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International Journal of Engineering Research Updates

Journal homepage: https://orionjournals.com/ijeru/

ISSN: 2783-0187 (Online)

(RESEARCH ARTICLE)

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Monochromatic ligth of short wavelength as applied to determine (N+/P/P+) Silicon solar cell base thickness under the influence of both magnetic field and temperature

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International Journal of Engineering Research Updates, 2022, 03(02), 013–025

Publication history: Received on 05 September 2022; revised on 15 October 2022; accepted on 18 October 2022

Article DOI: https://doi.org/10.53430/ijeru.2022.3.2.0055

Abstract

The magneto-transport equation relating to the density of the photogenerated minority carriers in the base of the silicon solar cell is studied under monochromatic illumination. The optimum thickness (Hopt) of the base of the solar cell is obtained, by the graphical method of representing the recombination velocity of the minority carriers on the back side. The optimum thickness (Hopt) decreases with both, the applied magnetic field and temperature, and justifies the material saving by established modeling expressions.

Keywords: Silicon Solar Cell; Absorption coefficient; Temperature; Magnetic Field; Diffusion Coefficient; Surface Recombination Velocity; Optimum Base Thickness

1 Introduction

The performance of a silicon solar cell (n+/p/p+) depends on phenomelogic parameter values of charge carriers' photogenerated in the material [1-3].

These are the lifetime (τ) [4- 8], the diffusion length (L) [9-11], the diffusion coefficient [12] and the mobility (μ) [13-15], as well as the surface recombination rates [16] in particular (Sf) at the junction (n+/p) [17- 20], (Sb) on the back side (p/p+) [21-25] and (Sg) at the grain joints, particularly for the 3D solar cell representation model[26-29].

However the architecture [30-33] and dimensions [34-38] of the different regions of the solar cell play an important role in order to obtain a better efficiency [39], when the physical phenomena that take place there are mastered [40-42]. The thickness of the base imposes the cost of manufacture, therefore influences the selling price of the solar cell [43- 47]. The base is the region of great thickness and generation of the maximum photocurrent by these electronic parameters [4, 3].

The search for the optimum thickness of the base has been the subject of multiple investigations under various conditions [48- 58] of operation of the solar cell, which can also be cut under different thicknesses [6, 32, 59, 60], in order to be characterized.

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Our study places the solar under a magnetic field (B) [3, 61, 62] and at temperature (T) [37, 63- 65] and illuminated by a monochromatic light with constant flux [9] and absorption coefficient (α(λ)) [66, 67, 68, 69].

The minority charge carriers created in the base, undergo Lorentz's law [61, 62] and the Umklap process [63, 64], leading to the temperature resonance of the diffusion coefficient that becomes (Dmax) [70], for a given magnetic field.

It is obtained by temperature variation, up to the resonance (Topt) value, keeping the magnetic field constant. The magneto-transport equation relating to the density of the minority charge carriers in the base in this condition is solved, provided with the boundary conditions defining the recombination velocity (Sf) at the junction [17, 18, 19] and (Sb) on the rear side [21-26].

The current density is deduced and represented as a function of (Sf), which also indicates the solar cell operating point [17, 20, 71].

Thus at the operating point of short circuit (Sf very large) [72], the two expressions of the recombination velocity (Sb) of the minority charge carriers are extracted, both dependent on the maximum diffusion coefficient and one has in addition a term of generation velocity [9, 18] associated with the absorption coefficient (α(λ)) of the material [66- 68].

The representation of the curves associated with these two expressions of the recombination velocity [49-55] on a vertical bi-axis curve as a function of thickness (H), allows to extract the optimum thickness (Hopt) from the base of the solar cell for a given value (Dmax) of the diffusion coefficient. The thickness (Hopt) obtained is then modeled as an increasing function of Dmax but decreasing with both B and Topt.

2 Theory

The figure. 1, gives the structure of the n+-p-p+ silicon solar cell [73], front illuminated with monochromatic light, is placed under both, magnetic field (B) and temperature (T).

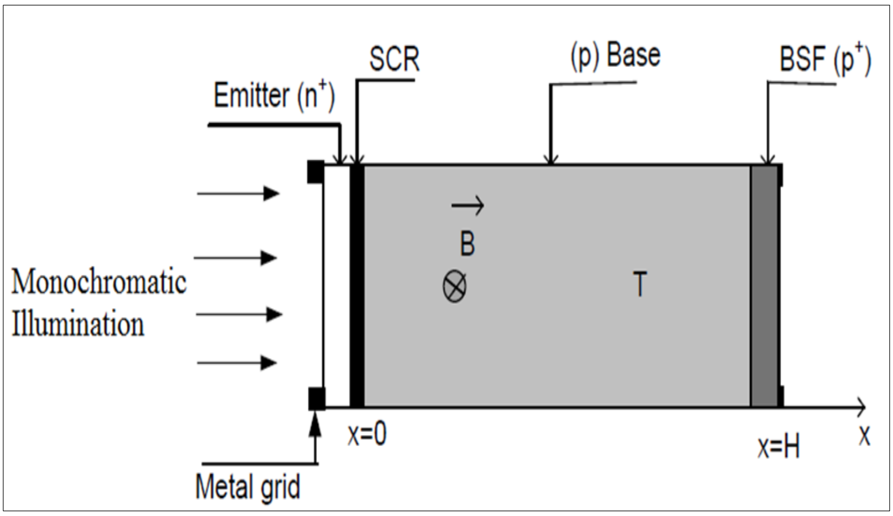

Figure 1 Structure of front illuminated solar cell under magnetic field and temperature

The excess minority carriers' density $\delta(x, B, T)$ generated in the base of the solar cell, under magnetic field B at temperature T, under monochromatic illumination, is governed by the following magneto transport equation:

$$D(B,T) \times \frac{\partial^2 \delta(x,B,T)}{\partial x^2} - \frac{\delta(x,B,T)}{\tau} = -G(x) \qquad \text{.................................(1)}$$

τ and $D(B,T)$ are respectively the lifetime and the diffusion coefficient of the excess minority carriers in the base under magnetic field and under temperature, given by the following relationship [[61, 62]:

$$D(B,T)=\frac{D(T)}{1+(\mu B)^2} \quad \text{……………….(2)}$$

With:

$$D(T)=\frac{\mu(T)\cdot K\cdot T}{q} \quad \text{……………. (3)}$$

And the mobility coefficient is given as:

$$\mu(T)=1{,}43.10^{19}.T^{-2{,}42} \quad \text{……………………….(4)}$$

L represents the diffusion length of excess minority carriers in the base:

$$L^2(B,T)=D(B,T)\cdot\tau \quad \text{………………….(8)}$$

Carrier generation rate $G(x,t)$ is given by the relationship :

$$G(x)=\alpha(\lambda)\cdot I_0(\lambda)\cdot(1-R(\lambda))\cdot e^{-\alpha\cdot(\lambda).x} \quad \text{…………….(9)}$$

x is the depth in the base.

2.1 The solution of equation (1) is:

$$\delta(x,B,T,\alpha)=A\cdot\cosh\left[\frac{x}{L(B,T)}\right]+E\cdot\sinh\left[\frac{x}{L(B,T)}\right]+K\cdot e^{-\alpha\cdot x} \quad \text{……………(10)}$$

With

$$K=\frac{\alpha\cdot I_0\cdot(1-R)\cdot[L(B,T)]^2}{D(B,T)\left[L(B,T)^2\cdot\alpha^2-1\right]} \quad \text{………………(11)}$$

and

$$\left(L(B,T)^2\cdot\alpha^2\neq 1\right) \quad \text{……………………. (12)}$$

Coefficients A and E are determined through the boundary conditions:

At the junction (x = 0)

$$\left.\frac{\partial\delta(x,\alpha,B,T)}{\partial x}\right|_{x=0}=Sf\cdot\left.\frac{\delta(x,\alpha,B,T)}{D(B,T)}\right|_{x=0} \quad \text{…………………….(13)}$$

- On the back side in the base (x = H)

$$\left.\frac{\partial\delta(x,\alpha,B,T)}{\partial x}\right|_{x=H} = -Sb\cdot\left.\frac{\delta(x,\alpha,B,T)}{D(B,T)}\right|_{x=H} \qquad (14)$$

Sf and Sb are respectively the recombination velocities of the excess minority carriers at the junction [17-20] and at the back surface [9, 21-25, 48].

3 Results

3.1 Diffusion coefficient

The derivative with respect to temperature, of the expression of the diffusion coefficient from equations (2, 3 and 4), gives the following relationship [70], while magnetic field remained constant:

$$T_{op}(B) = \sqrt[4{,}84]{2{,}4x(1{,}43.10^{9})^{2}.B^{2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots(15)$$

This relationship allows us to calculate the optimal temperature (Topt) for different values of the magnetic field (B) and to deduce the maximum diffusion coefficient (Dmax). Table. 1 below shows the results achieved.

Table 1 Maxima of the diffusion coefficient and the optimal temperature for a given magnetic field obtained by the analytical method

Magnetic field B(T)	**0.0003**	**0.0004**	**0,0005**	**0,0006**	**0.0007**	**0.0008**	**0.0009**	**0.001**
Optimum Temperature (K)	254.7	286.6	313	336.5	361.4	381.9	401.0	418.8
Maxima of diffusion Coefficient (cm2/s)	33,368	28,173	24,66	22.202	20.259	18.757	17.561	16.548

3.2 Photocurrent

The photocurrent density at the junction is obtained from the density of minority carriers in the base and is given by the following expression:

$$J_{ph}(Sf,Sb,\alpha,H,B,T) = qD(B,T)\left.\frac{\partial\delta(x,\alpha,H,Sf,Sb,B,T)}{\partial x}\right|_{x=0} \quad \ldots\ldots\ldots\ldots\ (15)$$

Where q is the elementary electron charge.

Figure 2 shows the photocurrent density obtained with strong absorption coefficient versus the junction surface recombination velocity for different diffusion coefficient (Dmax).

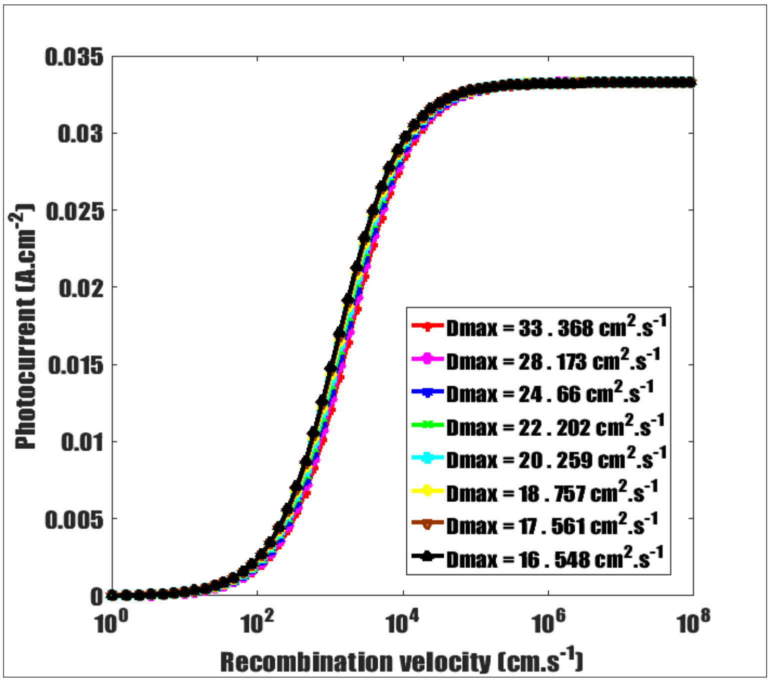

Figure 2 Module of photocurrent density versus recombination velocity for different diffusion coefficient values (α = 21000 cm^{-1})

At the large (Sf), values, figure 2 shows a small variation in the circuit current with (Dmax). Indeed the monochromatic light of short wavelength corresponding to a large value of (α(λ)) penetrates weakly into the solar cell.

Charge carriers are photogenerated near the junction. The distance to reach the junction is short, hence a small impact of the deflection produced by (B). The effect of the high value of the monochromatic absorption coefficient (α(λ)) prevails, over the phenomenon of deflection

3.3 Base thickness Optimization by study of the minority carriers' recombination velocity at the back surface

The plot of photocurrent density (Jph) according to the junction recombination velocity of minority carriers is done on figure. 2. The photocurrent density increases with the recombination velocity (Sf) at the junction, to reach an asymptotic value (Jphsc), which corresponds to the short-circuit current, for large (Sf) values. So, in this junction recombination velocity interval, we can write [18, 72]:

$$\left.\frac{\partial J_{ph}(\alpha, H, Sf, Sb, B, T)}{\partial Sf}\right|_{Sf \geq 10^5\, cm.s^{-1}} = 0 \text{ ....(16)}$$

The solution of equation (15) leads to the ac recombination velocity in the back surface expressions given by equations (16) and (17):

$$Sb1(B,T) = -\frac{D(B,T)}{L(B,T)}.\tanh\left(\frac{H}{L(B,T)}\right) \text{ .... (17)}$$

$$Sb2(B,T,\lambda) = \frac{D(B,T)}{L(B,T)} \cdot \left[\frac{\alpha(\lambda)\cdot L(B,T)\cdot\left(\exp(-\alpha(\lambda)\cdot H) - \cosh\left(\frac{H}{L(B,T)}\right) + \sinh\left(\frac{H}{L(B,T)}\right)\right)}{\exp(-\alpha(\lambda)\cdot H) - \cosh\left(\frac{H}{L(B,T)}\right) + \alpha(\lambda)\cdot L(B,T)\cdot\sinh\left(\frac{H}{L(B,T)}\right)}\right] \text{ ......(18)}$$

The figure 3 is a graphical representation of the two expressions of back surface recombination velocity versus solar cell base thickness, for different diffusion coefficient values (Dmax).

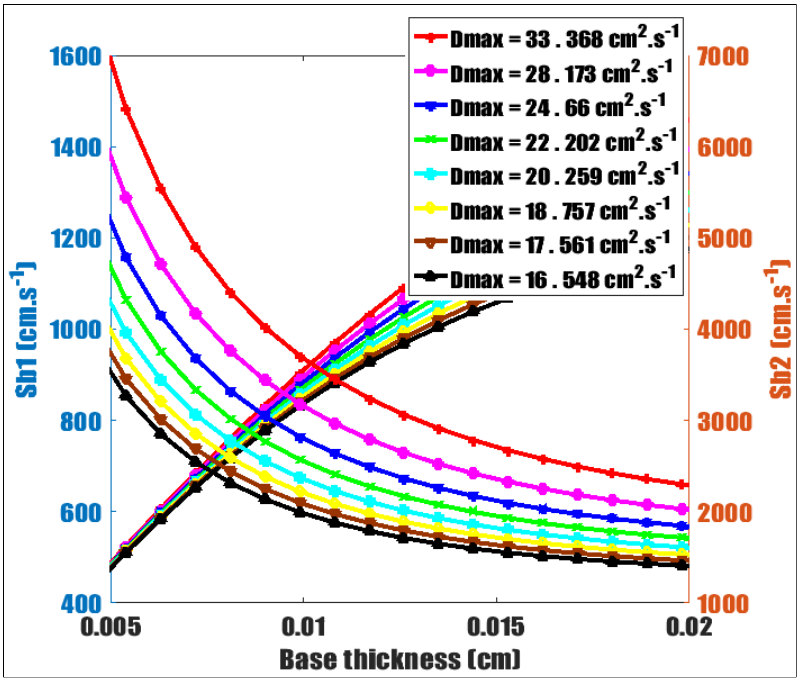

Figure 3 Sb1 and Sb2 versus depth in the base for given diffusion coefficient values

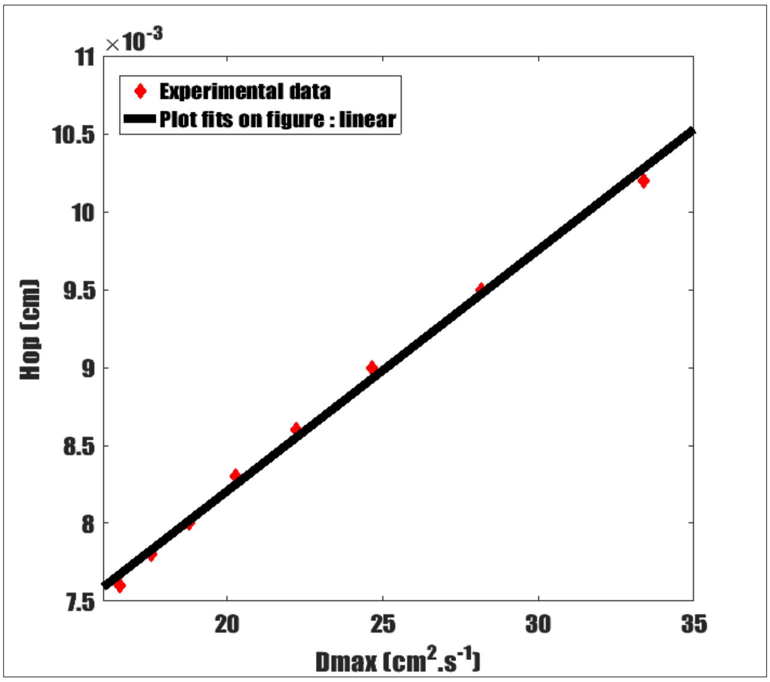

Figure 4 Optimum thickness versus Dmax

$$Hop(cm) = 1.5 \cdot 10^{-4} \times D\max + 0.0051 \text{ ....(19)}$$

Table 2 Result of the optimum thickness of the base, extracted from the figure. 3

Magnetic field B(T)	**0.0003**	**0.0004**	**0.0005**	**0.0006**	**0.0007**	**0.0008**	**0.0009**	**0.001**
Optimum Temperature (K)	254.7	286.6	313	336.5	361.4	381.9	401.0	418.8
Dmax (cm^2/s)	33.368	28.173	24.66	22.202	20.259	18.757	17.561	16.548
Hopt (cm)	0.0102	0.0095	0.0090	0.0086	0.0083	0.008	0.0078	0.0076

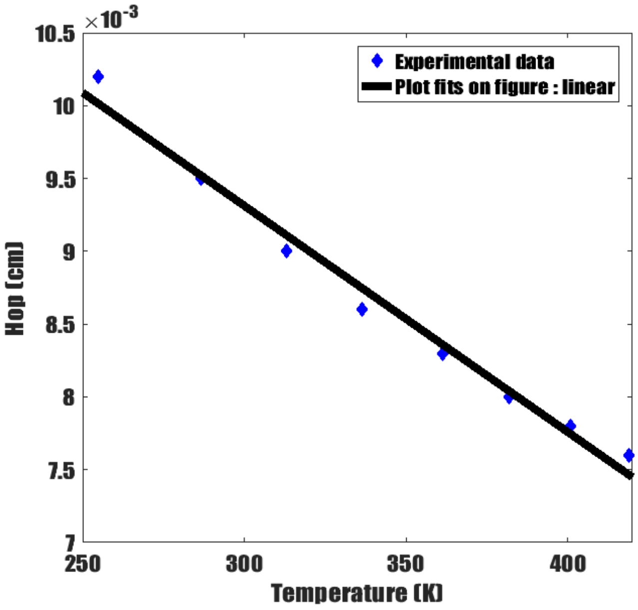

Figure 5 Optimum thickness versus temperature

$$Hop(cm) = -1.6 \cdot 10^{-5} \times T + 0.014 \quad \text{.................(20)}$$

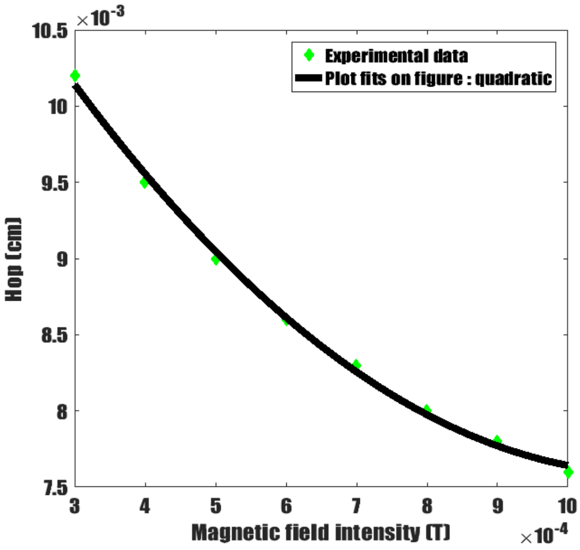

Figure 6 Optimum thickness versus magnetic field intensity

$$Hop = 3.8 \cdot 10^{3} \times B^{2} - 8.5 \times B + 0.012 \quad \text{...................... (21)}$$

4 Discussions

The high absorption (large α(λ) value) leads to a low penetration of light in the depth, so a generation of minority charge carriers near the junction is established. Therefore, the distance to be covered before arriving at the junction is obviously small [9, 50, 68].

Lorentz's law that applies has little effect on minority carriers with a short course.

.The effect of thermal agitation (Umklapp process) [51, 52, 57,75] near the junction, widens or reduces the space charge region (SCR), which influences the recovery of charge carriers [37] and their contribution to the photocurrent.

Other research results on the optimum thickness of the base of the silicon solar cell, have shown its decay with:

- the monochromatic absorption coefficient (α(λ)) of the illumination [50].
- the frequency of modulation(ω) of the incident light [54, 55, 58]
- the applied magnetic field (B) [53,74], associated with a temperature variation (T) [51, 52, 75], or a modulation frequency variation (ω, B) [76]
- The flow (ϕ) of charged particles allowing the irradiation of the base [77].
- With these results, investigations on thin films are necessary [43-46]

5 Conclusion

This work led to the extraction of the optimum thickness of the base of the silicon solar cell, under monochromatic illumination of high absorption and to establish the mathematical correlations with the maximum diffusion coefficient of the minority charge carriers obtained at the optimum temperature point, border between the physical phenomena of deflection due to the magnetic field and the Umklapp process.

For this, the magneto-transport equation relating to the density of the minority charge carriers in the base of the solar cell was solved, provided with boundary conditions, which made it possible to introduce the recombination velocity in front and rear face.

The graphical study of the expressions the recombination velocity of the minority carriers on the back side, deduced from the photocurrent density, made it possible to extract the optimum thickness of the base of the solar cell, and to carry out a modeling according to both, the applied magnetic field and the temperature.

The results show the possibility of reducing the thickness of the base in the industrial development of the silicon solar cell and reinforces the research track on thin-film solar cells, to achieve a material saving.

Compliance with ethical standards

Acknowledgments

In memory of the deceased colleagues, Professor Dianguina DIARISSO and Professor Ibrahima LY.

Disclosure of conflict of interest

The authors declare no conflicts of interest.

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