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Diffusion Coefficient at Resonance Frequency as Applied to n+/p/p+ Silicon Solar Cell Optimum Base Thickness Determination

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Abstract

The modelling and determination of the geometric parameters of a solar cell are important data, which influence the evaluation of its performance under specific operating conditions, as well as its industrial development for a low cost. In this work, an n+/p/p+ crystalline silicon solar cell is studied under monochromatic illumination in modulation and placed in a constant magnetic field. The minority carriers' diffusion coefficient ($D(\omega, B)$), in the (p) base leads to maximum values (Dmax) at resonance frequencies (ωr). These values are used in expressions of AC minority carriers recombination velocity (Sb(Dmax, H)) in the rear of the base, to extract the optimum thickness while solar cell is subjected to these specific conditions. Optimum thickness modelling relationships, depending respectively on Dmax, ωr and B, are then established, and will be data for industrial development of low-cost solar cells for specific use.

Keywords

Silicon Solar Cell, Resonance Frequency, Magnetic Field, Recombination Velocity, Base Thickness

1. Introduction

Several phenomenological parameters of the base of the silicon solar cell, are the subject of theoretical and experimental investigations, for their determination. These are parameters such as: diffusion coefficient (D) [1], lifetime (τ) [2] [3],

[4] [5], diffusion length (L) [6] [7] [8] [9], mobility (μ) [10] and recombination velocity [11] on surfaces of the different regions (front of the emitter [12] [13] [14], junction [15] [16] and rear side [8] [17] [18] [19] of the base) of the solar cell and grain joints recombination velocity (Sg) [20] [21] [22].

Geometric parameters' (different thicknesses and grain size) [23]-[29] optimization is important in studies aimed at improving the performance of the solar cell. In fact, they reduce both the distances to be covered by minority carriers before collection and the rate of recombination [30] [31]. Their determination is the subject of various theoretical and modelling studies and measurement techniques [3] [10] [32] [33] [34] [35] [36]

This work studies an n+/p/p+ silicon solar cell under monochromatic illumination ($\alpha(\lambda)$) [36] [37] in frequency modulation (ω) [24] [38], and placed under magnetic field (B) [3] [10] [35]. The magneto-transport equation [10] in dynamic mode [39] of the excess minority carrier's density in the base of the solar cell is solved. Conditions at the limits of the base, *i.e.* at the junction and in the rear, are characterized respectively by recombination velocity (Sf) and (Sb) [16].

The ac photocurrent produced by the base, is studied at the resonance frequencies (ωr) imposed by specific magnetic field values to the minority carrier diffusion coefficient $D(\omega, B)$ [40] [41] [42] [43]. It is then analyzed at the high values of the junction recombination velocity (Sf) that impose the short circuit operating point to the solar cell. The expressions of the ac recombination velocity, are then deduced [41] [44] [45] [46] and their comparison by the graphic method [47] [48] [49] [50], leads to the determination of optimum thickness (Hopt(Dmax)) and modeled according to the frequency of resonance (ωr).

2. Theoretical Model

The structure of the n^+-p-p^+ silicon solar cell [18] [51] under front monochromatic illumination, in frequency modulation, is given by **Figure 1**.

- The excess minority carriers' density $\delta(x,t)$ generated by an illumination in frequency modulation, in the base of the solar cell obeying to the continuity magneto-resistance equation, is given by:

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

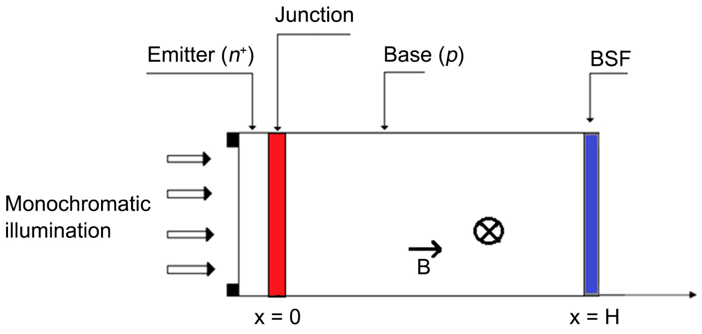

Figure 1. Structure of a front illuminated solar cell.

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

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

2.1. Generation Rate

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

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

The steady state generation rate is expressed as:

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

I_0 is the incident flux, while $R(\lambda)$ and $\alpha(\lambda)$ are respectively, the reflection and absorption coefficients in the silicon material

2.2. 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:

$$\frac{\partial^2\delta(x,\omega)}{\partial x^2}-\frac{\delta(x,\omega)}{L^2(\omega;B)}=-\frac{g(x)}{D(\omega,B)} \tag{5}$$

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

$$L(\omega,B)=\sqrt{\frac{D(\omega,B)\tau}{1+j\omega\tau}} \tag{6}$$

τ is the excess minority carriers lifetime in the base.

The solution of Equation (5) is:

$$\delta(x,\omega,B,\lambda)=A\cdot\cosh\left[\frac{x}{L(\omega,B)}\right]+B\cdot\sinh\left[\frac{x}{L(\omega,B)}\right]+K\cdot \mathrm{e}^{-\alpha\cdot x} \tag{7}$$

With

$$K=\frac{\alpha(\lambda)\cdot I_0\cdot\left(1-R(\lambda)\right)\cdot\left[L(\omega,B)\right]^2}{D(\omega,B)\left[L(\omega,B)^2\cdot\alpha(\lambda)^2-1\right]} \tag{8}$$

and

$$\left(L(\omega,B)^2\cdot\alpha(\lambda)^2\neq 1\right) \tag{9}$$

Coefficients A and B are determined through the boundary conditions:

- At the junction ($x=0$)

$$D(\omega,B)\left.\frac{\partial\delta(x,\omega,B,\lambda)}{\partial x}\right|_{x=0}=Sf\cdot\left.\frac{\delta(x,\omega,B,\lambda)}{D(\omega,B)}\right|_{x=0} \tag{10}$$

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

$$D(\omega,B)\frac{\partial\delta(x,\omega,B,\lambda)}{\partial x}\bigg|_{x=H}=-Sb\cdot\frac{\delta(x,\omega,B,\lambda)}{D(\omega,B)}\bigg|_{x=H} \tag{11}$$

Sf and Sb are respectively the recombination velocities of the excess minority carriers at the junction and at the back surface. The recombination velocity Sf reflects the charge carrier velocity of passage at the junction, in order to participate in the photocurrent. It is then imposed by the external load which fixes the solar cell operating point [15]. It has an intrinsic component which represents the carrier losses associated with the shunt resistor in the solar cell electrical equivalent model [20] [44] [45] [46]. The excess minority carrier recombination velocity Sb on the back surface is associated with the presence of the p^+ layer which generates an electric field for throwing back the charge carrier toward the junction [8] [17] [18].

3. Results of AC Back Surface Recombination and Optimum Base Thickness Determination at Ringing Frequency

3.1. AC Back Surface Recombination

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 AC short-circuit current density (Jphsc) [44] [45] [46]. So, in this junction recombination velocity interval, we can write [16]:

$$\frac{\partial J_{ph}(Sf,Sb,\omega,B,\lambda)}{\partial Sf}\bigg|_{Sf\geq 10^5\ \mathrm{cm\cdot s^{-1}}}=0 \tag{12}$$

The solution of Equation (12) leads to the expressions of AC recombination velocity in the rear surface [41] [44] [45] given by Equations (13) and (14):

$$Sb1(\omega,B)=-\frac{D(\omega,B)}{L(\omega,B)}\cdot\tanh\left(\frac{H}{L(\omega,B)}\right) \tag{13}$$

$$Sb2(\omega,B,\lambda)=\frac{D(\omega,B)}{L(\omega,B)}\cdot\left[\frac{\alpha(\lambda)\cdot L(\omega,B)\cdot\left(\exp(-\alpha(\lambda)\cdot H)-\cosh\left(\frac{H}{L(\omega,B)}\right)+\sinh\left(\frac{H}{L(\omega,B)}\right)\right)}{\exp(-\alpha(\lambda)\cdot H)-\cosh\left(\frac{H}{L(\omega,B)}\right)+\alpha(\lambda)\cdot L(\omega,B)\cdot\sinh\left(\frac{H}{L(\omega,B)}\right)}\right] \tag{14}$$

3.2. AC Diffusion Coefficient and Ringing Frequency

Minority carrier diffusion coefficient is influenced by external conditions applied to solar cell. It expression is dependent of parameter such as, temperature [52], magnetic field [10], charged particles fluence and intensity of irradiation [53], and others combined external conditions [42] [54] [55]. For this case under study $D(\omega,B)$ is the complex diffusion coefficient of excess minority carrier in the base under magnetic field and frequency modulation. Its expression is given by the relationship [40] [41] [43]:

$$D(\omega,B) = D\cdot\left[\frac{\left(1+\tau^2\cdot\left(\omega_c^2+\omega^2\right)\right)}{4\cdot\omega^2\cdot\tau^2+\left[1+\tau^2\left(\omega_c^2-\omega^2\right)\right]^2}-\frac{j\cdot\omega\cdot\tau\cdot\left(1-\tau^2\left(\omega_c^2-\omega\right)^2\right)}{4\cdot\omega^2\cdot\tau^2+\left[1+\tau^2\left(\omega_c^2-\omega^2\right)\right]^2}\right] \quad (15)$$

With

$$\omega_c = \frac{q\cdot B}{m_e^*} \quad (16)$$

is the cyclotron frequency, m_e^* the electron mass, and q the elementary charge.

The diffusion coefficient is plotted in **Figure 2**. It decreases with the modulation frequency for different magnetic field values. We observe the appearance of resonance peaks [41] [43] for intensities of the upper magnetic field 10^{-7} Tesla, giving the maximum diffusion coefficient (**Dmax**) value.

Two areas of very weak magnetic fields emerge in **Figure 2**, with semi-logarithmic scale of frequency:

- a first zone ($\omega < 10^4$ rad/s) where the complex diffusion coefficient is virtually constant corresponding to the quasi-static regime, which ends at the point of the cut-off frequency [24];
- a second zone (from 10^4 rad/s to 10^8 rad/s) where the complex diffusion coefficient decreases drastically with pulsation, marking the frequency dynamic regime, or excess minority carriers appear frozen, because of their low relaxation time.

The application of a magnetic field to the solar cell in this frequency region, reveals a third area where the amplitude of the complex diffusion coefficient produces a peak, at a given frequency called resonance frequency [43].

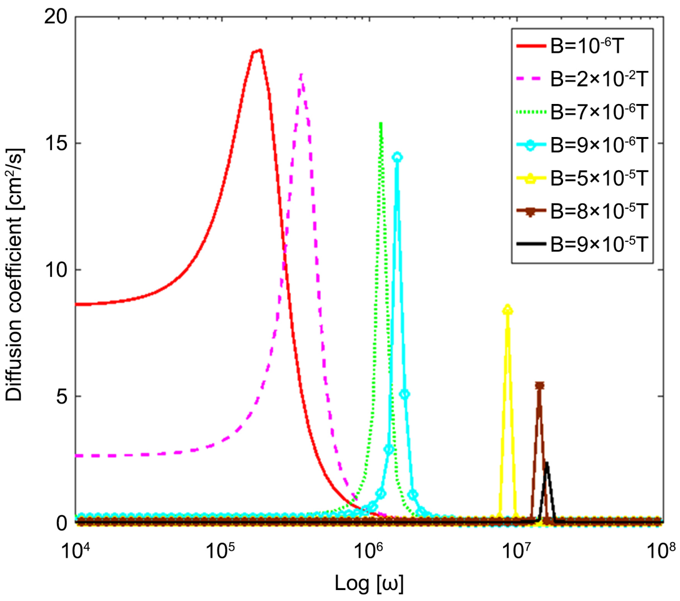

Figure 2. Diffusion coefficient versus frequencies for different magnetic field values ($D_0 = 35$ cm; $\tau = 10^{-5}$ s).

This resonance phenomenon is obtained when the modulation frequency is equal to the cyclotron frequency [41] [43] (*i.e.* frequency of the electron in its orbit in the presence of a magnetic field).

Thus, the frequency of modulation with or without the application of a magnetic field to the solar cell, causes the reduction of the effective diffusion of excess minority carriers.

Also the study of the solar cell in frequency modulation, requires a choice of the values of the magnetic field (**Table 1**) for an optimal response through the diffusion coefficient (Dmax) to produce large photocurrent. Then such data will be used for the next calculations.

3.3. Optimum Base Thickness

Figure 3 gives the profile of the two expressions of AC back surface recombination velocity for different ringing frequencies inducing *D*max values, versus thickness of the base of the solar cell, under long wavelength ($\alpha(\lambda) = 6.2\ \text{cm}^{-1}$). The technique [47] [48] [56] of the intercept point of the curves yields the optimum thickness of the base, and allow the establishment of data in **Table 1**.

As obtained in previous study [56] [57] [58] [59], the optimum thickness is an increasing straight line versus diffusion coefficient (**Figure 4**). Thus solar cell with large diffusion coefficient can be used for thick base solar cell manufacturing.

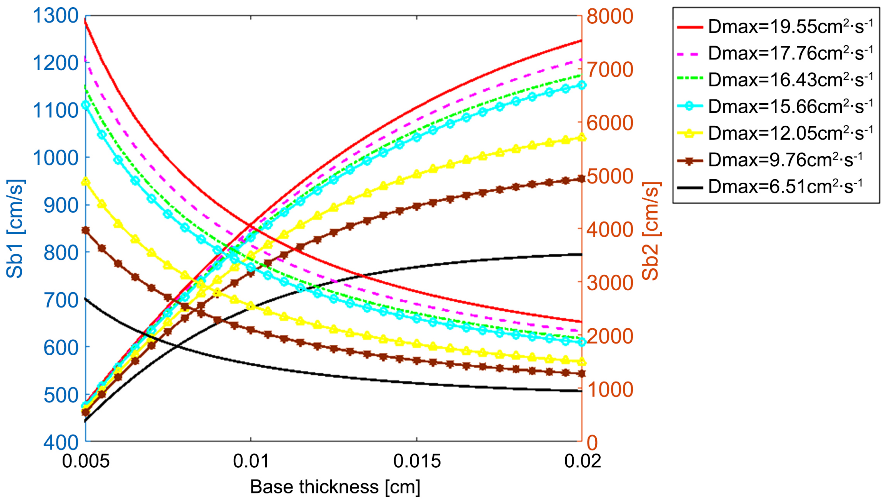

Figure 3. Sb1 and Sb2 versus depth in the base for different magnetic field values (D_0 = 35 cm^2/s; α = 6.2 cm^{-1}).

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}
ωr (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
Dmax (cm^2/s)	19.55	17.76	16.43	15.66	12.05	9.76	6.51
Lmax (cm)	0.014	0.0133	0.0128	0.0125	0.0110	0.0099	0.0081
Hop (cm)	0.01	0.0095	0.0092	0.0090	0.0085	0.0080	0.0075

The relationship obtained is expressed as:

$$Hop(\text{cm}) = 1.8\times 10^{-4} \times D\max\left(\text{cm}^2/\text{s}\right) + 0.0063 \tag{17}$$

From obtained diffusion length in **Table 1**, base optimum thickness is represented in **Figure 5**.

The representation is also an increase strait line [50] expresses as:

$$Hop(\text{cm}) = 0.39\times L\max(\text{cm}) + 0.0042 \tag{18}$$

Figure 6 and **Figure 7**, give the representation of the optimum thickness versus (*ωr*) and magnetic field (*B*) respectively. The plots of Hopt, are similar, because of the ratio (q/m_e^*) in Equation (6), then the effects of both the resonance frequency and the magnetic field impose thin thicknesses base.

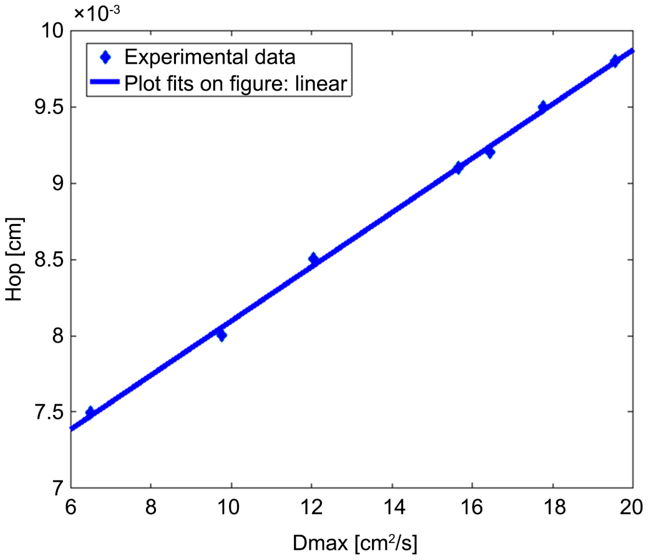

Figure 4. Optimum thickness of the base versus Dmax.

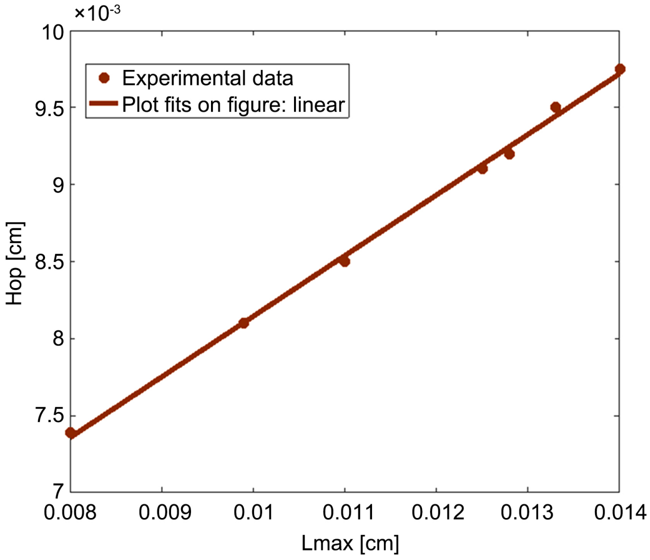

Figure 5. Lmax versus optimum thickness of the base.

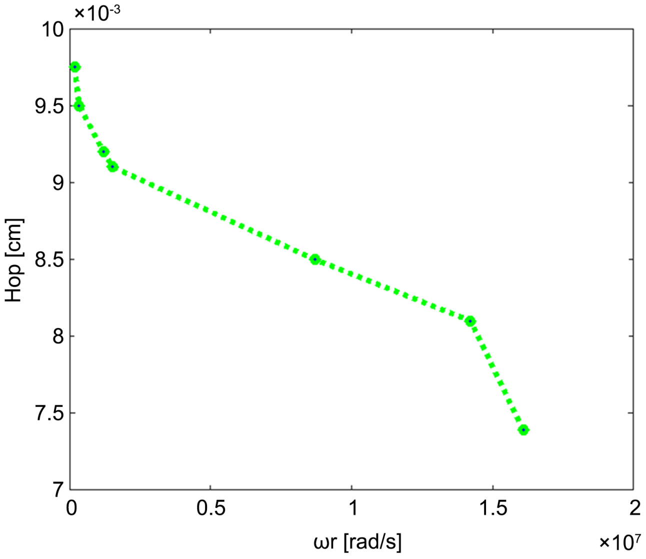

Figure 6. Optimum thickness of the base versus ωr.

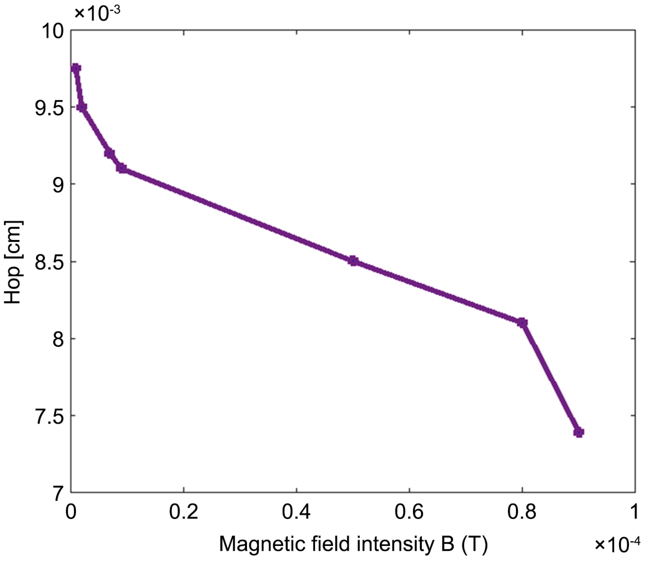

Figure 7. Optimum thickness of the base versus magnetic field.

4. Discussions

The technique of determining the optimum thickness of the base of the solar cell from the expressions of the recombination velocity in the rear face, was widely used and produced Hopt expressions according to the parameters of the experiment, including the magnetic field, temperature, irradiation flow of charged particles. The results obtained take into account the conditions of development of the solar cell (Doping rate) [60] and experimental. Thus the solar cell remained in static or dynamic frequency regime and with the possibility of variation of:

1) The parameters influencing the diffusion coefficient:

- by applying a magnetic field (B) [48], or irradiation by a flux (ϕp) of charged particles [61], temperature variation (T) [62]

- by combining several external experience factors, above mentioned [50] [58]

2) The parameters influencing recombination velocity expressions, including:

- the spectral composition of light (monochromatic [49] [56] or polychromatic [63]) having a constant incident photons flux or in frequency modulation
- the mode of illumination that can be, perpendicular to the junction (by the front [64] or by the back side [49]) or parallel to the junction (Vertical Muti-junctions) [57] [62] [65]

These two types of parameters influence the technique of determining the optimum thickness of the base, taking into account the optoelectronic factors.

The different results showed a linear growth of the optimum thickness of the base with the diffusion coefficient of excess minority carriers, regardless of the experimental conditions [47] [48] [49] [50] [56] [57] [58] [62] [65].

5. Conclusions

In the case of our study, the variation in the frequency of illumination on the solar cell maintained in a magnetic field has also produced large thicknesses of the solar cell consistent with the large values of the diffusion coefficient (*i.e.* long diffusion length), corresponding to the frequency of resonance. The optimum thickness (Hopt), depending on parameters, such as, the magnetic field, temperature, the irradiation flow of charged particles, suffered a decrease, as in our study.

This study expands the results on the determination of the optimum thickness of the (*p*) base of the silicon solar cell, allowing the best choices in the optimization of low-cost wafers in the industrial elaboration of the solar cell, for its adaptation to the conditions of use.

Conflicts of Interest

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

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