}\right] + 3.2.10^{18}}}} \qquad (7)$$

For the determination of the enlargement of the SCR, we use a variation method. The expression of the enlargement of the SCR is given by the following equation:

$$\Delta x_j = x_{j(\emptyset)} = \left[\frac{\emptyset R_c\left[\frac{1 + 2\sigma(\emptyset)}{\sigma(\emptyset) + [\sigma(\emptyset)^2]}\right]\left[n_i^2.e^{\frac{\emptyset R_c}{P_0}} + (P_0)^2.e^{\frac{-\emptyset R_c}{P_0}}\right]}{2N_d(P_0)^2} \\ X\left[\sqrt{\frac{2V0^{\varepsilon}s\frac{1}{\sigma(\emptyset) + [\sigma(\emptyset)^2]}}{qN_d}}\right]\right] \qquad (8)$$

$$\text{Where } \sigma(\emptyset) = \frac{(P(\emptyset))^2 - n_i^2}{N_d.P(\emptyset)} \qquad (9)$$

N_d is the donors atoms concentration in the emitter, ε_s is the silicon electric permittivity, and V_0.is the built-in voltage. Figure 3, present the variations of the width of the SCR i.e. decrease in the thickness of the base

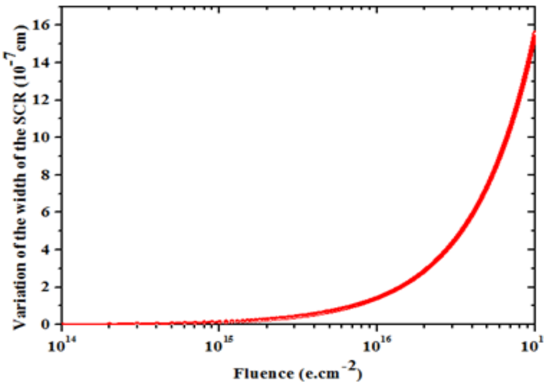

Figure 3. Variation of width of the SCR versus fluences

It appear that, for the value of the fluences equal to $10^{17}\ e.cm^{-2}$, the width of the SCR increase of about15.53 nm

2. Continuity equation

Taking into account decrease in diffusion length and removal of majority charged carriers

Considering the different expressions of the diffusion length and diffusion coefficient, we establish a continuity equation which describes the behavior of minority excess charged carriers, in steady state and in 1-D is given by the Eq (10).

$$\frac{d^2\delta_{n(x)}}{dx^2}+\frac{\delta_{n(x)}}{L_n^2(\emptyset)}=\frac{1}{D_{n(\emptyset)}}G(x) \qquad (10)$$

Where $G(x)$ is the AM 1.5 generation rate of the solar spectrum, given by the following expression:

$$G(x)\sum_{i=0}^{3} a_i\, e^{-b_1 x} \qquad (11)$$

a_i and b_i are tabulated given by [11].

$$a_1 = 6.13.10^{20} \quad a_2 = 0.54.10^{20} \quad a_3 = 0.0991.10^{20}$$

$$b_1 = 6630 \quad b_2 = 1000 \quad b_3 = 130$$

The density of excess minority charged carriers is given by Eq. (12)

$$\delta(x,o)=\left[\sum_{i-1}^{3}\frac{\begin{matrix}A\cosh-1\left[\frac{1}{L_{n(\emptyset)}.x}\right]+B\,\mathrm{sech}^{-1}\left[\frac{1}{L_{n(\emptyset)}.x}\right]+\\ a_i\end{matrix}}{D_n(\emptyset)\left[\left[\frac{1}{L_{n(\emptyset)}}\right]^2-b_i^2\right]}e^{(-b_i.x)}\right] \qquad (12)$$

A and B are coefficients which can be determine by using these following boundaries conditions

$$D_n(\emptyset).\left.\frac{\partial\delta(x,\emptyset)}{\partial x}\right|_{x=0}=-S_f.\delta(0,\emptyset) \qquad (13)$$

$$D_n(\emptyset).\left.\frac{\partial\delta(x,\emptyset)}{\partial x}\right|_{x=0}=.-S_f.\delta(H,\emptyset) \qquad (14)$$

$$D_n(\emptyset).\left.\frac{\partial\delta(x,\emptyset)}{\partial x}\right|_{x=x_j(\emptyset)}=-S_f.\delta[x_j(\emptyset),\emptyset] \qquad (15)$$

Where S_f and S_b are respectively junction dynamic velocity and recombination velocity at the rear side of the base.

From the expressions of the charged carriers density, we then determine the expressions of some electrical parameters such as short-circuit photocurrent, open circuit photovoltage and conversion efficiency respectively given by the following equations

$$J_{sc}(\emptyset)=\lim_{S_f\to\alpha} J_{ph}(\phi) \qquad (16)$$

Considering the change in the wide of the SCR,

$J_{ph}(\emptyset)$ is given by:

$$J_{ph}(\emptyset)=qD_n\left.\frac{d\delta_{n(x)}}{dx}\right|_{x=x_j(\emptyset)} \qquad (17)$$

$$V(S_f,\emptyset)=\frac{k_BT}{q}\ln\left[\frac{\delta_n[x_j(\emptyset),\emptyset]}{n_0}+1\right] \qquad (18)$$

Neglecting the change in the wide of the SCR,

$J_{ph}(\emptyset)$ is given by:

$$J_{ph}(\emptyset)=qD_n\left.\frac{d\delta_{n(x)}}{dx}\right|_{x=0} \qquad (19)$$

Thus,

$$V_\alpha = V(S_f,\emptyset)\text{for } S_f = 0\ cm.s^{-1} \qquad (20)$$

Where $V(S_f,\emptyset)=\frac{k_BT}{q}\ln\left[\frac{\delta_n(0,\emptyset)}{n_0}+1\right]$ (21)

$$\eta(\phi)=\frac{P_{el}\max^{(\phi)}}{P_{inc}} \qquad (22)$$

$$P_{inc} = 1000\,W.m^{-2} \qquad (23)$$

Results and Discussions

In this session, in order to understand the contribution of the different assumptions lies to some phenomenon, we present the results of our two different models, namely the one tacking into account change in diffusion length and removal of majority charged carriers and the second one tacking into account change in diffusion length, removal of majority charged carriers and change in the wide of the SCR.

- Model tacking into account change in diffusion length and removal of majority charged carriers (L and Rc changes).

The figure 4 present the curve of open circuit photovoltage versus fluences of 1 MeV incident electrons

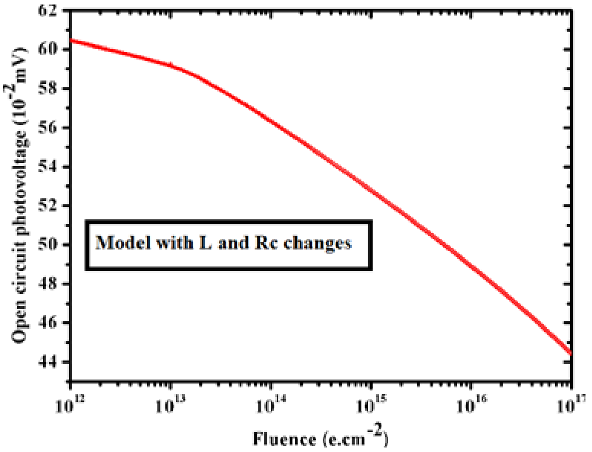

Figure 4. Open circuit voltage versus fluences

We observe a decrease in open circuit photovoltage with the increase of the fluences of the 1 MeV incident electrons. This can be explained by the fact that, the incident particles produces defect which lead to the decrease in the number of the minority charged carriers able to be store at the junction and decrease in the number of the majority charged carriers. It is important to notice that the decrease in the number of majority charged carriers seems to be favorable to the diffusion of the minority charged carriers because of the fact that those majority charged carriers constitute a recombination centers for the minority charged carriers. In this case the phenomenon of change in diffusion length prevails over that of removal of majority charged carriers. Thus, there are more defaults susceptible to produce change in the diffusion length induced than those susceptible to remove majority charged carriers

The figure 5 present the curve of the normalized short circuit current versus the fluences of the incident particles

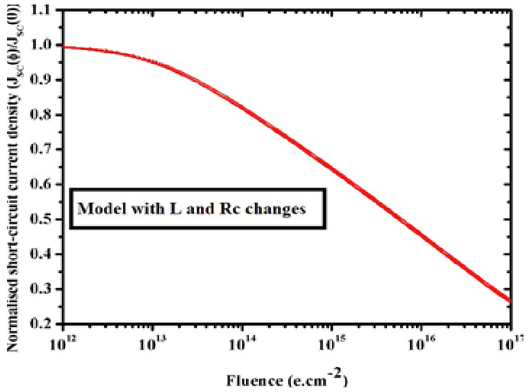

Figure 5. Normalized short circuit current versus fluences

We observe a decrease in the short circuit current with the increase of the fluences of the incident particles. That can be explained by the fact that the number of the minority charged carriers able to cross the junction decrease with the increase of the fluences of the incident particles.

The figure 6 present the curve of the conversion efficiency versus fluences of the incident particles.

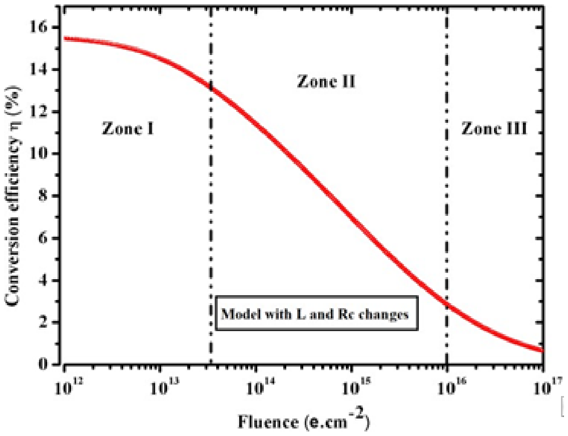

Figure 6.Conversion efficiency versus fluences

We observe that the curve of the conversion efficiency globally decrease with the fluences, but present three (03) characteristics zones with a change in the concavity of the curve. The behavior of the conversion efficiency in each zone can be explain as follow:

In the zone I, the concavity faces downwards. In this zone, the conversion efficiency drops slightly. This slight decrease can be explained by the fact that, the defects generated by irradiation being electrically active, they not only constitute recombination centers for minority carriers which are electrons but also suppression centers for the majority carriers which are holes. In fact, in this zone the photogenerated electrons recombine with the defects generated by irradiation and at the same time, these defects remove part of the holes found in the valence band of the base. The conjunction of these two phenomena leads to both a reduction of the number of minority charged carriers which arrive at the junction and the reduction of the concentration of majority carriers in the base, what leads inevitably to the drop in conversion efficiency as observed.

In the zone II, the conversion efficiency drop significantly abrupt. This sudden drop is due to the fact that, with the increase in the fluences, there is an increase in the concentration of the defects. So, these last two phenomena of recombination and suppression increase the probability of electron recombination and promote the breakdown of the phenomenon of electron diffusion because the removal of the majority carriers (holes) tends to break the balance of charges in the base, thus leading to the type inversion of the base. This naturally leads to a sharp drop in short-circuit current as observed on the curve in figure 5. In this zone, the conversion efficiency drop from 13 to 2.5%.

In the zone III, the concavity faces upwards. In this zone, the conversion efficiency takes very low values and tends to cancel out. In this zone and beyond we are witnessing a degradation of the PV cell due to a type conversion of the material constituting the base of the solar cell. Because of the increase of the fluences the concentration of the holes decreases sharply and they are no longer the majority, but become the minority. Thus leading to the cell failure. This reflects a gradual decrease in p-type carrier concentration as the material becomes more compensated due to the introduction donor states, followed by an increase in carrier concentration once the material is n-type [12].

- Model tacking into account change in diffusion length, removal of majority charged carriers and change in the wide of SCR (L , Rc and W changes)

The figure 7 present the curve of open circuit photovoltage versus fluences of 1 MeV incident electrons.

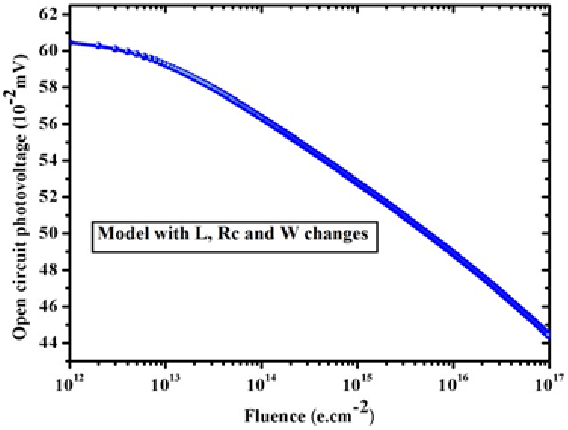

Figure 7. Open circuit voltage versus fluences

We observe that the curve in figure 7 is the same with the one of figure 4. Thus, we can conclude that taking into account change in the wide of the SCR doesn't affect the open circuit photovoltage.

Figure 8 present the curve of short-circuit current versus fluences.

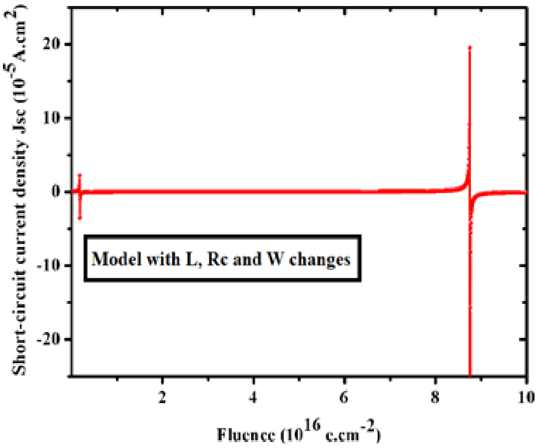

Figure 8. Short-circuit current versus fluences

We observe that, short-circuit current present two peaks. One at the value of fluences for about 10^{15} e/cm2 and other, more significant at about $8.8.10^{16}$ e/cm2. These peaks represents an anomalous behavior of the short-circuit current as observed by some authors in theirs works [13, 14, 15, 5]. From this observation, we can conclude that change in the wide of the SCR is responsible of that anomalous behavior of the short-circuit current [9] and that, this anomalous behavior can be occur for different values of the fluences include in the range of the fluences in our study. It is important to specify that, in the case of the short-circuit current, our model taking into account change in W does not allow us to find exactly the experimental curve obtained by the previous authors but nevertheless allows us to determine the fluences which produce the anomalous behavior of the short-circuit current.

We present on the figure 9, the curve of conversion efficiency versus fluences.

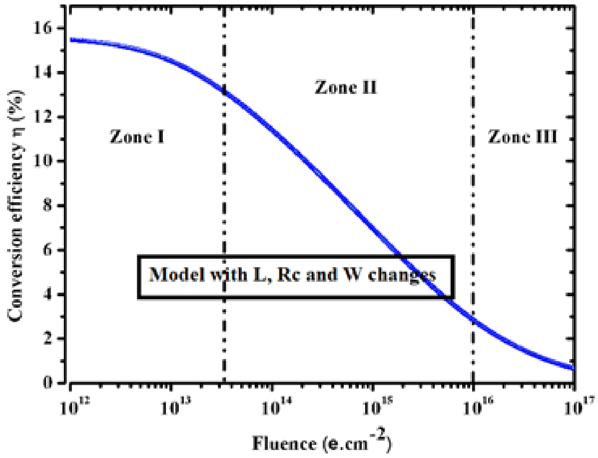

Figure 9. Conversion efficiency versus fluences

We observe that the curve in figure 9 is the same with the one of figure 6. Thus, we can conclude that taking into account change in the wide of the SCR doesn't affect the conversion efficiency and that it is removal of majority charged carriers (Rc changes) which is responsible of the type-conversion of the base. Of course, the previous studies taking into account only change in diffusion length don't exhibit type conversion [16, 17, 18].

For a good understanding of the change of the type of the base, we present on the figure 10, the sets of processes leading to the change of the type of the base.

Conclusion

This work put in evidence first of all the effectiveness of the widening of the SCR of the solar cell irradiated by high energy particles and the responsibilities of the reducing in diffusion length of the minority charged carriers, removal of the majority charged carriers and widening of the SCR on the anomalous behavior of the short- circuit current and the type conversion of the base of the solar cell. Thus, we used two different models, to know the first one tacking into account reducing in diffusion length of the minority charged carriers and removal of the majority charged carriers, the second one tacking into account in addition of reducing in diffusion length of the minority charged carriers and removal of the majority charged carriers, also the widening of the SCR. For each model we studied the evolution of open circuit photovoltage, short-circuit current and conversion efficiency in function of the fluences of 1 MeV electrons.

It appears that, for the cases of open circuit photovoltage and conversion efficiency, the two different models gives the same curves. In order way, it appeared on the curves of conversion efficiency a change of the concavity, thus translating a change in type of the base (type conversion). For the first model, short-circuit current decrease with the fluences of the incident 1 MeV electrons and don't present any anomalous behavior. This leads us to conclude that, it is removal of majority charged carriers which is responsible of the type conversion.

For the second model, in the case of the short-circuit current we noticed the presence of some peaks, thus translate an anomalous behavior of the short-circuit current. Tis leads us to conclude that it is the widening of the SCR which is responsible of the anomalous behavior of the short-circuit current as observed by some authors mentioned in this paper.

These results show the contribution of each type of phenomenon (reducing in diffusion length, removal of the majority charged carriers, widening of the SCR) occurs during the interaction of 1 MeV electrons with a solar cell. Thus it allow to determine the responsibility of these phenomena on the anomalous behavior of the short-circuit current and the type conversion of the base of the solar cell.

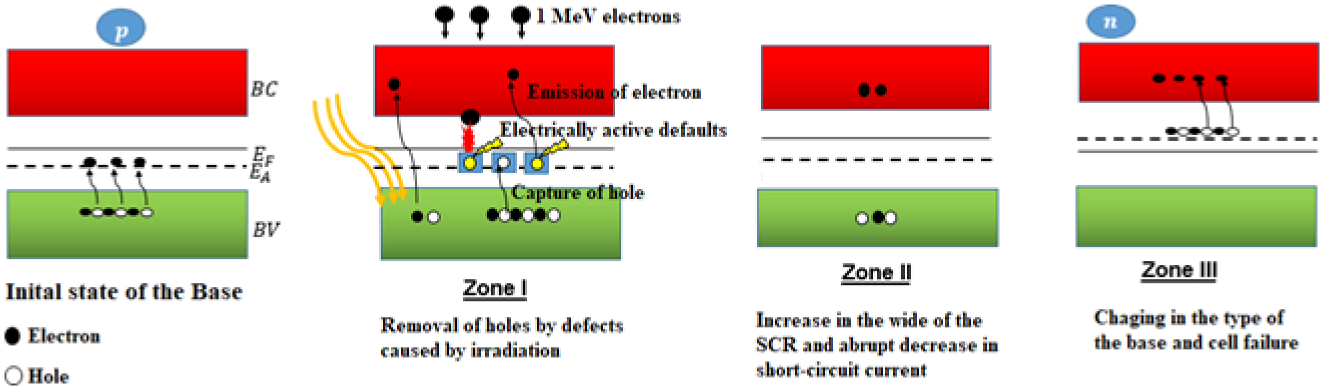

Figure 10. Sets of processes leading to the change of the type of the base

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