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(n+/p/p+) Silicon solar cell base thickness optimization under modulated short wavelength illumination, at resonances in both frequency and temperature of minority carriers' diffusion coefficient

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Abstract

The magneto-transport equation relating to the density of photogenerated minority carriers in the (p) base of the (n+/p/p+) solar cell illuminated by monochromatic light in frequency modulation, is solved. The diffusion coefficient of the minority carriers in the base, placed under temperature and magnetic field variation, passes through a maximum, at the double resonance points, in temperature and at the frequency of the cyclotron. The photocurrent is reproduced as a function of the recombination velocity at the junction, for the maximum values of the diffusion coefficient. The expressions of the minority carriers 'recombination velocity on the rear side are deduced and their graphical representation gives the optimum thickness, specific to a high absorption coefficient, for the maximum values of the diffusion coefficient. The results obtained from the optimum thickness are modelled and analyzed, in favor of a reduction of silicon material, for the development of economical solar cells.

Keywords: Silicon Solar Cell; Diffusion Coefficient; Resonance-Temperature; Magnetic field; Recombination Velocity; Absorption coefficient; Optimum Base Thickness

1 Introduction

The search for solar cell efficiency improvement, led to the optimization of the thickness of the base [1, 2], by the characterization of samples with different thicknesses, cut from the massif [3, 4, 5, 6, 7]. However, the depth of the other regions (emitter and space charge region) of the solar cell are also important [8, 9, 10] and allow the decoupling of the physical mechanisms that govern the operation of the solar cell [11, 12].

This work consists in looking for the optimum thickness of the (p) base [1, 2, 13, 14, 15, 16, 17, 8, 19] of a silicon solar cell (n+/p/p+) [20, 21], when subjected to a magnetic field (B) and placed under a temperature (T).

It is then illuminated by a monochromatic light in frequency modulation (ω) [22, 23, 24, 25, 26], of short wavelength (λ), inducing a very large absorption coefficient (α(λ)) of the material (Si) [27, 28].

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The illumination then, penetrates weakly into the base [29] and therefore the carriers are photogenerated near the junction in the base, because (α (λ)) is very large and they are subsequently subjected to Lorentz's law (effect of B) [30, 31, 32] and the Umklapp process due to thermal agitation (effect of T) [33, 34, 35, 36, 37, 35].

Under these conditions the diffusion coefficient D(ω, B, T) of the minority charge carriers in the base under the action of the variation of (B) undergo the ringing effect:

- At the cyclotron frequency (ωc) [39, 40, 41]
- At the optimum temperature (Topt) [35]
- This double resonances, in frequency and temperature makes it possible to establish a new expression of the diffusion coefficient D (ωc, Topt) of the minority carriers in the base [42].

The diffusion equation of the minority carriers in the base is then solved and the solution δ(x, ω, B, T, α(λ)) of the density of the minority charge carriers is completed by taking into account boundary conditions in the base, which are (Sf) and (Sb), respectively recombination rates [11, 43] at the junction (n+/p) [44, 45, 46, 47, 48] and back side (p/p+)[49, 50, 51, 52].

From the profile obtained, the density of the photocurrent Jph (D (ωc, Topt), α(λ), H, Sf, Sb) as a function of the recombination velocity (Sf), the expressions of the recombination velocity

(Sb [D (ωc, Topt), α(λ), H] are established [53, 54, 55, 56, 57]. The representation of these expressions [1, 2, 13, 14, 15, 16, 17] in the form of bi-axis curves as a function of thickness (H), for different values of D (ωc, Topt) and given α(λ), allow to extract the optimum thickness (Hopt), which is then modeled as a function of both D (ωc, Topt), and Topt.

2 Theory

The front illuminated (n+-p-p+) silicon solar cell [20, 21] with modulated monochromatic light, and placed under magnetic field B and temperature T, is presented below, by figure 1

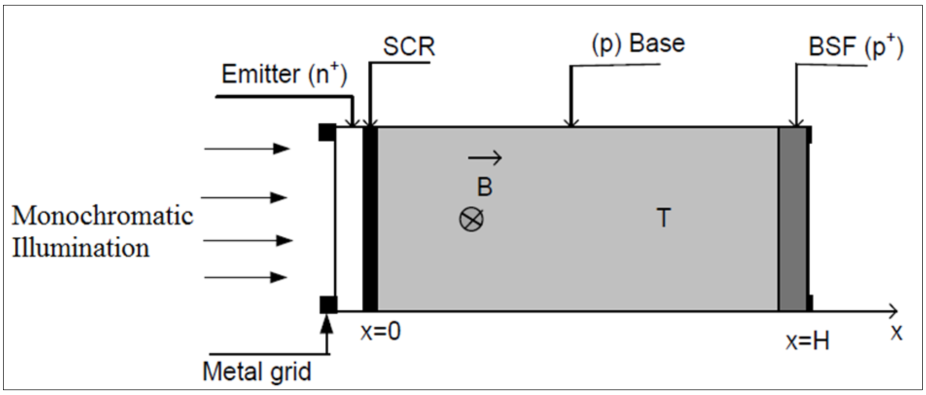

Figure 1 Structure of front illuminated solar cell

The excess minority carriers' density $\delta(x,t)$ generated in the base of the solar cell obeying to the magneto-transport equation at T temperature, under monochromatic illumination in frequency modulation, is given by [5, 6, 25, 58]:

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

The expression of the excess minority carriers' density is written, according to the space coordinates (x) and the time t, as:

$$\delta(x,t)=\delta(x)\cdot e^{-j\omega t} \quad \text{..... (2)}$$

The excess minority carriers' lifetime in the base is (τ) and the generation rate $G(x,t)$ is given by the following relationship:

$$G(x,t) = g(x) \cdot e^{-j\omega t} \quad \text{.............................. (3)}$$

With:

$$g(x) = \alpha(\lambda) \cdot I_0(\lambda) \cdot (1 - R(\lambda)) \cdot e^{-\alpha \cdot (\lambda) \cdot x} \quad \text{.............................. (4)}$$

$I_0(\lambda)$ is the monochromatic incident flux, while $\alpha(\lambda)$ and $R(\lambda)$ are optical parameters of Si material [27, 28, 59, 60, 61].

$D(\omega, B, T)$ is the complex diffusion coefficient of excess minority carrier in the base under magnetic field and temperature and frequency modulation [39, 40].The solution of equation (1) is:

$$\delta(x,\omega,B,T) = A \cdot \cosh\left[\frac{x}{L(\omega,B,T)}\right] + E \cdot \sinh\left[\frac{x}{L(\omega,B,T)}\right] + K \cdot e^{-\alpha \cdot x} \quad \text{.............................. (5)}$$

With

$$K = \frac{\alpha \cdot I_0 \cdot (1 - R) \cdot [L(\omega,B,T)]^2}{D(\omega,B,T)\left[L(\omega,B,T)^2 \cdot \alpha^2 - 1\right]} \quad \text{.............................. (6)}$$

And

$$\left(L(\omega,B,T)^2 \cdot \alpha^2 \neq 1\right) \quad \text{.............................. (7)}$$

Coefficients A and E are determined through the boundary conditions expressed as:

At the junction (x = 0)

$$\left.\frac{\partial \delta(x,\omega,B,T)}{\partial x}\right|_{x=0} = Sf \cdot \left.\frac{\delta(x,\omega,B,T)}{D(\omega,B,T)}\right|_{x=0} \quad \text{.............................. (8)}$$

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

$$\left.\frac{\partial \delta(x,\omega,B,T)}{\partial x}\right|_{x=H} = -Sb \cdot \left.\frac{\delta(x,\omega,B,T)}{D(\omega,B,T)}\right|_{x=H} \quad \text{.............................. (9)}$$

The excess minority carriers'recombination velocities are Sf and Sb respectively at the junction [44, 45, 47] and at the back surface [44, 49, 50].

3 Results

3.1 Minority carriers' diffusion Coefficient

- Its expression is given by the relationship [39, 40]:

$$D(\omega,B,T)=D(B,T)\times\frac{\left[\left(1+\tau^2(\omega_c(B)^2+\omega^2)\right)\right]+j\omega\tau\left[\tau^2\left(\omega_c(B)^2-\omega^2\right)-1\right]}{\left[1+\tau^2\left(\omega_c(B)^2-\omega^2\right)\right]^2+4\omega^2\tau^2} \quad \text{.................................} (10)$$

With the cyclotron frequency expressed as :

$$\omega_c=\frac{q\cdot B}{m_e^*} \quad \text{.................................} (11)$$

$D(B,T)$ is the diffusion coefficient of the excess minority carriers in the base of the solar cell, under magnetic field and under temperature.

Under magnetic field, the diffusion coefficient is given by the following relation [30, 32]:

$$D(B,T)=\frac{D(T)}{1+(\mu B)^2} \quad \text{.................................} (12)$$

With :

$$D(T)=\frac{\mu(T)\cdot K\cdot T}{q} \quad \text{.................................} (13)$$

And the mobility coefficient is given as [5, 38]:

$$\mu(T)=1{,}43.10^{19}.T^{-2{,}42} \quad \text{.................................} (14)$$

The representation of the diffusion coefficient of the minority charge carriers as a function of temperature admits a maximum corresponding to the optimum temperature Topt (ω,B). The optimum temperature is obtained by solving the following equation [42]:

$$\frac{dD(\omega,B,T)}{dT}=0 \quad \text{.................................} \textbf{(15)}$$

From this equation one can deduce the values of the optimum temperature Topt (ω,B) for different values of the cyclotron frequency and magnetic field (**Table.1**). Finally we get [42]:

$$T_{opt}(\omega,B)=\sqrt[-1{,}84]{\frac{2{,}272\times10^{-19}}{1{,}184\times B^2}\,\frac{\left[1+\tau^2\left(\omega_c(B)^2+\omega^2\right)\right]+j\omega\tau\left[\tau^2\left(\omega_c(B)^2-\omega^2\right)-1\right]}{j\omega\tau^3\omega_c(B)^2-j\omega^3\tau^3-j\omega\tau+\left[1+\tau^2\left(\omega_c(B)^2+\omega^2\right)\right]}} \quad \text{.................................} \textbf{(16)}$$

Table 1 Maximum values of minority carriers'diffusion coefficient and optimal temperature for different cyclotron frequency and magnetic field values

ω_c(B) rad/s	**5,30.10^7**	**7,03.10^7**	**8,84.10^7**	**1,06.10^8**	**1,76.10^8**
B(Tesla)	3.10^{-4}	4.10^{-4}	5.10^{-4}	6.10^{-4}	10^{-3}
D (cm^2/s)	16,212	14,079	11,138	9,934	8,108
Topt (K)	257	290	318	343	424

3.2 Photocurrent

The photocurrent density at the junction is deduced from the density of minority carriers in the base and is expressed as:

$$J_{ph}(Sf, Sb, \omega, B, T) = qD(\omega, B, T)\left.\frac{\partial\delta(x, Sf, Sb, \omega, B, T)}{\partial x}\right|_{x=0} \quad \text{.............................. (17)}$$

Where q is the elementary electron charge.

Figure 2 shows, ac photocurrent versus junction surface recombination velocity for different diffusion coefficient values (Dmax).

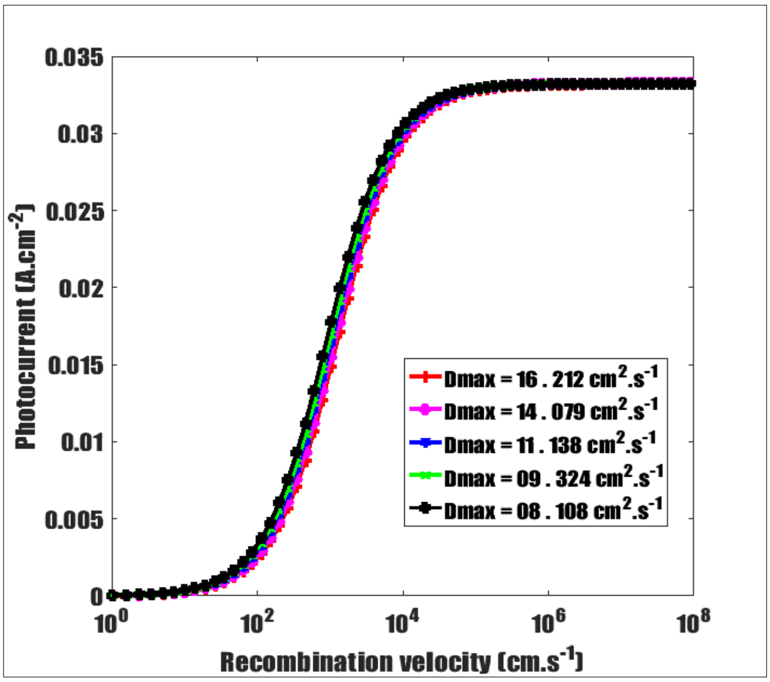

Figure 2 Module of photocurrent density versus recombination velocity for different diffusion coefficient (α = 21000 cm^{-1})

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

On figure.2, for large (Sf) values, variation in the short circuit current with Dmax is small). Indeed the monochromatic light of short wavelength corresponding to a large ($\alpha(\lambda)$) value, penetrates weakly into the solar cell. Then charge carriers are photogenerated near the junction. The distance to reach the junction is short, hence the deflection induced by (B) has very weak impact. The deflection phenomenon can be underestimated, compare to the effect of high monochromatic absorption coefficient ($\alpha(\lambda)$) value.

The increase in the modulation frequency (ω) brings the maximum density of the charge carriers closer to the junction [2, 13, 19, 54]. Then the photocurrent represented in the figure. 2, is not very sensitive to the effect of deflection due to the magnetic field (B). The effect of large frequencies is analogous to that of large monochromatic absorption coefficient ($\alpha(\lambda)$) value [2, 13, 17, 18, 19, 29, 41, 54].

3.3 Base thickness optimization

For very large Sf, the representation of photocurrent density according to the junction recombination velocity of minority carriers shows the short-circuit current density (Jphsc), that is constant whatever the diffusion coefficient (Dmax). So, in this velocity interval of junction recombination, we can write [44, 48, 50, 51, 52, 53, 54, 57]:

$$\left.\frac{\partial J_{ph}(Sf, Sb, \alpha, \omega, B, T)}{\partial Sf}\right|_{Sf \geq 10^5\, cm.s^{-1}} = 0 \quad \text{.............................. (18)}$$

The solution of equation (18) leads to the ac recombination velocity in the back surface expressions given by equations (19) and (20):

$$Sb1(\omega,B,T)=-\frac{D(\omega,B,T)}{L(\omega,B,T)}.\tanh\left(\frac{H}{L(\omega,B,T)}\right) \quad .... (19)$$

$$Sb2(\omega,B,T,\lambda)=\frac{D(\omega,B,T)}{L(\omega,B,T)}\cdot\left[\frac{\alpha(\lambda)\cdot L(\omega,B,T)\cdot\left(\exp(-\alpha(\lambda)\cdot H)-\cosh\left(\frac{H}{L(\omega,B,T)}\right)+\sinh\left(\frac{H}{L(\omega,B,T)}\right)\right)}{\exp(-\alpha(\lambda)\cdot H)-\cosh\left(\frac{H}{L(\omega,B,T)}\right)+\alpha(\lambda)\cdot L(B,T)\cdot\sinh\left(\frac{H}{L(\omega,B,T)}\right)}\right] \quad .... (20)$$

The figure 3 gives back surface recombination velocity representation versus solar cell base thickness as described in previous works [1, 2, 13, 14,15, 16, 17, 18, 19, 62, 63, 64]., for different maximum diffusion coefficient in our case.

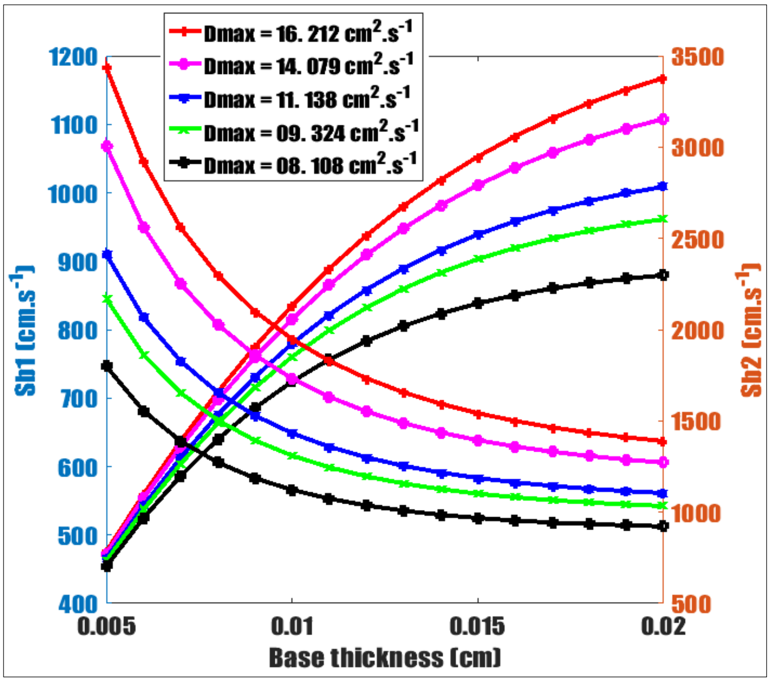

Figure 3 Sb1 and Sb2 versus depth in the base for different diffusion coefficient

Table 2 Base optimum thickness obtained with maximum values of minority carriers'diffusion coefficient and optimal temperature for different cyclotron frequency and magnetic field values

$\omega_c(B)$ **rad/s**	**5.30·10⁷**	**7.03·10⁷**	**8.84·10⁷**	**1.06·10⁸**	**1.76·10⁸**
B(Tesla)	3.10^{-4}	4.10^{-4}	5.10^{-4}	6.10^{-4}	10^{-3}
D (cm^2/s)	16.212	14.079	11.138	9.934	8.108
Topt (K)	257	290	318	343	424
Hopt (cm)	0.0095	0.009	0.0083	0.008	0.0075

Figures. 4, 5, and 6, are the plots of solar cell base optimum thickness as function respectively, of maximum diffusion coefficient, temperature and magnetic field.

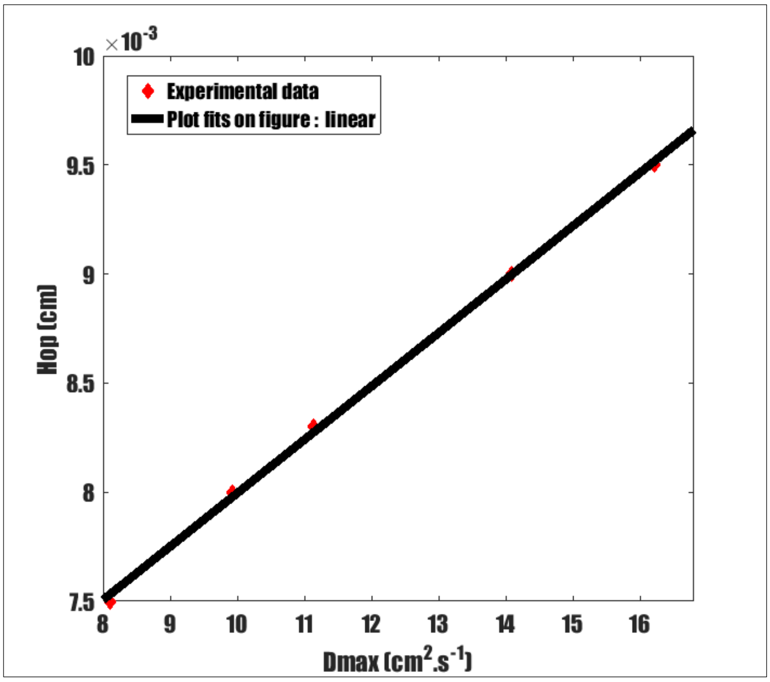

Figure 4 Optimum thickness versus Dmax

Figure. 4 gives the plot of the base optimum thickness, versus maximum diffusion coefficient, deduced from table. 2, and the modeling relationship is as follow:

$$Hopt(cm) = 2.4 \cdot 10^{-4} \times D\max + 0.0055 \quad (21)$$

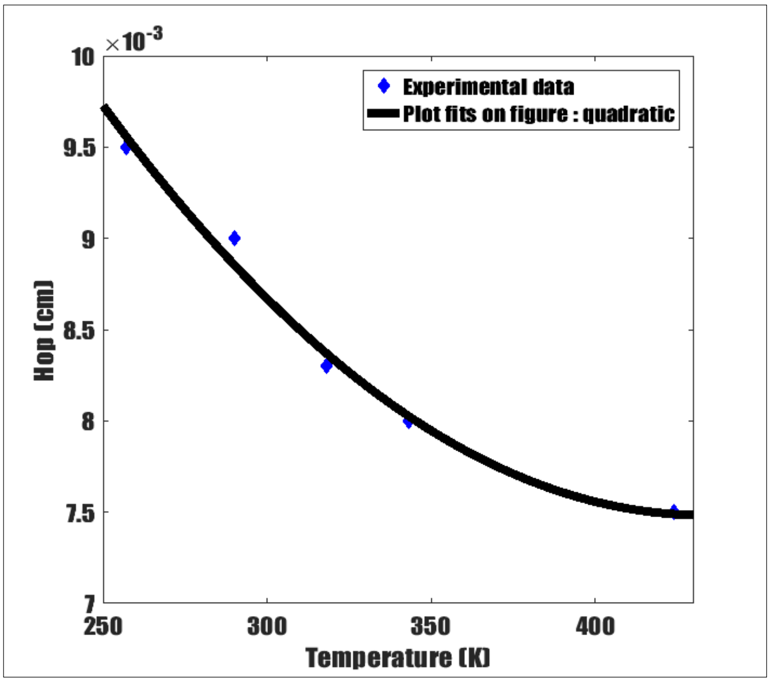

Figure 5 Optimum thickness versus temperature

From figure. 5, base optimum as fitted and gives the following relation:

$$Hopt(cm) = 6.7 \cdot 10^{-8} \times T^2 - 5.8 \cdot 10^{-5} \times T + 0.02 \quad \text{.............................} \quad (22)$$

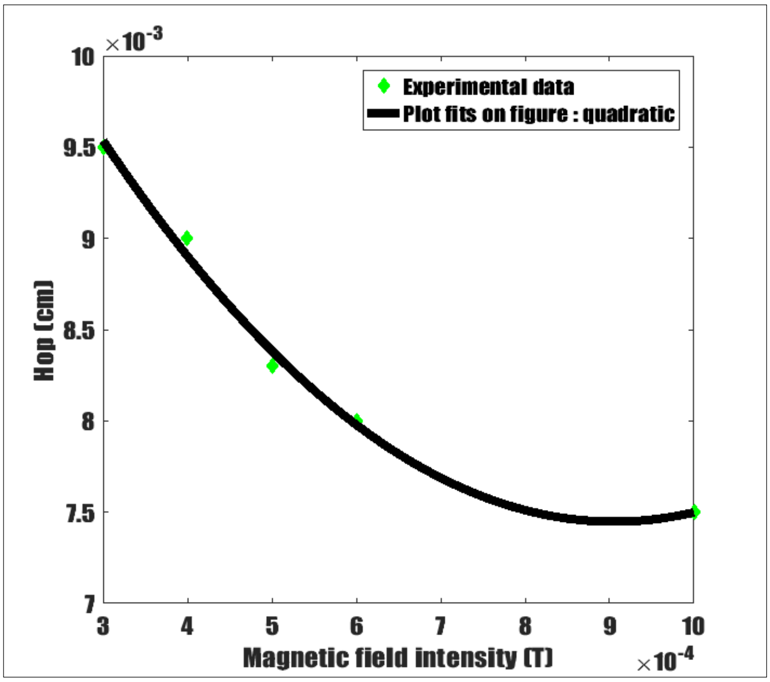

Figure 6 Optimum thickness versus magnetic field intensity

Figure. 6, gives the modeling relationship as:

$$Hop = 5.7 \cdot 10^3 \times B^2 - 10 \times B + 0.012 \quad \text{.............................} \quad (23)$$

4 Discussions

- A high absorption leads to a low penetration of light (alfa grand) so a generation near the junction (therefore short distance to travel before arriving at the junction [29].
- A high modulation frequency (ωτ >> 1) causes the density of the photo generated carriers to be reduced towards the incident surface of the illumination, thus near the junction [13, 19, 53, 54].
- From sections a) and b), it appears that the Lorentz forces have a small effect on charge carriers with a short path to perform. [30], because deflection is not enough to slow down their collection to participate in the photocurrent.
- Thermal agitation by temperature rise (Umklapp) shows a decrease in the diffusion coefficient (Table. 2), which is therefore associated with a low diffusion length.

Other recent works have produced results that corroborate this trend of decreasing the optimum thickness of the silicon solar cell base with external factors:

- Under monochromatic illumination in frequency modulation, by the front [17] and rear [2, 13], or on vertical junctions connected in series [19].
- Under polychromatic illumination in frequency modulation by the front surface [5] and with effect of temperature [51, 62] or applied magnetic field [41].
- Under polychromatic illumination, by the front face or on vertical junctions connected in series and with effect of the magnetic field applied [14, 63, 64].
- Under polychromatic illumination, by the front face with effect of temperature and magnetic field [15, 36].

The thicknesses obtained were modeled according to these external parameters, as decreasing functions, thus showing a gain in material.

It emerges from the analysis of the physical mechanisms that control the optimization of the thickness of the base of the silicon solar cell [44, 46, 49, 50], that investigations on thin films [9, 23, 65, 66, 67] would lead to appreciable results and allowing a gain in material economy.

5 Conclusion

The magneto-transport equation relating to the density of the minority charge carriers in the base of the silicon solar (n+/p/p+), under monochromatic illumination, in frequency modulation, has been solved.

The profile of the dynamic photocurrent as a function of the recombination velocity at the junction, was represented, for different values of the diffusion coefficient of the excess minority carriers in the base, at temperature and frequency, both in a resonance situation.

This representation made it possible to deduce the expressions of the dynamic recombination velocity of the minority carriers on the back side of the base, depending on the diffusion parameters with the values of resonance and absorption of high value, for a low penetration of the illumination.

The graphical representation of these expressions on a two-axis curve, for different values of the diffusion coefficient in a resonance situation, made it possible to extract the optimum thickness of the base. The latter is represented as a function of the diffusion coefficient, the temperature and the magnetic field applied, for a high value of the absorption coefficient.

The analysis and mathematical modeling of these curves, give an optimum thickness growth as a function of the diffusion coefficient and a decrease as a function of temperature and magnetic field, from which we can deduce the possibility of reduction of the thickness in the manufacture of the solar cell by considering an economy of silicon material.

Compliance with ethical standards

Acknowledgments

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Disclosure of conflict of interest

The authors declare no conflicts of interest.

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