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n^+-p-p^+ Silicon Solar Cell Base Optimum Thickness Determination under Magnetic Field

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Abstract

Base optimum thickness is determined for a front illuminated bifacial silicon solar cell n^+-p-p^+ under magnetic field. From the magneto transport equation relative to excess minority carriers in the base, with specific boundary conditions, the photocurrent is obtained. From this result the expressions of the carrier's recombination velocity at the back surface are deducted. These new expressions of recombination velocity are plotted according to the depth of the base, to deduce the optimum thickness, which will allow the production, of a high short-circuit photocurrent. Calibration relationships of optimum thickness versus magnetic field were presented according to study ranges. It is found that, applied magnetic field imposes a weak thickness material for solar cell manufacturing leading to high short-circuit current.

Keywords

Silicon Solar Cell, Magnetotransport, Surface Recombination Velocity, Base Thickness

1. Introduction

One major problem of silicon solar cells is the small collection of minority charge carriers which may be due among others at short diffusion lengths and carrier's mobility and surfaces recombination velocity issues. In order to improve its performance, several characterization techniques relating to minority carriers deflection under magnetic field, were presented [1]-[6]. Thus, the structure solar cell studied can be with:

1) horizontal junction (monofacial, bifacial or double side surface field) [7] [8] [9].

2) multiple vertical junction (series or parallel) [10] [11] [12].

The operating conditions are various regimes *i.e.*: static [13] [14] [15] and dynamic [16] [17] [18] [19]. The phenomenological parameters to be determined are, diffusion length (L), diffusion coefficient (D), lifetime (τ), surface recombination velocities respectively at the junction (Sf) and the rear (Sb) [20] [21] [22] [23] [24]. The imposed both, thickness (H) [25] and doping rate [26] are to be take into account. The applied external conditions such as, radiation flux and energy [27], temperature and magnetic field [28] [29] [30], influence the phenomenological parameters.

In this work, we present a method to determinate the optimum thickness ($Hopt$) of silicon solar cell under external conditions *i.e.* magnetic field (B) and polychromatic illumination.

2. Theoretical Study

2.1. Monofacial Solar Cell Presentation

Silicon solar cell type $n^+/p/p^+$ [5] subjected to multi spectral illumination and a constant magnetic field (perpendicular to Ox axis), is presented in **Figure 1**.

2.2. Magnetotransport Equation

The $\boldsymbol{B}$ magnetic field influences the movement of minority charge carriers. In this condition the distribution equation relative to minority charge carriers $\delta(x,B)$ in the base is given as follows [4] [6] [14] [31] [32].

$$\frac{\partial^2\delta(x,B)}{\partial x^2}-\frac{\delta(x,B)}{L(B)^2}=-\frac{G(x)}{D} \tag{1}$$

$G(x)$ is the minority carrier's generation rate [33]

$$G(x)=n\times\sum_{i=1}^{3}a_i\times \mathrm{e}^{-b_i\cdot x} \tag{2}$$

$D(B)$ is the minority carrier's diffusion coefficient depending on B [25] [28] [31] [34] and D_0 is diffusion coefficient without magnetic field.

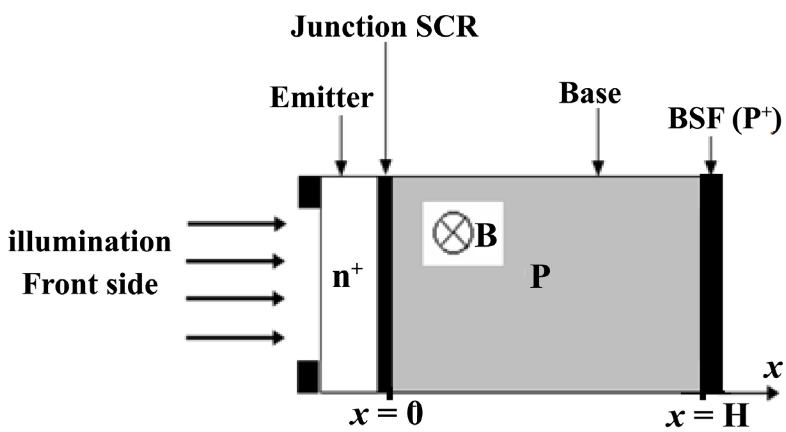

Figure 1. Front illuminated silicon solar cell structure type $n^+/p/p^+$.

$$D(B)=\frac{D_0}{1+(\mu B)^2} \tag{3}$$

$$L(B)=\sqrt{\tau \times D(B)} \tag{4}$$

L is the minority carrier's diffusion length B depending and τ their lifetime.

2.3. Solution

The Magnetotransport equation solution is given by following expression $\delta(x,B)$ for front illumination:

$$\delta(x,B)=E\times\cosh\left(\frac{x}{L(B)}\right)+F\times\sinh\left(\frac{x}{L(B)}\right)+n\times\sum_{i=1}^{3}a_i\times e^{-b_i\cdot x} \tag{5}$$

The previous relationship is fully defined, by determining the coefficients E and F, using base boundary conditions, what are junction (*i.e.* space charge region) and back side (p/p+ surface).

2.4. Boundary Conditions

- At the junction $x = 0$:

$$\left.\frac{\partial\delta(x,B)}{\partial x}\right|_{x=0}=\frac{Sf}{D(B)}\delta(x,B)\Big|_{x=0} \tag{6}$$

Sf is excess minority carrier junction recombination velocity and describes the solar cell operating point [35] [36].

- At back side $x = H$:

$$\left.\frac{\partial\delta(x)}{\partial x}\right|_{x=H}=\frac{-Sb}{D}\delta(x)\Big|_{x=H} \tag{7}$$

Sb is back surface recombination velocity induced by the back surface field for low high junction (p/p+) and thus minority carriers are pushed back to the junction. The space charge region's (n+/p) electrical field allows them to be collected and to contribute to the photocurrent [37] [38] [39].

2.5. Photocurrent Density for Different Magnetic Field Values

The excess minority charge carriers collected through junction give photocurrent density $Jph(Sf,B)$ obtained from the following Fick relation.

$$Jph(Sf,B)=q\times D(B)\times\left[\frac{\partial\delta(x,B)}{\partial x}\right]\Bigg|_{x=0} \tag{8}$$

Figure 2 gives the plot of photocurrent density versus minority carrier's recombination velocity at the junction (Sf).

Regardless of the magnetic field values, the photocurrent increases with the junction recombination (Sf). When junction recombination velocity is high, short circuit photocurrent is obtained, and then, magnetic field reduced by deflection the electric charges due to increased Lorentz force intensity. Thus two study intervals will be defined according to magnetic field B value.

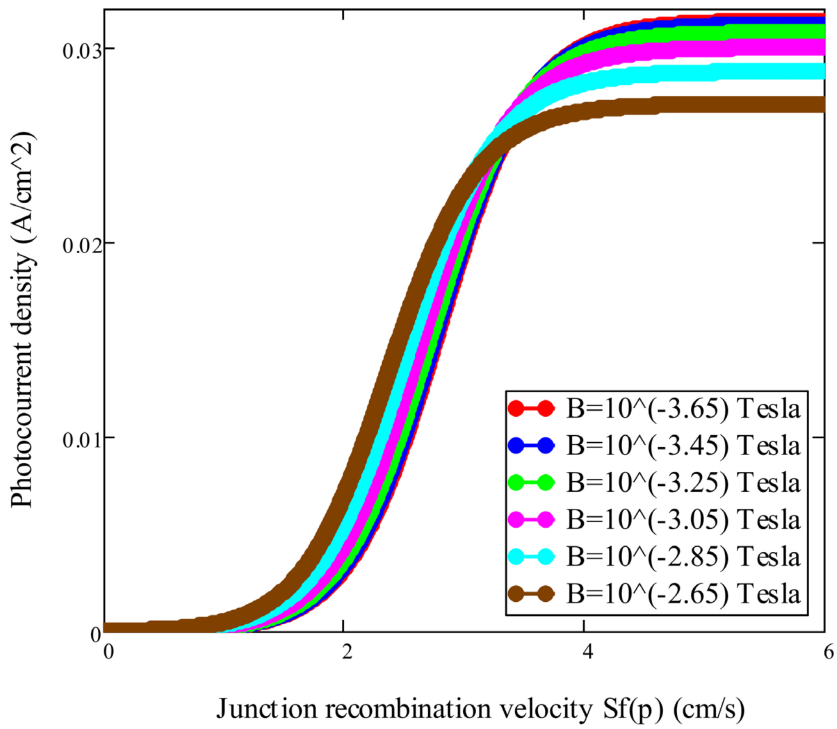

Figure 2. Photocurrent density for large magnetic field values versus junction recombination velocity (in front side $H = 200$ µm, $D = 35$ cm²/s).

2.6. Back Surface Recombination Velocity and Optimum Thickness Determination

Otherwise, we note that at high values recombination velocity *Sf*, photocurrent remains constant and becomes short circuit current *Jsc*(*B*, *H*). So its derivative with respect to *Sf*, is therefore zero [39]. Solving such an equation gives the new back surface recombination velocity (*Sb*) expressions, of excess minority carriers, magnetic field dependent.

$$\left.\frac{\partial J_{ph}(Sf,B)}{\partial Sf}\right|_{Sf\geq 10^4} = 0 \tag{9}$$

Equation (9) leads to two expressions of back surface recombination velocity of excess minority charge carriers in the base respectively, *Sb*1 and *Sb*2 [24] [39]:

$$Sb1(H,B) = -\frac{D(B)}{L(B)} \times \tanh\left(\frac{H}{L(B)}\right) \tag{10}$$

$$Sb2(H,B) = \frac{D(B)}{L(B)} \cdot \sum_{i=1}^{3} \frac{L(B)\cdot b_i\left(e^{b_i\cdot H} - \cosh\left(\frac{H}{L(B)}\right)\right) - \sinh\left(\frac{H}{L(B)}\right)}{-L(B)\cdot b_i \cdot \sinh\left(\frac{H}{L(B)}\right) + \cosh\left(\frac{H}{L(B)}\right) - e^{b_i\cdot H}} \tag{11}$$

*Sb*1 electronic parameters dependent (*D* and *L*), is designed as intrinsic back surface recombination, while *Sb*2 also depending of average (composite) absorption coefficient (b_i) [33] is considered as extrinsic one.

2.7. The Base Optimum Thickness Determination

The optimum thickness determination technique, already used on solar cells maintained under other conditions [26] [29] [30] [40] [41] [42] [43] is applied here, according to two ranges of magnetic field values. *Sb*1 and *Sb*2 are plotted versus *H* base thickness, for given magnetic values.

1) Low range values:

Figure 3 gives the representation of *Sb*1 and *Sb*2 versus *H*, for given magnetic field values *B* as: $10^{-3.75} \le B \le 10^{-3.55}$ T.

For each magnetic field *B* value, the optimum base thickness (*Hopt*) is determined by projection on absciss-axis of the intercept point of velocity curves *Sb*1 and *Sb*2. Thus the different values are presented in Table 1, and represented on Figure 4, as *Hopt* versus *B*.

The correlation between optimum thickness and magnetic field is established below:

$$\square\, Hopt(\text{cm}) = u \times B + y \tag{12}$$

with: $u = -1.9508\ \text{cm}\cdot\text{T}^{-1}$ and $y = 0.0634\ \text{cm}$

2) Large range values:

Figure 5 shows *Sb*1 and *Sb*2 versus thickness *H*, for the second range of magnetic field *B* values: $10^{-3.45} \le B \le 10^{-3.25}$ T.

The previous technique is used to determine the numerical optimum thickness (*Hopt*) value of the base. Thus the different values are presented in Table 2. Figure 6, gives the obtained *Hopt* values representation versus *B*.

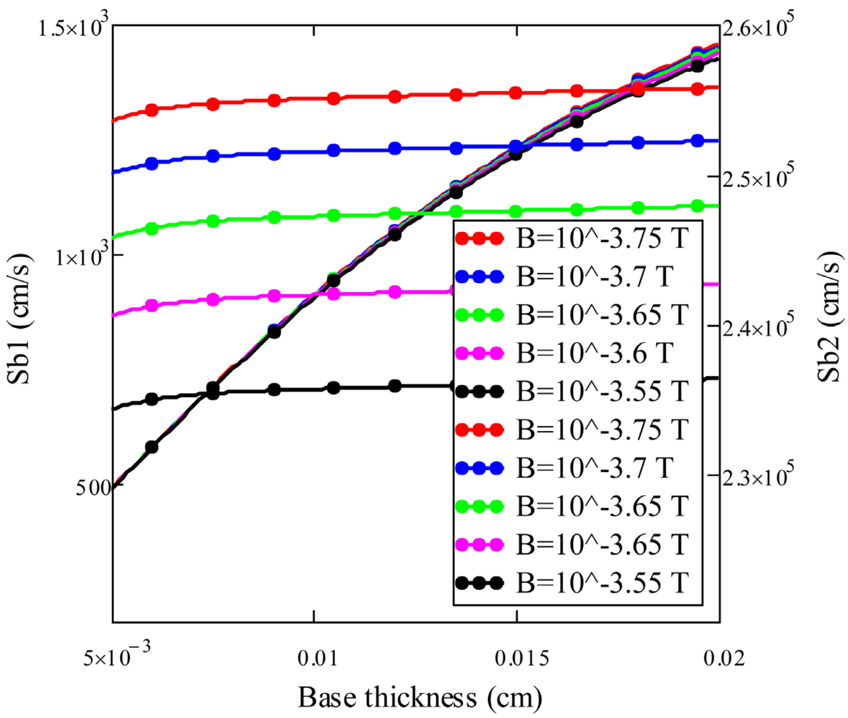

Figure 3. Back surface recombination velocity versus solar cell base thickness for different magnetic field values.

Table 1. Optimum thickness (*Hopt*) for different magnetic field (*B*) values.

B (T)	$10^{-3.75}$	$10^{-3.7}$	$10^{-3.65}$	$10^{-3.6}$	$10^{-3.55}$
Hopt (cm)	0.0176	0.0150	0.0127	0.0100	0.0074

Table 2. Optimum thickness (*Hopt*) for different magnetic field (*B*) values.

B (T)	$10^{-3.45}$	$10^{-3.4}$	$10^{-3.35}$	$10^{-3.3}$	$10^{-3.25}$
Hopt (cm)	0.0158	0.0149	0.0139	0.0129	0.0117

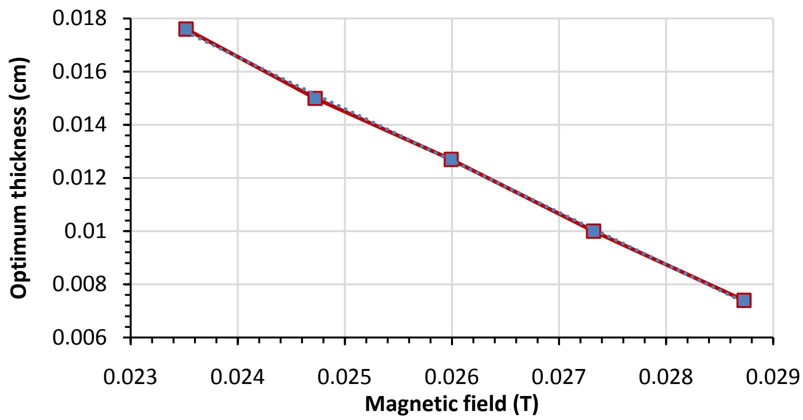

Figure 4. Optimum thickness Hop of base versus magnetic field.

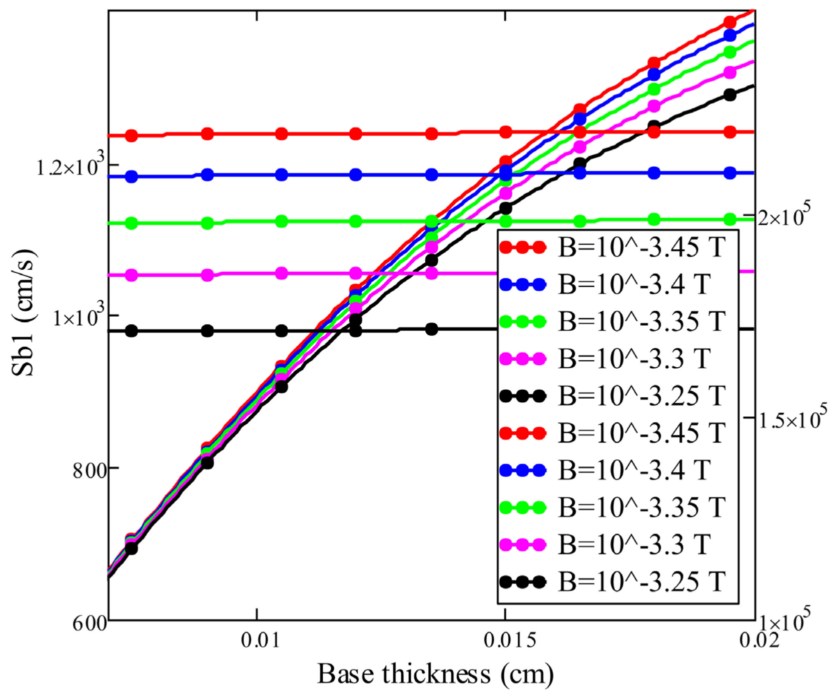

Figure 5. Back surface recombination velocity versus thickness base for different values magnetic field.

The correlation between optimum thickness and magnetic field is established below:

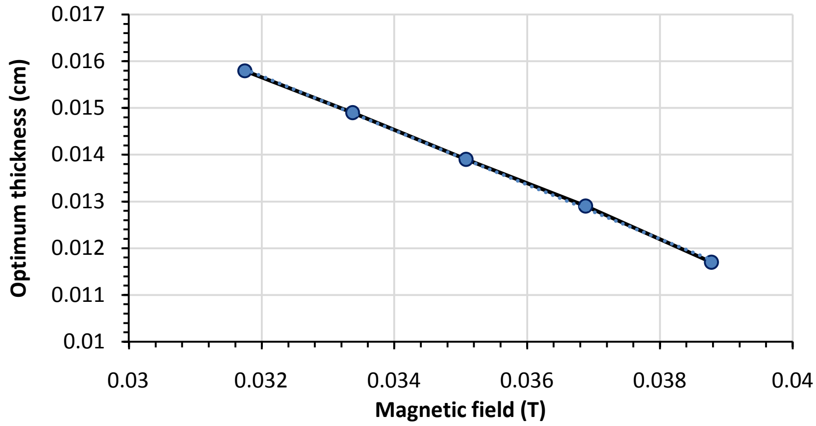

Figure 6. Optimum thickness Hop versus magnetic field B.

$$\square\ Hopt(\mathrm{cm}) = \gamma \times B + \psi \tag{13}$$

with: $\gamma = -0.581\,\mathrm{cm}\cdot\mathrm{T}^{-1}$ and $\psi = 0.0343\,\mathrm{cm}$

The results obtained by the application of the optimum thickness determination technique, show here, a thickness decrease with the magnetic field, for the two magnetic field ranges. This means that Lorentz's strength increases with the magnetic field imposes lower thicknesses to recover minority carriers, for a maximum photocurrent delivered by the solar cell. Both lowest and highest magnetic field values give respectively 176 µm and 117 µm solar cell base optimum thickness. This appears as a compromise between the different physical mechanisms of generation-diffusion-recombination-deflection, which take place in the base of the solar cell. This allows us to conclude that a front illuminated silicon solar to operate under magnetic field requires less material for its manufacturing.

It should be noted that previous work, using the same technique or other [44], has produced very interesting results, maintaining the solar cell (horizontal or vertical junction [41] [45]) under variation of: absorption coefficient [45], doping rate (hence the lifetime, the diffusion coefficient) [26] and irradiation flux by nuclear particles [40].

Modelling studies by combination of two to two or three of the previous conditions [29] [30] [42] have revealed the important economy of matter in the manufacture of solar cell, for these specific uses. The mathematical relationships between the optimum thickness of the base of the solar cell and the parameters of these specific conditions have been established

It appears from the analysis of these results that the deflection of minority carriers due to the magnetic field, leads to lower optimum thicknesses than in other cases, such as thermal agitation (Umklap process), or the use of monochromatic absorption coefficient radiation (short wavelengths).

3. Conclusion

The calibrating silicon solar cell base thickness under polychromatic illumination operating and applied magnetic field, was realized. The optimal thickness (*Hopt*) decreases significantly with the external applied magnetic field. This yield makes a judicious and optimal choice of the thickness of the base solar cell during its manufacture for an application of this kind.

Conflicts of Interest

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

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