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Determination of the Base Optimum Thickness of Back Illuminated (n⁺/p/p⁺) Bifacial Silicon Solar Cell, by Help of Diffusion Coefficient at Resonance Frequency

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Abstract

The bifacial silicon solar cell subjected to a magnetic field, is illuminated by the back side by a monochromatic light in frequency modulation, with high absorption, At minority carriers diffusion coefficient resonance frequency, a graphical study of the expressions of recombination velocity on the rear side is carried out. The optimum thickness of the base of the bifacial solar cell is deduced for each resonance frequency.

Keywords

Bifacial Silicon Solar Cell, Frequency, Magnetic Field, Wavelength-Recombination Velocity, Base Thickness

1. Introduction

The realization of a junction (p/p^+) (low-high junction or BSF) [1] [2] [3] on the (p) base of the ($n^+/p/p^+$) solar cell [4] [5] [6] improves the photoconversion efficiency. However, the depth (H) at which this junction must be made in the base is often evaluated after the complete elaboration of the solar cell with wafers of different thicknesses which are cut [7] [8] [9] [10]. Recent works on the location of this junction (p/p^+) [11] [12] [13] [14] [15], based on the study of mathematical expressions of the recombination velocity (*Sb*) of minority carriers on this rear surface [16]-[21], has made it possible to obtain the optimum thickness (Hopt) of the base of the solar cell under various operating conditions [22] [23]

[24]. These expressions [21] [25] [26] are dependent on the diffusion coefficient (*D*), the diffusion length (*L*) of the minority carriers, the thickness (*H*) and the absorption coefficient of the material (Si).

This work is based on the expressions of the diffusion coefficient expressed by the Einstein relation and influenced by parameters of many conditions:

1) External which are: temperature [27] [28] [29], electromagnetic field [30] [31] [32] [33] [34], irradiation flux by charged particles [35] [36] [37], the frequency [38]-[43] of modulation of incident light.

2) Intrinsic, linked to manufacturing through doping rates [44] [45] [46].

The possibility of combining the different conditions [47] [48] [49] [50] [51] allows us to propose this present work, which considers the silicon solar cell ($n^+/p/p^+$) under the influence of the magnetic field, and illuminated by the back side, by a monochromatic light in frequency modulation. The optimum thickness (H_{opt}) of the base, is obtained by studying the expressions of the recombination velocity (*Sb*), for the diffusion coefficient at the frequency of the cyclotron (ω_c), for a given magnetic field.

2. Theory

The structure of (n^+-p-p^+) bifacial silicon solar cell [52]-[57] under back monochromatic illumination, in frequency modulation, is given in **Figure 1**.

The excess minority carriers' density $\delta(x,t)$ generated by illumination in frequency modulation, in the base of the solar cell obeying the continuity magneto-resistance equation, is given by [31] [32] [39] [40] [41]:

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

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

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

2.1. Generation Rate

AC carrier generation rate $G(x,t)$ is given by the relationship [39] [40] [41] [53] as:

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

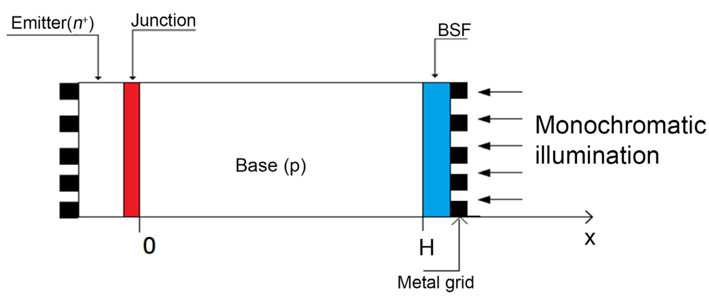

Figure 1. Structure of back illuminated bifacial silicon solar cell under magnetic field.

With $g(x)$ the spatial component:

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

The monochromatic optical parameters [58] [59] of the (Si) material at wavelength (λ) are respectively, incident flux ($I_0(\lambda)$), absorption coefficient ($\alpha(\lambda)$) and reflection coefficient $R(\lambda)$. Base depth is represented by (H).

2.2. AC Diffusion Coefficient

The expression of complex diffusion coefficient of excess minority carrier in the base under magnetic field and frequency modulation $D(\omega, B)$ is given by the following relationship [38] [48] [49] whose representation as a function of (ω), reveals peaks at given (B), which correspond to the resonance:

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

With

$$\omega_c = \frac{q \cdot B}{m_e^*} \tag{6}$$

The electron has a circle as trajectory, for given cyclotron frequency, leading to decreasing minonority carriers diffusion coefficient. The elementary charge is (q) while m_e^* is the effective mass.

2.3. Boundary Conditions and Solution

By replacing Equations (2) and (3) in Equation (1), the continuity equation for the excess minority carriers' density in the base is reduced to the following relationship:

$$\frac{\partial^2 \delta(x, \omega)}{\partial x^2} - \frac{\delta(x, \omega)}{L^2(\omega, B)} = -\frac{g(x)}{D(\omega, B)} \tag{7}$$

$L(\omega, B)$ is the complex diffusion length, under magnetic field and frequency modulation, of excess minority carriers in the base, given by:

$$L(\omega, B) = \sqrt{\frac{D(\omega, B)\tau}{1 + j\omega\tau}} \tag{8}$$

τ is the excess minority carriers lifetime in the base.

The solution of Equation (7) is given as:

$$\delta(x, \omega, B, \lambda) = A \cdot \cosh\left[\frac{x}{L(\omega, B)}\right] + B \cdot \sinh\left[\frac{x}{L(\omega, B)}\right] + K \cdot e^{-\alpha \cdot (H-x)} \tag{9}$$

With

$$K = \frac{\alpha(\lambda) \cdot I_0 \cdot (1 - R(\lambda)) \cdot [L(\omega, B)]^2}{D(\omega, B)\left[L(\omega, B)^2 \cdot \alpha(\lambda)^2 - 1\right]} \tag{10}$$

and

$$L(\omega,B)^2 \cdot \alpha(\lambda)^2 \neq 1 \quad (11)$$

Coefficients A and B are determined through the boundary conditions:

- At the (n^+/p) junction ($x = 0$)

$$\left.\frac{\partial \delta(x,\omega,B,\lambda)}{\partial x}\right|_{x=0} = Sf \cdot \left.\frac{\delta(x,\omega,B,\lambda)}{D(\omega,B)}\right|_{x=0} \quad (12)$$

- On the back side (p/p^+) in the base ($x = H$)

$$\left.\frac{\partial \delta(x,\omega,B,\lambda)}{\partial x}\right|_{x=H} = -Sb \cdot \left.\frac{\delta(x,\omega,B,\lambda)}{D(\omega,B)}\right|_{x=H} \quad (13)$$

Boundary conditions are characterize by the recombination velocity [16]-[22] [35] [60] [61] [62] [63] respectively, (Sf) at the junction (p/p^+) and Sb at the rear (p/p^+) of the base.

3. Results and Discussions

3.1. AC Back Surface Recombination and Optimum Base Thickness Determination at Ringing Frequency

The representation of AC photocurrent density according to the junction recombination velocity of minority carriers [21] [22] [64] shows that, for very large Sf, the AC short-circuit current density (J_{phsc}) prevails as constant. So, in this junction recombination velocity interval, the derivative of AC photocurrent density with respect to (Sf), can write as:

$$\left.\frac{\partial J_{ph}\left(Sf,Sb,\omega,B,\alpha(\lambda),H\right)}{\partial Sf}\right|_{Sf \geq 10^5\ \text{cm}\cdot\text{s}^{-1}} = 0 \quad (14)$$

The solution of Equation (14) leads to the expressions of AC recombination velocity in the rear surface [16] [17] [18] [19] [20] given by Equations (15) and (16):

$$Sb_1(\omega,B) = -\frac{D(\omega,B)}{L(\omega,B)} \cdot \tanh\left(\frac{H}{L(\omega,B)}\right) \quad (15)$$

$$Sb_2\left(H,\alpha(\lambda),\omega,B\right) = \frac{D(\omega,B)}{L(\omega,B)} \cdot \frac{L(\omega,B)\cdot\alpha(\lambda) - \left(L(\omega,B)\cdot\alpha(\lambda)\cdot ch\left(\frac{H}{L(\omega,B)}\right) + sh\left(\frac{H}{L(\omega,B)}\right)\right)e^{-\alpha(\lambda)\cdot H}}{\left(ch\left(\frac{H}{L(\omega,B)}\right) + L(\omega,B)\cdot\alpha(\lambda)\cdot sh\left(\frac{H}{L(\omega,B)}\right)\right)e^{-\alpha(\lambda)\cdot H} - 1} \quad (16)$$

Figure 2, gives the profile of the two expression of AC back surface recombination velocity for different ringing frequencies inducing Dmax values, versus thickness of the base of the solar cell, under short wavelength ($\alpha(\lambda)$ = 21,000 cm^{-1}). The technique [11] [12] [13] [15] [23] [24] [50] [51] of the intercept point of the curves, produces the optimum thickness of the base, and allow the establishment of Table 1 data.

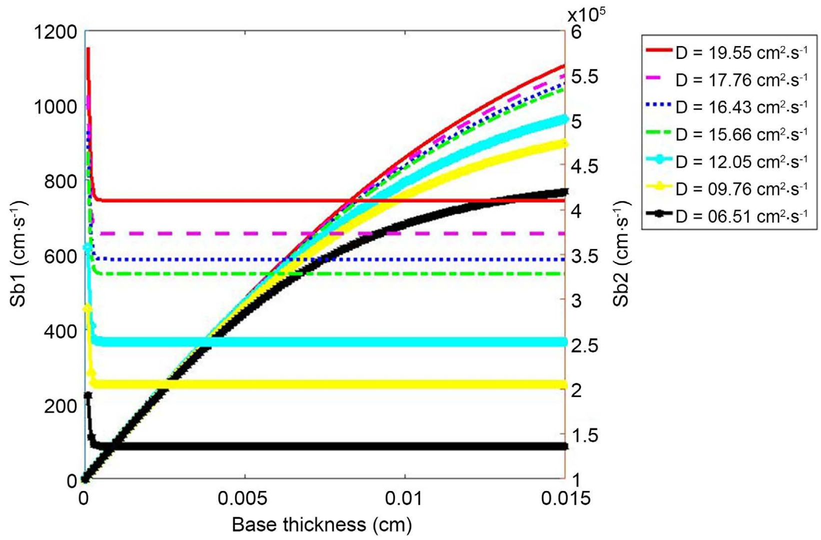

Figure 2. Sb_1 and Sb_2 versus depth in the base for different magnetic field values (D_0 = 35 cm/s; α = 21,000 cm^{-1}).

Table 1. Ringing frequencies, maximum diffusion coefficient and diffusion length for given magnetic field.

B (T)	10^{-6}	2×10^{-6}	7×10^{-6}	9×10^{-6}	5×10^{-5}	8×10^{-5}	9×10^{-5}
ω_r (rad·s^{-1})	1.831×10^5	3.434×10^5	1.198×10^6	1.536×10^6	8.687×10^6	1.422×10^7	1.608×10^7
D_{max}	19.55	17.76	16.43	15.66	12.05	9.76	6.51
L_{max}	0.014	0.0133	0.0128	0.0125	0.0110	0.0099	0.0081
H_{op} (cm)	0.0083	0.0072	0.0063	0.0059	0.0039	0.0026	0.001

From **Figure 3**, the relationship obtained is expressed as:

$$H_{op}\left(\text{cm}\right) = 5.6 \times 10^{-4} \times D_{\max}\left(\text{cm}^2/\text{s}\right) - 0.0028 \tag{17}$$

From obtained **Table 1**, base optimum thickness versus L_{max}, is represented in **Figure 4**.

The representation is also an increase strait line, expresses as:

$$H_{op}\left(\text{cm}\right) = 1.2 \times L_{\max}\left(\text{cm}\right) - 0.0094 \tag{18}$$

3.2. Discussion

The results obtained from (H_{opt}) show the decay with the resonance frequency, consequently with the magnetic field (**Table 1**). The physical phenomena to be taken into account are:

- The absorption-generation of minority carriers in low penetration therefore close to the incident rear surface (p/p$^+$) [12] [16] [21] [57] [65].

- The modulation frequency, which at the resonance point of Dmax, causes the decay of both, D_{max} and L_{max} (in **Table 1**) for a given magnetic field (B), reflects the degradation of the electronic properties of the material and the difficulties of movement of minority carriers.

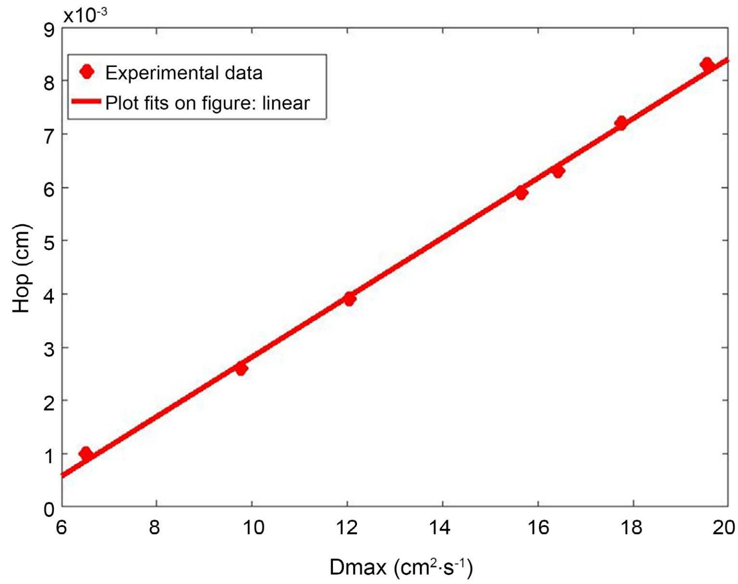

Figure 3. D_{max} versus base optimum thickness.

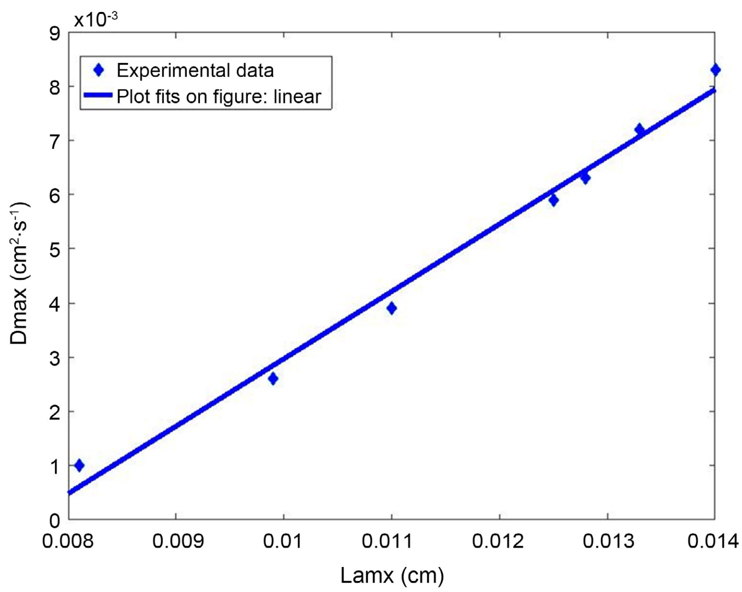

Figure 4. Optimum thickness of the base versus L_{max}.

At resonance, the study of $D(\omega, B)$ [15] [38] [48] [49] shows an opposition of capacitive and inductive phenomena to the detriment of the resistive phenomenon, which favors the diffusion of minority charge carriers. The increase in frequency and magnetic field, leads to deflection of minority charge carriers.

Thus when the electronic properties of the material are degraded (under the reversible action of the two parameters that are the magnetic field and the modulation frequency, Equations (5) and (8)), then the optimum thickness is low (**Figure 3** and **Figure 4**), to allow the collection of minority carriers in thin base. For high electronic quality material, large optimum thickness can be used.

Previous results have shown the decrease in the optimum thickness of the base:

- For low penetration of incident light (strong $\alpha(\lambda)$), regardless of the illuminated face [11] [12] [65] front or rear.
- With the increase in the frequency of incident light.
- With the increase of the applied magnetic field.
- With the increase in applied temperature.
- The combination [23] [24] [50] [51] [57] [65] of these physical phenomena leads to a decrease in the optimum thickness of the base.

This study on the solar cell in the one-dimensional model can be reinforced by the three-dimensional study [26] [49], taking into account the effects of both, recombination velocity at grain boundaries and grain size.

4. Conclusions

This study used the phenomenon of resonance of the diffusion coefficient of minority carriers, to determine the optimum thickness of the base of the bifacial silicon solar cell. The latter is placed under magnetic field and illuminated from the back side by a monochromatic light of low penetration. Thus the optimum thickness of the base delimited by the junction (p/p^+), is low because of:

- Strong absorption of incident light near the rear surface;
- Decay with the frequency of the diffusion coefficient of the excess minority carriers, near the rear surface and their deflection with the applied magnetic field.

The optimum thickness decreases as the diffusion coefficient decreases (poor quality material). In this situation, the low thicknesses of the base of the bifacial silicon solar cell illuminated by the back side are better suited for improving photoconversion efficiency.

Conflicts of Interest

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

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