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Diffusion Coefficient at Double Resonances in Frequency and Temperature, Applied to ($n^+/p/p^+$) Silicon Solar Cell Base Thickness Optimization under Long Wavelength Illumination

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Abstract

The diffusion coefficient of the minority charge carriers in the base of a silicon solar cell under temperature and subjected to a magnetic field, passes in resonance at temperature (T_{opt}). For this same magnetic field, the diffusion coefficient of the photogenerated carriers by a monochromatic light in frequency modulation enters into resonance, at the frequency (ω_c). Under this double resonance in temperature and frequency, the diffusion coefficient is used in the expression of the recombination velocity of the minority charge carriers on the back side of the base of the solar cell ($n^+/p/p^+$), to obtain, by a graphical method, the optimum thickness. A modeling of the results obtained shows a material saving (Si), in the development of the solar cell.

Keywords

Silicon Solar Cell-Diffusion Coefficient, Recombination Velocity, Absorption Coefficient, Magnetic Field-Temperature-Thickness

1. Introduction

The control and optimization of the thickness of the different regions [1]-[10] that make up the solar cell is of great interest for the manufacture and commercial distribution of photovoltaic systems.

This study deals with the optimization of the thickness of the base of an ($n^+/p/p^+$) silicon solar cell [11]-[18] under monochromatic illumination [19] [20] in frequency modulation [21]-[27] performed under the conditions of applied magnetic field [24] and temperature [28] [29] [30] [31] [32].

The photogenerated minority carriers, deep away from the junction in the base by a light of wavelength $\alpha(\lambda)$ in frequency modulation (ω), are subject to Lorentz's law by the application of the magnetic field (B) [33] and to the Umklapp process due to the thermal agitation imposed by the temperature (T) [4] [34] [35] [36].

The diffusion coefficient $D(\omega, B, T)$ of the minority charge carriers in the base, becomes optimum, by a double resonance in frequency (ω_c) [24] [37] and then in temperature (T_{opt}) [34] to give $D(\omega_c, T_{opt})$ [38], the maximum of minority carrier diffusion coefficient.

The magneto-transport equation in dynamic regime, relative to the density of minority carriers in the base, provided with the boundary conditions, represented by Sf and Sb respectively, the recombination velocities at the junction [39] [40] [41] [42] and on the back side [24] [25] [26] [41]-[49] of the base, allows to establish, the expression of the density of dynamic photocurrent under these conditions of magnetic field and temperature.

Expressions of the dynamic recombination velocity (Sb) of the minority charge carriers in the rear-facing base (p/p^+), are extracted from the dynamic photocurrent density [15] [16] [26] [35] [36] [44] [49] [50] [51]. They are function of, maximum diffusion coefficient $D(\omega_c, T_{opt})$, absorption coefficient of monochromatic illumination ($\alpha(\lambda)$) and thickness (H) of the base. As resonance offers the optimal response of the structure, this advantage is doubly (ω_c, T_{opt}) used in this work through the study of minority carriers recombination velocity expressions on the rear side of the solar cell in order to produce a maximum photocurrent.

Then the curves of their representations, as a function of thickness (H), make it possible to determine the optimum thickness (H_{opt}) of the base, which is then modeled by mathematical relations related to maximum diffusion coefficient ($D_{\max}$), magnetic field (B), temperature (T) and cyclotronic frequency (ω_c).

2. Theory

The structure of the n^+-p-p^+ monofaciale silicon solar cell under monochromatic illumination, magnetic field B and temperature T, is given by **Figure 1**.

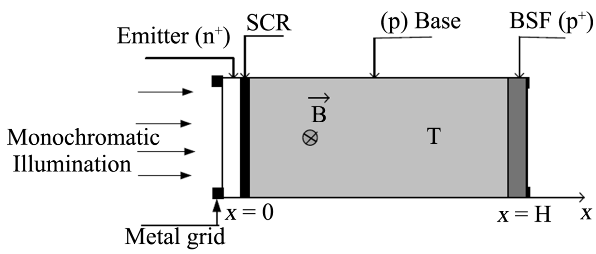

Figure 1. Structure of front illuminated solar cell under modulated frequency.

The excess minority carriers' density $\delta(x,t)$ generated in the base of the solar cell obeying to the continuity equation at T temperature, under monochromatic illumination in frequency modulation, is given by [21] [22] [23] [52]:

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

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

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

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

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

With:

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

Optics parameters [19] [20] [53] [54] are: I_0 incident flux, ($\alpha(\lambda)$) and $R(\lambda)$ are monochromatic absorption and reflection coefficient of the Si material.

$D(\omega,B,T)$ is the complex diffusion coefficient of excess minority carrier in the base under magnetique field and temperature and frequency modulation. Its expression is given by the relationship [24] [26] [37] [55]:

$$D(\omega,B,T)=D(B,T)\times\frac{\left[1+\tau^2\left(\omega_c(B)^2+\omega^2\right)\right]+j\omega\tau\left[\tau^2\left(\omega_c(B)^2-\omega^2\right)-1\right]}{\left[1+\tau^2\left(\omega_c(B)^2-\omega^2\right)\right]^2+4\omega^2\tau^2} \quad (5)$$

With

$$\omega_c=\frac{q\cdot B}{m_e^*} \quad (6)$$

is the cyclotron frequency, that imposes to an electron, with mass (m_e^*), a circle as trajectory, and reduces drastically the diffusion of the carriers, that must be contributed to the photocurrent.

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.

Under magnetic field, the diffusion coefficient is given by the following relation [33] [56] [57]:

$$D(B,T)=\frac{D(T)}{1+(\mu B)^2} \quad (7)$$

With:

$$D(T)=\frac{\mu(T)\cdot K\cdot T}{q} \quad (8)$$

And the mobility coefficient is given as [58]:

$$\mu(T)=1.43\times10^{19}\cdot T^{-2.42} \quad (9)$$

The solution of Equation (1) is then:

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

With

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

and

$$L(\omega,B,T)^2\cdot\alpha^2 \neq 1 \quad (12)$$

Coefficients A and E are determined through the boundary conditions, respectively, at the junction and the rear:

- At the junction ($x = 0$)

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

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

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

Sf and Sb are respectively the recombination velocities of the excess minority carriers at the junction [41] [43] and at the back surface [43] [59] [60]. The recombination velocity Sf reflects the charge carrier velocity of passage through the junction, as imposed by the external load which fixes the solar cell operating point [40] [41] [43] [61]. An intrinsic component is suggested in the solar cell electrical equivalent model [39] [46] [55], which represents the carrier losses through the shunt resistor. The excess minority carrier recombination velocity Sb on the back surface [42] [43] [48] [59] [60] is associated with the presence of the p^+ layer which generates an electric field for throwing back the charge carrier toward the junction.

3. Results and Discussions

1) AC Diffusion coefficient under both magnetique field and temperature

The diffusion coefficient under magnetic field (Equation (7)), under temperature (Equation (8)) and the mobility under temperature (Equation (9)), trough (Equation (5)), yield the optimum temperature ($T_{opt}(\omega,B)$) by solving (Equation (14, a)), as zero temperature gradient of $D(\omega,B,T)$:

$$\frac{\mathrm{d}D(\omega,B,T)}{\mathrm{d}T} = 0 \quad (14,\ a)$$

Finally the following relation [38] is obtained as:

$$T_{opt}(\omega,B) = \sqrt[-1.84]{\frac{2.272\times10^{-19}}{1.184\times B^2}\cdot\frac{\left[1+\tau^2\left(\omega_c(B)^2+\omega^2\right)\right]+j\omega\tau\left[\tau^2\left(\omega_c(B)^2-\omega^2\right)-1\right]}{j\omega\tau^3\omega_c(B)^2-j\omega^3\tau^3-j\omega\tau+\left[1+\tau^2\left(\omega_c(B)^2+\omega^2\right)\right]}} \quad (14,\ b)$$

This equation leads to the determination of optimal temperature values for different cyclotronic frequency, for given magnetic field values (Table 1).

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

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

where q is the elementary electron charge.

Figure 2 shows ac photocurrent versus junction surface recombination velocity for different diffusion coefficient.

2) Base thickness optimization

The representation of AC photocurrent density according to the junction recombination velocity of minority carriers shows that, for very large *Sf*, a bearing sets up and corresponds to the short-circuit current density (Jphsc). Thus, in this region of junction recombination velocity, it therefore comes [43] [49] [50] [51] [61]:

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

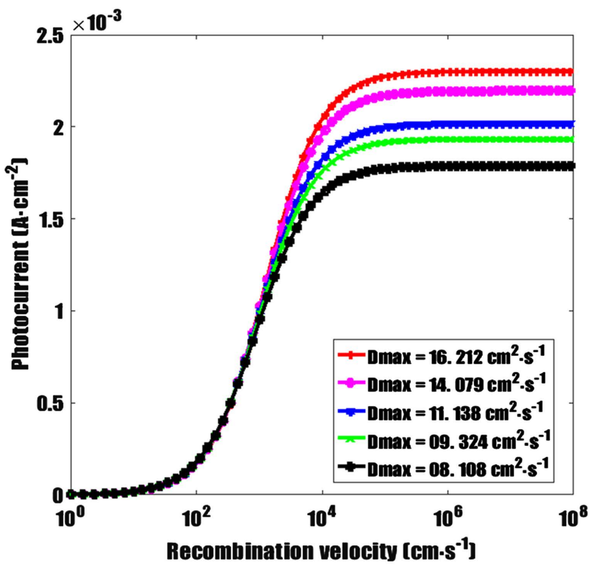

Figure 2. Module of photocurrent density versus recombination velocity for different diffusion coefficient values ($\alpha = 6.2\ \text{cm}^{-1}$).

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

$\omega_c(B)$ rad/s	5.30×10^7	7.03×10^7	8.84×10^7	1.06×10^8	1.76×10^8
B(Tesla)	3.03×10^{-4}	4.004×10^{-4}	5.031×10^{-4}	6.031×10^{-4}	1.001×10^{-3}
T_{opt}(K)	257,871	290,422	318,475	343,396	424,099
D_{max} (cm²/s)	16,209	14,078	11,137	9934	8108

The solution of Equation (16) leads to the ac recombination velocity in the back surface expressions given by Equations (17) and (18):

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

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

Figure 3 is the representation the two expressions of back surface recombination velocity versus thickness of solar cell base for different diffusion coefficient values.

Table 2 gives the results extracted from Figure 3.

Figures 4-6 are the plots of solar cell base optimum thickness as function respectively, of maximum diffusion coefficient, temperature and magnetic field. Equations (19), (20) and (21), are the result of mathematical modeling of the curves of the associated figures.

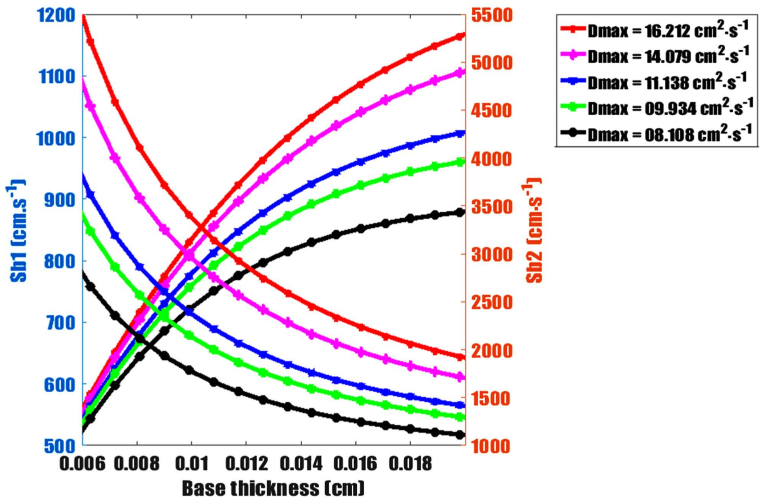

Figure 3. *Sb*1 and *Sb*2 versus depth in the base for different diffusion coefficient.

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	5.30×10^{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 (cm²/s)	16.212	14.079	11.138	9.934	8.108
T_{opt} (K)	257	290	318	343	424
H_{opt} (cm)	0.0108	0.0103	0.0096	0.0092	0.0087

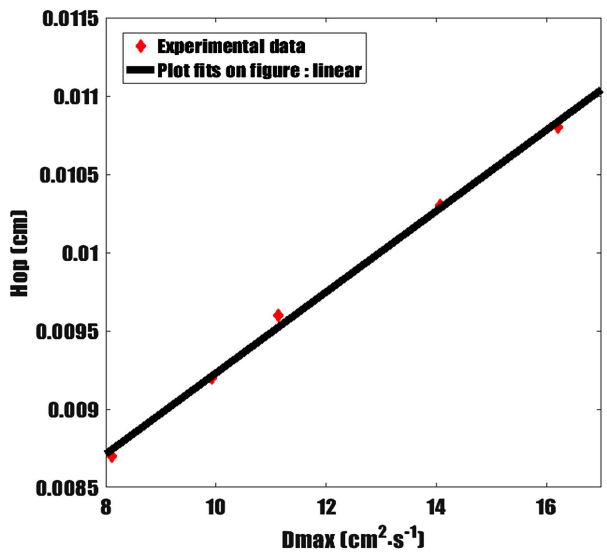

Figure 4. Optimum thickness versus $D_{\max}$.

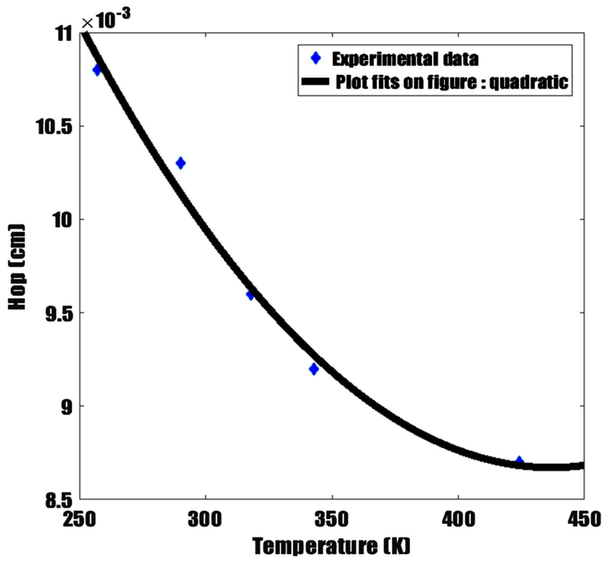

Figure 5. Optimum thickness versus temperature.

$$H_{opt}(\text{cm}) = 2.6\times10^{-4}\times D_{\max} + 0.0066 \tag{19}$$

$$H_{opt}(\text{cm}) = 6.8\times10^{-8}\times T^2 - 5.9\times10^{-5}\times T + 0.022 \tag{20}$$

$$H_{opt} = 5.9\times10^{3}\times B^2 - 11\times B + 0.014 \tag{21}$$

3) Discussions

This work highlights several physical processes, which are in competition. These are absorption-generation in frequency modulation, deflection and thermal agitation, which can be analyzed individually or simultaneously by a judicious choice of their combination in order to produce a maximum photocurrent, linked to the optimum diffusion parameter associated with the adequate thickness of the base of the solar cell (**Figure 4**).

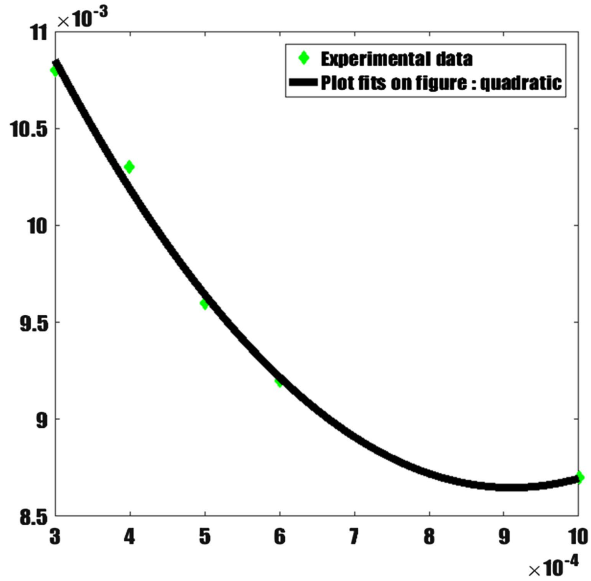

Figure 6. Optimum thickness versus magnetic field intensity.

A low absorption coefficient by an incident illumination by the front face, leads to a strong penetration of light (small $\alpha(\lambda)$) and a generation of charge carriers far from the junction, deep in the base [19] [20] [54] [62]. Under these conditions the results obtained from the optimum thickness are large [63]. On the other hand, for an incident illumination from the rear side, the optimum thickness is reduced [64].

For our study the charge carriers will therefore have a greater distance to travel before arriving at the junction [15] [63] [64], which then leads to a very marked effect of the magnetic field (B), on the photocurrent at the low values of Dmax on the curves of the (**Figure 2**). Indeed, long-distance carriers undergo deflections, and few carriers arrive at the junction to be collected, which induces a low photocurrent *i.e.*, with reduced thickness (**Figure 6**).

Also it has been shown, the need to reduce the thickness of the base of the solar cell under these conditions of applied magnetic field (see **Figure 6**), in order to obtain, therefore, an optimal photocurrent [65] [66].

For monochromatic illumination in frequency modulation ($\omega\tau \gg 1$), the photogenerated carriers approach near the surface of the junction, for an incident light from the front face [26] [49]. On the other hand, for an incidence by the rear surface, the density of the photogenated carriers are close to it, especially for (large $\alpha(\lambda)$). Then the optimum thickness decreases with frequency (**Table 2**) regardless of the illuminated face. The optimum thickness is greater for an illumination of low absorption coefficient ($\alpha(\lambda)$), than in the case of a large coefficient, regardless of the frequency [15] [16] [67]. The increase in frequency plays a similar role to the increase in the monochromatic absorption coefficient ($\alpha(\lambda)$), due to the reduction in the relaxation time of photogenated carriers.

The dual action of the magnetic field and temperature produced an optimum resonance temperature [34], the boundary between the normal process and the

Umklapp process. The optimum thickness obtained (**Figure 5** and **Figure 6**), for an incident illumination on the front side, decreases respectively with the two parameters of temperature and magnetic field [68] [69] [70] [71].

In the case of the double action [24] [37], the applied magnetic field and the frequency of modulation of the incident illumination on the front face, the optimum thickness obtained decreases with the resonance frequency [44]. **Table 2** actually shows this decrease in our study. When the illumination is incident on the back side, the result gives a much lower thickness [69] [71].

The concomitance of the different physical mechanisms [44] [72], in the basis of the solar cell, namely:

Absorption, generation, deflection, thermal agitation and frequency modulation, act on the density of excess minority carriers, their generation depth in the base, the possibility of their displacement due to the diffusion coefficient ($D(B, T)$) and their relaxation time ($\omega\tau \gg 1$) due to the frequency of modulation [21] [22] [26] [49] [50] [52].

4. Conclusions

Our study chose to optimize the combination of the different mechanisms, (generation-absorption) by a deep generation in the base (weak $\alpha(\lambda)$), offering a great possibility of displacement of the charge carriers respectively, at the optimum temperature ($D(T_{opt}, B)$), and at the resonance point (ω_c) of the diffusion coefficient $D(\omega_c, B)$ also due to the magnetic field

The recombination velocity of the minority carriers on the back side, is expressed according to all these parameters as well as the thickness of the base. The optimum thickness obtained is therefore modeled as decreasing functions of (T_{opt}) and (B) and leads to an interesting reduction of material necessary for the development of the solar cell.

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Conflicts of Interest

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

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