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# Base Thickness Optimization of a ($n^+$-p-$p^+$) Silicon Solar Cell in Static Mode under Irradiation of Charged Particles

**Mamadou Lamine Ba[1], Ndeye Thiam[1], Moustapha Thiame[2], Youssou Traore[2], Masse Samba Diop[2], Mamour Ba[2], Cheikh Tidiane Sarr[2], Mamadou Wade[1], Gregoire Sissoko[2]**

[1]Laboratory of Sciences and Techniques of Water and Environment, Polytechnic School of Thiès, Thiès, Senegal
[2]Laboratory of Semiconductors and Solar Energy, Physics Department, Faculty of Science and Technology, University Cheikh Anta Diop, Dakar, Senegal
Email: gsissoko@yahoo.com

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## Abstract

In this work, we propose a method to determinate the optimum thickness of a monofacial silicon solar cell under irradiation. The expressions of back surface recombination velocity depending the damage coefficient ($kl$) and irradiation energy ($\phi_p$) are established. From their plots, base optimum thickness is deduced from the intercept points of the curves. The short-circuit currents $Jsc0$ and $Jsc1$ corresponding to the recombination velocity $Sb0$ and $Sb1$ are determinated and a correlation between the irradiation energy, the damage coefficient and optimum thickness of the base is established.

## Keywords

Silicon Solar Cell, Irradiation, Recombination Velocity, Base Thickness

## 1. Introduction

Studies of the effect irradiation of charged particles on photovoltaic solar cells have always preoccupied scientific minds around different aspects and parameters. The study of the displacement of atoms during irradiation was first presented in 1956 [1]. It follows that of the radiation effects in solids in 1957 [2] then the solar cell radiation handbook in 1982 [3]. The fundamental processes occurring in GaAs solar cells exposed to ionizing radiation, such as energetic electrons and protons were presented in 1996. The interaction of radiation with matter and the resulting deposition of energy are covered, along with the corollary subjects of radiation exposure and dose [4].

On the other side, authors have studied the effect of irradiation of these particles on the solar cells (mono or bifacial [5], vertical multi-junctions [6]) for the determination of electrical parameters [7] such as photocurrent density, open circuit voltage, fill factor, maximum power, conversion efficiency [8], shunt and series resistances and diffusion capacitance [9].

Also, on determining phenomenological parameters *i.e.* excess minority carrier recombination velocity [10] at the junction and back surfaces, mobility, lifetime [11] and diffusion length [12] [13], charged particles irradiation effects were pointed out.

The incident illumination wavelength under steady [14] [15] [16] or dynamic frequency mode [17]-[21] was investigated.

This work deals with a method, to determinate the optimum thickness of a silicon solar cell under the effect of irradiation charged particles. Then, from the excess minority carrier density continuity equation in the base, expressions of photocurrent density [20] and recombination velocity of the rear surface, all depending on the irradiation of the charged particles are deducted. The optimum thickness (*H*) of the silicon solar cell base dependent of both irradiation energy flows ($\phi_p$) and damage coefficient (*kl*), is determined through the intercept point of the curves of the excess minority carrier recombination velocity (*Sb*0 and *Sb*1) at the back surface. As a result, the manufacture of the solar cell would be calibrated according to the irradiation conditions, thus allowing to reduce the amount of material to be used in the base.

## 2. Theory

Figure 1 shows the structure of a front-illuminated silicon solar cell (**n⁺-p-p⁺**) [22] under irradiation.

### 2.1. Minority Carrier's Density

When the solar cell is properly illuminated by a static polychromatic light, all the processes for generation, recombination in the bulk and surfaces and diffusion of excess minority carrier in the base are governed by the following continuity equation:

$$D(kl,\phi_p)\frac{\partial^2\delta(x,kl,\phi_p)}{\partial x^2}-\frac{\delta(x,kl,\phi_p)}{\tau}+G(x)=0\,. \tag{1}$$

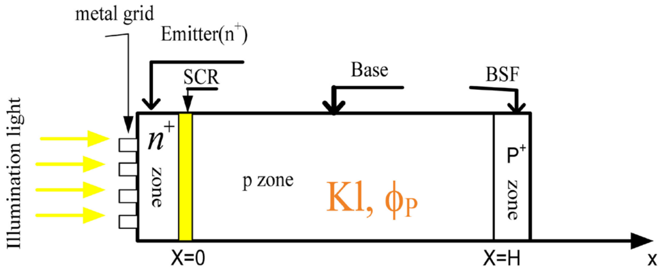


Figure 1. Structure of the silicon solar cell (**n⁺-p-p⁺**).

$\delta\left(x,kl,\phi_p\right)$ represents the excess minority carrier density in the base of the solar cell at the x-position, dependent of the irradiation energy.

$D\left(kl,\phi_p\right)$ and $\tau$ are respectively the diffusion coefficient of the electrons in the base under irradiation and the lifetime of the excess minority carrier in the base of the solar cell linked by the following Einstein relationship:

$$\left[L\left(kl,\phi_p\right)\right]^2=\tau\times D\left(kl,\phi_p\right), \tag{2}$$

with $L\left(kl,\phi_p\right)$ the diffusion length of the excess minority carrier in the base as a function of the irradiation energy flux ($\phi_p$) and the damage coefficient intensity (*kl*). It also represents the average distance traveled by the minority carrier before their recombination in the base under irradiation. It is related to the diffusion length before irradiation by the following empirical relation [10]:

$$L\left(kl,\phi_p\right)=\frac{1}{\left(\frac{1}{L_0^2}+kl\cdot\phi_p\right)^{1/2}}, \tag{3}$$

where:

$L_0$ is the diffusion length of the excess minority carriers in the base before irradiation.

$\phi_p$ is the irradiation energy flux.

*kl* is the damage coefficient intensity.

➢ $G(x)$ is the excess minority carrier generation rate [23] [24], given by:

$$KlG\left(x\right)=n\cdot\sum_{i=1}^{3}a_i\mathrm{e}^{-b_i\cdot x}. \tag{4}$$

- *n* is the number of sun or illumination concentration [25].
- The coefficients $a_i$ and $b_i$ take into account the tabulated values of solar radiation and the dependence of the absorption coefficient of silicon with the wavelength [24].

The carrier density is subjugated to the following boundary conditions:

1) At the junction: emitter-base ($x = 0$)

$$D\left(kl,\phi_p\right)\frac{\partial\delta\left(x,kl,\phi_p\right)}{\partial x}\Bigg|_{x=0}=Sf\cdot\delta\left(0,kl,\phi_p\right). \tag{5}$$

2) At the back side ($x = H$)

$$D\left(kl,\phi_p\right)\frac{\partial\delta\left(x,kl,\phi_p\right)}{\partial x}\Bigg|_{x=H}=-Sb\cdot\delta\left(H,kl,\phi_p\right). \tag{6}$$

*Sf* is the excess minority carrier recombination velocity at the junction and also indicates the solar cell operating point [26] [27].

*Sb* is the excess minority carrier recombination velocity on the back side surface [28] [29] [30].

It is the consequence of the electric field produced by the **p-p⁺** junction and characterizes the behavior of the density of the excess carrier at this interface. It yields to send back to the emitter-base interface the minority carriers generated near the rear face.

The resolution of the differential Equation (1) gives the expression of the excess minority carrier density in the base as:

$$\delta\left(x,kl,\phi_p\right)=A\cdot\cosh\left[\frac{x}{L\left(kl,\phi_p\right)}\right]+B\cdot\sinh\left[\frac{x}{L\left(kl,\phi_p\right)}\right]-\sum K_i\cdot \mathrm{e}^{-b_i\cdot x}, \quad (7)$$

where:

$$K_i=-\frac{n\times\left[L\left(kl,\phi_p\right)\right]^2\times a_i}{D\left(kl,\phi_p\right)\left(b_i^2\times L\left(kl,\phi_p\right)^2-1\right)}. \quad (8)$$

The expressions of, $A$ and $B$ are determined from the following boundary conditions and are given by:

$$A=L\left(kl,\phi_p\right)\times K_i\frac{\left[D\left(kl,\phi_p\right)\times Sb\left(kl,\phi_p\right)-D^2\left(kl,\phi_p\right)\times b_i\right]\mathrm{e}^{-b_i\cdot H}+\chi\left(kl,\phi_p\right)}{Y\times\sinh\left(\frac{H}{L\left(kl,\phi_p\right)}\right)+X\times\cosh\left(\frac{H}{L\left(kl,\phi_p\right)}\right)}, \quad (9)$$

$$\chi\left(kl,\phi_p\right)=\left(D\left(kl,\phi_p\right)\times\cosh\left(\frac{H}{L\left(kl,\phi_p\right)}\right)+L\left(kl,\phi_p\right)\times Sb\left(kl,\phi_p\right)\times\sinh\left(\frac{H}{L\left(kl,\phi_p\right)}\right)\right)\times\left[Sf+D\left(kl,\phi_p\right)\times b_i\right], \quad (10)$$

$$Y=\left[L^2\left(kl,\phi_p\right)\times Sb\left(kl,\phi_p\right)\times S_f+D^2\left(kl,\phi_p\right)\right], \quad (11)$$

$$X=D\left(kl,\phi_p\right)\times L\left(kl,\phi_p\right)\times\left[Sf+Sb\left(kl,\phi_p\right)\right], \quad (12)$$

$$B=L\left(kl,\phi_p\right)\times K_i\frac{L\left(kl,\phi_p\right)\times Sf\times\left[Sb\left(kl,\phi_p\right)-D^2\left(kl,\phi_p\right)\times b_i\right]\mathrm{e}^{-b_i\cdot H}+\zeta\left(kl,\phi_p\right)}{Y\times\sinh\left(\frac{H}{L\left(kl,\phi_p\right)}\right)+X\times\cosh\left(\frac{H}{L\left(kl,\phi_p\right)}\right)}, \quad (13)$$

$$\zeta\left(kl,\phi_p\right)=\left(D\left(kl,\phi_p\right)\times\sinh\left(\frac{H}{L\left(kl,\phi_p\right)}\right)+L\left(kl,\phi_p\right)\times Sb\left(kl,\phi_p\right)\times\cosh\left(\frac{H}{L\left(kl,\phi_p\right)}\right)\right)\times\left[Sf+D\left(kl,\phi_p\right)\times b_i\right]. \quad (14)$$

## 2.2. Photocurrent Density

The expression of the photocurrent density is given by the relation:

$$Jph\left(Sf,H,kl,\phi_p\right)=q\cdot D\left(kl,\phi_p\right)\cdot\left[\frac{\partial\delta\left(Sf,x,H,kl,\phi_p\right)}{\partial x}\right]_{x=0}. \quad (15)$$

For polychromatic illumination we obtain:

$$Jph\left(Sf,H,kl,\phi_p\right)=q\cdot D\left(kl,\phi_p\right)\left[\frac{B\left(Sf,H,kl,\phi_p\right)}{L\left(kl,\phi_p\right)}+\sum_{i=1}^{3}K_i\cdot b_i\right]. \tag{16}$$

This photocurrent density is constant for the large values of the carrier recombination rate at the junction between $3\times10^3\le Sf\le6\times10^6$ cm/s [27] [31] [32] [33].

The $Sb$ expression is obtained from the derivative of the photocurrent density for large $Sf$ values [28] [33].

$$\left[\frac{\partial Jph\left(Sf,kl,\phi_p\right)}{\partial Sf}\right]_{Sf\succ4\times10^4\ \mathrm{cm\cdot s^{-1}}}=0. \tag{17}$$

The resolution of this equation yields to establish the following expressions of the excess minority carrier recombination velocity at the rear face, $Sb0\left(H,kl,\phi_p\right)$ and $Sb1\left(H,kl,\phi_p,b_i\right)$:

$$Sb0\left(H,kl,\phi_p\right)=-\frac{D\left(kl,\phi_p\right)}{L\left(kl,\phi_p\right)}\times\tanh\left(\frac{H}{L\left(kl,\phi_p\right)}\right). \tag{18}$$

It represents the intrinsic recombination velocity at the **p-p⁺** junction of the minority carrier.

$$Sb1\left(H,kl,\phi_p\right)=\frac{D\left(kl,\phi_p\right)}{L\left(kl,\phi_p\right)}\cdot\sum_{i=1}^{3}\frac{L\left(kl,\phi_p\right)\cdot b_i\left(e^{b_i\cdot H}-\cosh\left(\frac{H}{L\left(kl,\phi_p\right)}\right)\right)-\sinh\left(\frac{H}{L\left(kl,\phi_p\right)}\right)}{-L\left(kl,\phi_p\right)\cdot b_i\cdot\sinh\left(\frac{H}{L\left(kl,\phi_p\right)}\right)+\cosh\left(\frac{H}{L\left(kl,\phi_p\right)}\right)-e^{b_i\cdot H}}. \tag{19}$$

It represents the recombination rate at the rear face influenced by the effect of the absorption of light in the material through the coefficients ($b_i$) and leads to a generation rate.

## 3. Results and Discussion

### 3.1. Photocurrent Density

From the expression (16), we represent in **Figures 2-4** the profiles of the photocurrent density as a function of excess minority carrier recombination velocity at the junction for different values of the irradiation energy, the damage coefficient and the base thickness.

**Figure 2** and **Figure 3** show the profile of the photocurrent density as a function of the excess minority carrier recombination velocity at the junction for different values of both the irradiation energy and the damage coefficient.

On this figure, we note three different parts on the profile of the photocurrent density:

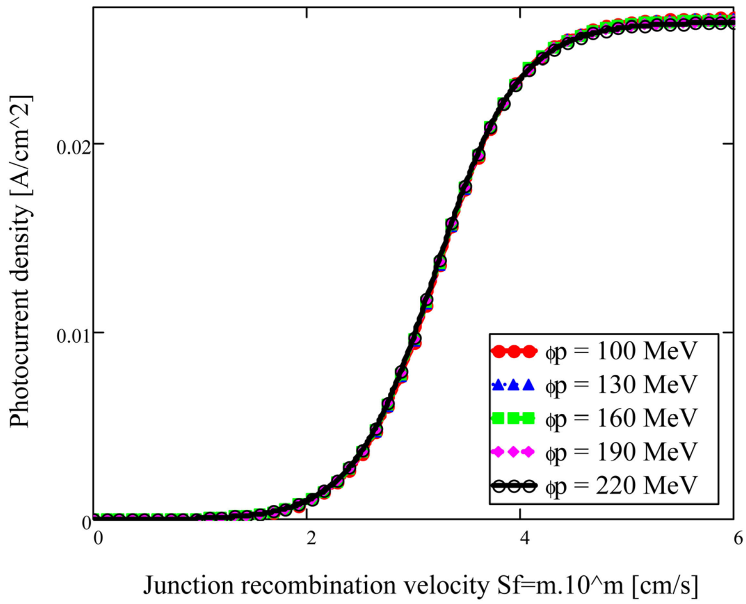


**Figure 2.** Photocurrent density versus junction recombination velocity for different irradiation energy values with $kl = 5\ \text{cm}^{-2}/\text{MeV}$, $H = 170\ \mu\text{m}$, $Sb(kl,\phi_p)$.

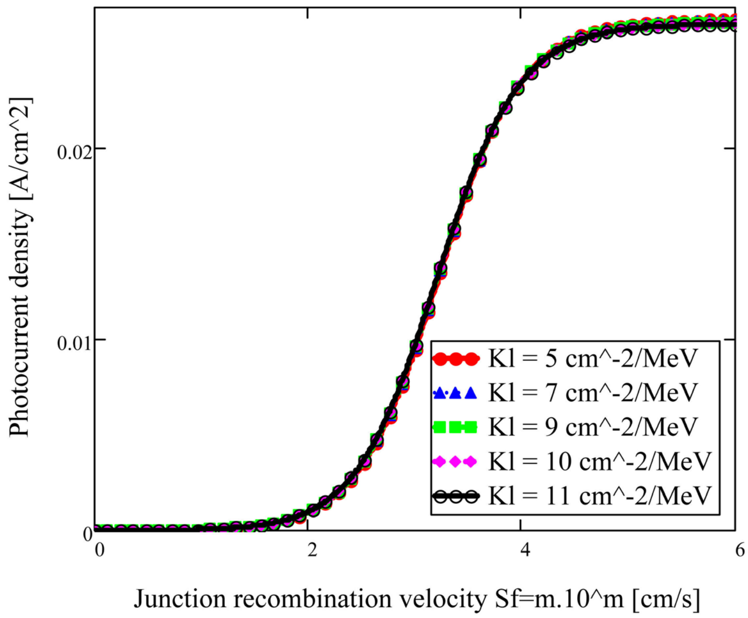


**Figure 3.** Photocurrent density versus junction recombination velocity for different damage coefficients values with $\phi_p = 100\ \text{MeV}$, $H = 170\ \mu\text{m}$, $Sb(kl,\phi_p)$.

- The photocurrent density is almost zero for low values of the recombination velocity ($Sf < 200$ cm/s), the solar cell operates then in open circuit.
- Then for 200 cm/s < $Sf$ < 4 × $10^4$ cm/s, the photocurrent density increases with the recombination velocity to reach a maximum of amplitude. This shows that the excess minority carrier has acquired sufficient energy to cross the junction.

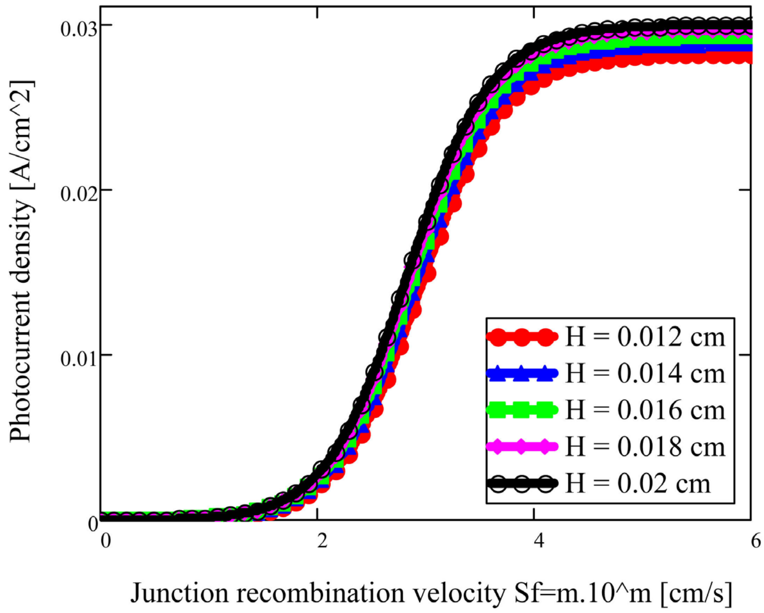


**Figure 4.** Photocurrent density versus junction recombination velocity for different values of base thickness with $kl = 11\ \text{cm}^{-2}/\text{MeV}$, $\phi_p = 220$ MeV and $D(kl,\phi_p) = 27\ \text{cm}^2/\text{s}$.

- For $Sf > 4 \times 10^4$ cm/s, the photocurrent density is maximum and constant, corresponding to the short-circuit photocurrent. The figure also shows that as the irradiation energy and damage coefficient increases, the maximum amplitude of the photocurrent density decreases. This phenomenon can be explained by the interaction of the irradiating particles with the silicon material which increases and reduces the excess minority carrier density.

Figure 4 shows that the photocurrent density increases with the junction recombination velocity for different values of the thickness.

## 3.2. Back Surface Recombination Velocity

### 3.2.1. Influence of the Irradiation Energy on the Back Surface Recombination Velocity

Figure 5 below shows the plots of excess minority carrier recombination rates at the back as a function of the base thickness for different values of the irradiation energy.

In Figure 5, the optimum thickness of the base of the solar cell subjected to variations in the irradiation energy flux is obtained with the intercept point from the curves of $Sb0$ ($H$) and $Sb1$ ($H$), representing the excess minority carrier recombination velocity at the rear face.

Table 1 below shows the variations of the optimum thickness in the base of the solar cell under irradiation energy leading to the different precise values of the diffusion coefficient, short-circuit currents $Jsc0$ and $Jsc1$ corresponding to $Sb0$ and $Sb1$.

Figure 6 below shows the profile of the thickness in the base as a function of both, irradiation energy and constant damage coefficient.

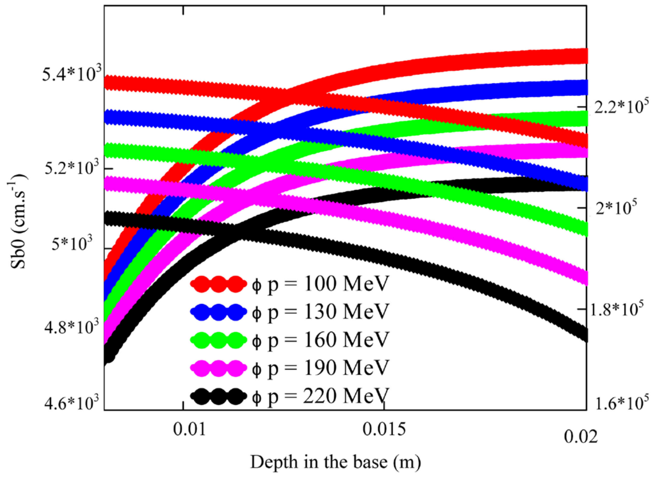


**Figure 5.** Recombination velocity at the back face as a function of the thickness for different irradiation energy values with $kl = 11\ \text{cm}^{-2}/\text{MeV}$.

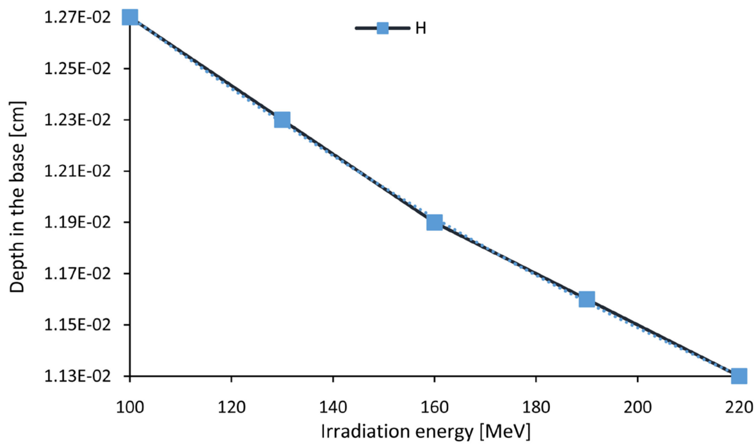


**Figure 6.** Optimum depth in the base versus irradiation energy.

**Table 1.** Thickness values in the base *H*, diffusion coefficient *D*, short-circuit currents *Jsc*0 and *Jsc*1 corresponding to *Sb*0 and *Sb*1 for different irradiation energy flows.

| $\phi_p$ (MeV) | 100 | 130 | 160 | 190 | 220 |
|---|---|---|---|---|---|
| $D$ (cm$^2$/s) | 30.063 | 29.204 | 28.375 | 27.546 | 26.688 |
| $H$ (cm) | 0.0127 | 0.0123 | 0.0119 | 0.0116 | 0.0113 |
| *Sb*0 (cm/s) | 5377.5 | 5287.5 | 5202.5 | 5127.5 | 5042.5 |
| *Sb*1 ($10^5$ cm/s) | 2.222 | 2.150 | 2.082 | 2.022 | 1.954 |
| *Jsc*0 (A/cm$^2$) | 0.0353 | 0.0353 | 0.0353 | 0.0354 | 0.0354 |
| *Jsc*1 (A/cm$^2$) | 0.0266 | 0.0266 | 0.0265 | 0.0265 | 0.0264 |

The correlation between the irradiation energy and optimum thickness of the base is established:

$$H(\text{cm}) = a \times \phi_p^2 - b \times \phi_p + c. \tag{20}$$

With: $a = 2\times10^{-8}\ \text{cm/MeV}$, $b = 2\times10^{-5}\ \text{cm/MeV}$, $c = 0.014\ \text{cm}$.

### 3.2.2. Influence of the Damage Coefficient on the Back Surface Recombination Velocity

Figure 7 below shows the plots of excess minority carrier recombination velocity at the back as a function of the thickness in the base for different values of the damage coefficient.

In Figure 7, the optimum thickness of the base of the solar cell subjected to variations in the level of degradation of the solar cell during the interactions of the particles is obtained by the intercept point deduced of the plotted curves of excess minority carrier recombination velocity at the rear face $Sb0$ ($H$) and $Sb1$ ($H$).

Table 2 below shows the variations of the thickness in the base as a function of the damage coefficient leading to the different precise values of the diffusion coefficient, short-circuit currents $Jsc0$ and $Jsc1$ corresponding to $Sb0$ and $Sb1$.

Figure 8 below shows the profile of the thickness in the base as a function of the damage coefficient and constant irradiation energy.

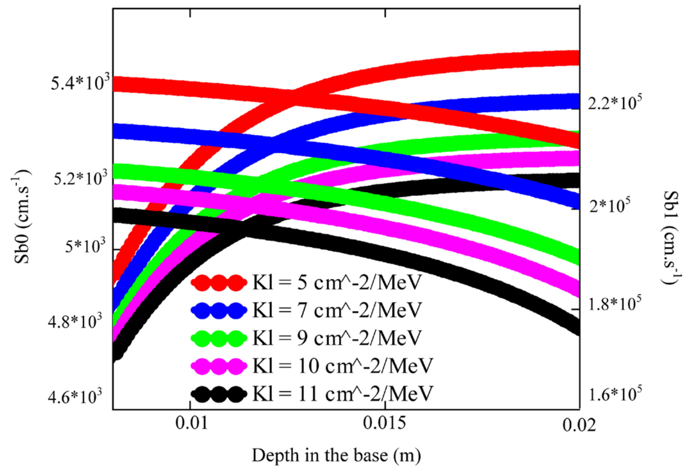


Figure 7. Recombination velocity at the back face as a function of the thickness for different damage coefficients values with $\phi_p$ = 220 MeV.

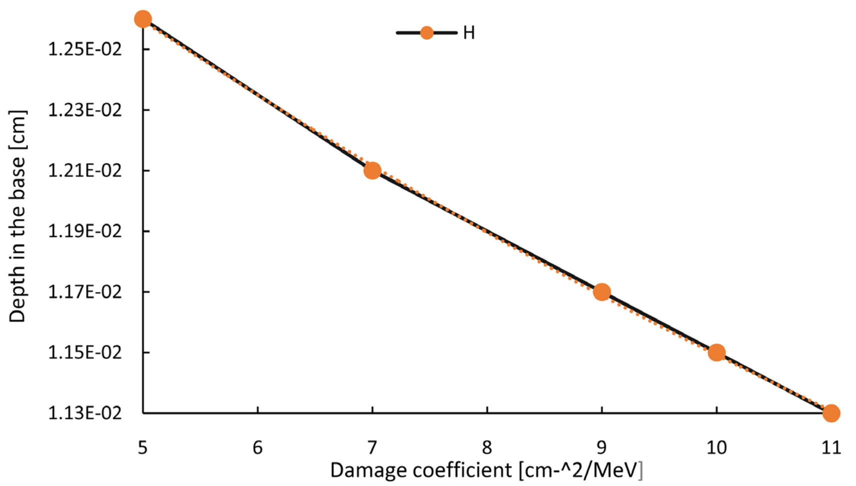


Figure 8. Optimum depth in the base versus damage coefficient.

**Table 2.** Thickness values in the base *H*, diffusion coefficient *D*, short-circuit currents *Jsc*0 and *Jsc*1 corresponding to *Sb*0 and *Sb*1 for different damage coefficients.

| $kl$ (cm$^{-2}$/MeV) | 5 | 7 | 9 | 10 | 11 |
|---|---|---|---|---|---|
| $D$ (cm$^2$/s) | 30.079 | 28.895 | 27.895 | 27.368 | 26.789 |
| $H$ (cm) | 0.0126 | 0.0121 | 0.0117 | 0.0115 | 0.0113 |
| $Sb0$ (cm/s) | 5377.5 | 5267.5 | 5165 | 5107.5 | 5052.5 |
| $Sb1$ (10$^5$ cm/s) | 2.222 | 2.134 | 2.052 | 2.006 | 1.962 |
| $Jsc0$ (A/cm$^2$) | 0.0353 | 0.0353 | 0.0353 | 0.0354 | 0.0354 |
| $Jsc1$ (A/cm$^2$) | 0.0266 | 0.0265 | 0.0265 | 0.0264 | 0.0264 |

The correlation between the damage coefficient and optimum thickness of the base is established:

$$H(\text{cm}) = a \times \phi_p^2 - b \times \phi_p + c . \tag{21}$$

With: $a = 6\times10^{-6}\ \text{MeV}\cdot\text{cm}/\text{cm}^{-2}$ , $b = 3\times10^{-4}\ \text{MeV}\cdot\text{cm}/\text{cm}^{-2}$ , $c = 0.014\ \text{cm}$ .

## 4. Conclusions

In this work, we have proposed a method for determining the optimal thickness of a monofacial solar cell subjected to the effect of the irradiation of charged particles. The expressions of the excess minority carrier in the base and the photocurrent density have been proposed. Calibration curves of the photocurrent density were plotted versus the junction recombination rate for different values of the irradiation energy and the damage coefficient.

The expressions of the excess minority carrier recombination rates at the back face have been deduced from the derivative of the photocurrent density with respect to the excess minority carrier recombination velocity at the junction, when this tends to large values corresponding to the short-circuit situation of the solar cell.

The graphical resolution of the equations of recombination rates at the rear face yields to obtain at the points of intersection of the curves the value of the optimum thickness for a given irradiation energy and a given damage coefficient in the vicinity of the short-circuit current.

Finally, a correlation between the irradiation energy, the damage coefficient and the optimal thickness of the solar cell has been established.

## Conflicts of Interest

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

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