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***Journal of Scientific and Engineering Research*, 2022, 9(11):152-165**

Research Article

ISSN: 2394-2630
CODEN(USA): JSERBR

Bifacial Silicon (N+/P/P+) Silicon Solar Cell Base Thickness Optimization under Back Illumination of Long Wavelengh: Effect of Diffusion Coefficient Resonance in Teperature under Applied Magnetic Field

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Abstract This work aims to save silicon material, for the realization of the solar cell, by reducing the thickness of the base. For this, the ($n^+/p/p^+$) silicon solar cell at temperature (T) is placed in a variable magnetic field (B) and back illuminated by a monochromatic light of deep penetration into the base.The magneto-transport equation relating to the density of the photogenerated carriers at depth in the base is solved and allows to extract the expressions of the recombination velocity on the rear side. A graphic technique of the study of these expressions in a situation of resonance of minority carriers diffusion, gives the optimum thickness of the base.
The results obtained show a decrease in optimum thickness with both parameters, temperature and magnetic field. Mathematical modeling of these results, shows the possibility of making thin solar cells and saving silicon material

Keywords Silicon Solar Cell, Diffusion Coefficient, Resonance, Temperature, Magnetic field, Recombination Velocity, Absorption Coefficient, Base Thickness

1. Introduction

Improving the efficiency [1, 2] of silicon solar cells involves examining:

i) Architecture such as monofacial [3], bifacial [4-9], multi-junction silicon [10, 11] (vertical or series) and thin films [12, 13]

ii) Phenomological parameters [14 -24], which are: lifetime, diffusion length, mobility, which are related by the Einstein relation, as well as surface recombination, at the surface of the emitter, at the emitter-base (junction), at the back side of the base, and at the grain boundaries

iii) The parameters of the model electrical equivalent to the solar cell in static mode [25-29], given by the series and shunt resistors, the capacitance of the space charge zone and the diffusion capacitance. In dynamic mode, ie transient decay [16, 17, 30, 31, 32] or impedance spectroscopy [33 - 38], it will be impedance, conductance and capacitance determination.

External factors influence the operation of the solar cell and must be taken into account, as they act on the elements mentioned above.
These are:
1) Illumination through it's: concentration [18, 35, 39], angle of incidence [40] and shading [41] produced, spectral quality (mono or polychromatic light) [42], its incident flux of constant amplitude [43], pulsed [16, 17, 31, 32] or with frequency modulation [15, 24, 44-46]
2) Effects of applied: temperature [47, 48, 49], electromagnetic field [14, 50-53], and irradiation by electrically charged particles [54, 55].
The concomitance of external factors can be imposed on the solar cell [38, 56-62].
The geometric parameters [21], which are the dimensions of the different regions that make up the solar cell, are also important for the analysis of the physical mechanisms that take place there [22]. This is the thickness of: the emitter [63], the space charge region [13, 64, 65] the base [23, 57, 58, 61, 66, 67] and also the grains size [21].
This work aims to save silicon material, for the realization of bifacial silicon solar cell, by reducing the thickness of the base and the production of maximum photocurrent, while phenomelogical parameter, such as, diffusion coefficient gives high response i.e. in resonance [38, 59, 60, 61, 62, 66, 67].
For this, the bifacial silicon solar cell ($n^+/p/p^+$) at temperature (T) is placed in a variable magnetic field (B) and back illuminated by a monochromatic light of deep penetration into the base (L< H <1/α) [68, 69], i.e, reciprocal absorption coefficient (α) larger than both base thickness (H) and diffusion length (L).
The optimized thickness [2] in a condition of temperature resonance of the diffusion coefficient of the minority carriers [59], would lead to an optimization of the photocurrent delivered and a saving of material used in the manufacture of a bifacial solar cell.

2. Theory

The structure of the (n^+-p-p^+) bifacial silicon solar cell [4-9] under monochromatic illumination, under magnetic field B at temperature T, is shown by figure.1.

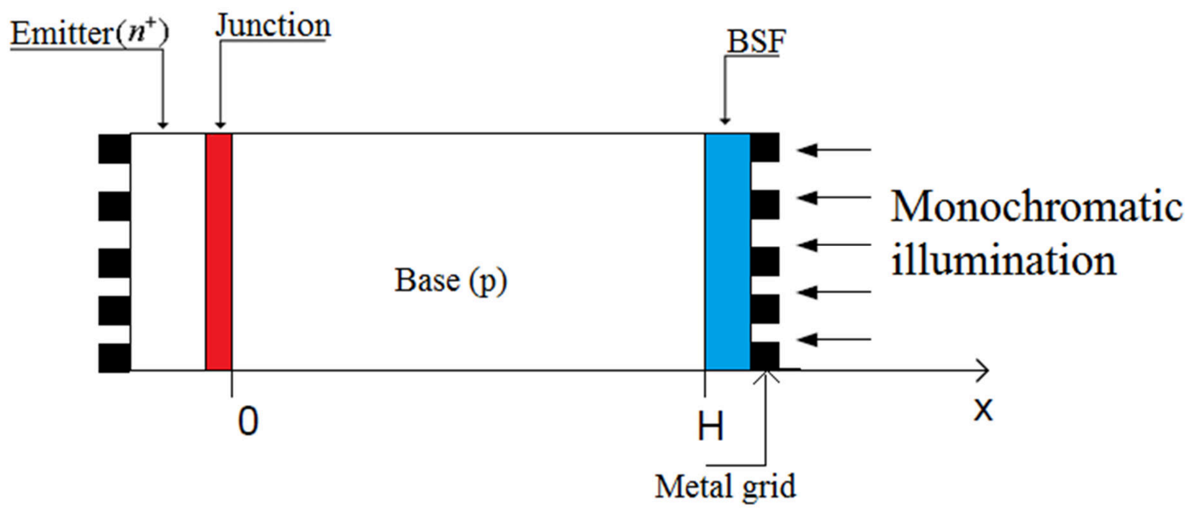

Figure 1: Structure of monofaciale solar cell

The generated excess minority carriers' density $\delta(x, B, T)$ at coordinate (x), 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 in steady state [14, 50-53]:

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

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.

Under magnetic field, the diffusion coefficient is given by the following relation [50, 51]

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

With Einstein relation: $D(T)=\dfrac{\mu(T)\cdot K\cdot T}{q}$ (3)

The elementary charge of electron is q, and K is the Boltzmann constant.

And the mobility coefficient is given as temperature dependent [24, 49]:

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

- L represents the excess minority carriers' diffusion length in the base:

$$L^2(B,T)=D(B,T)\cdot\tau \quad (5)$$

- The carrier generation rate $G(x)$ is given by the relationship [6, 9]:

$$G(x)=\alpha\cdot I_0\cdot(1-R)\cdot e^{-\alpha\cdot(H-x)} \quad (6)$$

The incident flux on the rear of the base is (Io), (α) and (R) are the monochromatic absorption and reflection coefficients of the silicon material [17, 43, 68, 69].

The solution of equation (1) is:

$$\delta(x,\alpha,B,T)=A\cdot\cosh\left[\frac{x}{L(B,T)}\right]+E\cdot\sinh\left[\frac{x}{L(B,T)}\right]+K\cdot e^{-\alpha(H-x)} \quad (7)$$

With $K=-\dfrac{\alpha\cdot I_0\cdot(1-R)\cdot[L(B,T)]^2}{D(B,T)\left[L(B,T)^2\cdot\alpha^2-1\right]}$ (8)

And $\left(L(B,T)^2\cdot\alpha^2\neq 1\right)$ (9)

Coefficients A and E are determined through the boundary conditions:

- At the junction (x = 0)

$$\left.\frac{\partial\delta(x,\alpha,B,T)}{\partial x}\right|_{x=0}=Sf\cdot\left.\frac{\delta(x,\alpha,B,T)}{D(B,T)}\right|_{x=0} \quad (10)$$

- On the back side in the base (x = H) (11)

$$\left.\frac{\partial\delta(x,\alpha,B,T)}{\partial x}\right|_{x=H}=-Sb\cdot\left.\frac{\delta(x,\alpha,B,T)}{D(B,T)}\right|_{x=H} \quad (12)$$

Sf and Sb are respectively the recombination velocities of the excess minority carriers at the junction [19, 32] and at the back surface [19, 20, 44, 45].

3. Results and Discussions

3.1 Diffusion coefficient at resonance

Combining equations 2, 3, 4, the optimum temperature (Topt) is obtained at the maximum (Dmax) of the curve D(B, T), for a given magnetic field (B). Thus the expression [59] is given by:

$$T_{op}(B) = \sqrt[4{,}84]{2{,}4x(1{,}43.10^{9})^{2}.B^{2}} \tag{13}$$

This relationship allows 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.

3.2 Photocurrent density

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

$$J_{ph}(Sf,\alpha,B,T) = q \cdot D(B,T) \cdot \left.\frac{\partial \delta(x,\alpha,B,T)}{\partial x}\right|_{x=0} \tag{14}$$

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

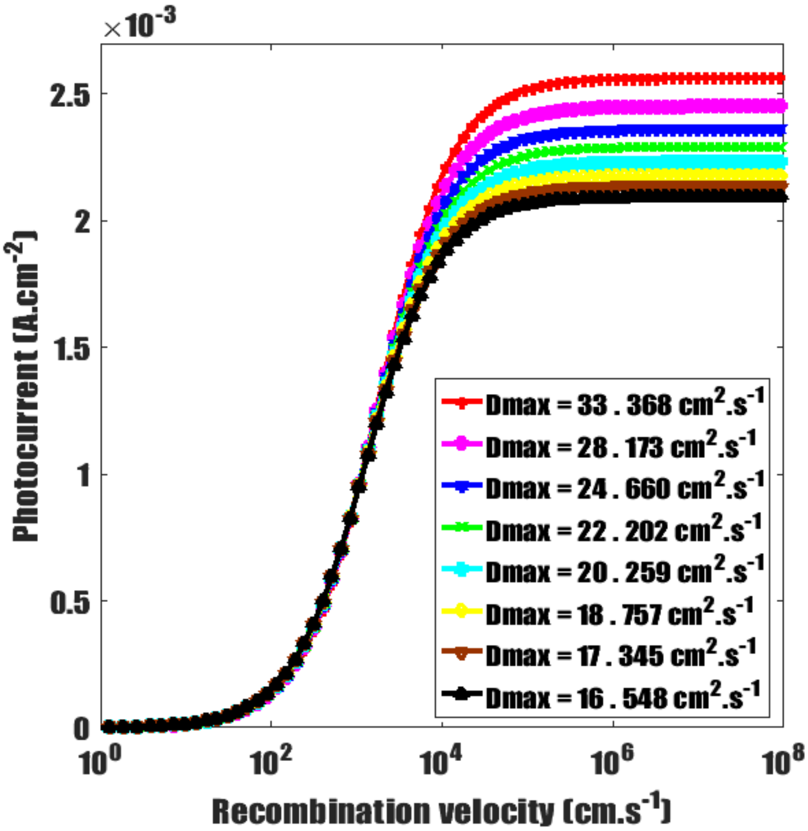

Figure 2: Photocurrent density versus recombination velocity for different diffusion coefficient ($\alpha = 6.2\ cm^{-1}$)

3.2 Base thickness optimization

The plotted photocurrent density versus (Sf) minority carriers' recombination velocity at the junction (Figure. 2), is marked by three zones [19, 70, 71]. At low recombination (Sf) velocity values, the carriers are locked at the junction, which corresponds to an open circuit operation, because the photocurrent density is zero. Then the photocurrent grows rapidly in the second region, to reach an asymptotic value in the third region, which is the short-circuit current density. This flat region is well marked whatever the values of the diffusion coefficient (Dmax). The short-circuit current density increases with the diffusion coefficient, which decreases with optimum temperature and magnetic field (See Table. 1). The thermal agitation and deflection of the charge carriers, in high velocity, reduces the density of short-circuit photocurrent. From this situation of constant short-circuit current, it comes that:

$$\left.\frac{\partial J_{ph}(Sf, Sb, \alpha, H, B, T)}{\partial Sf}\right|_{Sf \geq 10^5\,cm.s^{-1}} = 0 \tag{15}$$

The solution of this equation leads to the mathematical expressions of the (Sb) recombination velocity of the minority carriers on the back side of the base, as:

$$Sb1(H,B,T) = -\frac{D(B,T)}{L(B,T)}.\tanh\left(\frac{H}{L(B,T)}\right) \tag{16}$$

$$Sb_2(H,\alpha,B,T) = \frac{D(B,T)}{L(B,T)} \cdot \left[\frac{L(B,T)\cdot\alpha - \left(L(B,T)\cdot\alpha\cdot ch\left(\frac{H}{L(B,T)}\right) + sh\left(\frac{H}{L(B,T)}\right)\right)e^{-\alpha\cdot H}}{\left(ch\left(\frac{H}{L(B,T)}\right) + L(B,T)\cdot\alpha\cdot sh\left(\frac{H}{L(B,T)}\right)\right)e^{-\alpha\cdot H} - 1}\right] \tag{17}$$

Figure 3 shows the application of the graphical technique [57, 58, 61, 72, 73] which makes it possible to deduce the optimum thickness of the base, by the intersection of the curves Sb1 and Sb2, for every maximum diffusion (Dmax) value, and for weak absorption coefficient (α(λ)).

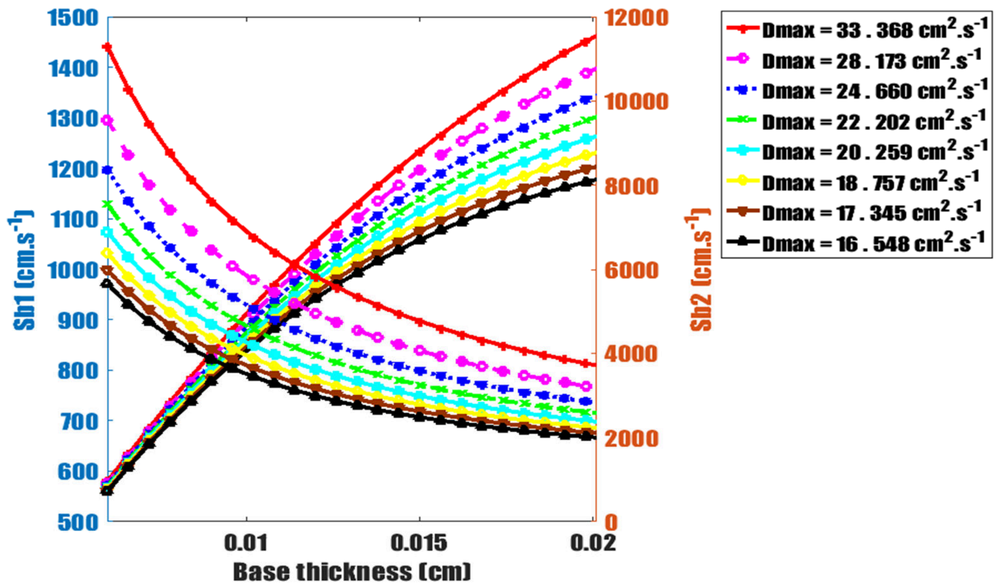

Figure 3: Sb1 and Sb2 versus depth in the base for different diffusion coefficient

The table. 1 gives the results extracted from the curves of figure. 3.

Table 1: Base optimum thickness obtained with maximum values of minority carriers' diffusion coefficient and optimal temperature for different magnetic field values

Magnetic field B (T)	0.0003	0.0004	0.0005	0.0006	0.0007	0.0008	0.0009	0.001
Optimum temperature Topt (K)	255	285	308	335	355	380	400	410
Maximumdiffusion Coefficient Dmax (cm^2/s)	33.364	28.178	24.694	22.206	20.276	18.763	17.571	16.642
Optimum thickness Hopt (cm)	0.0114	0.0108	0.0102	0.0099	0.0096	0.0093	0.0091	0.009

Extracted from the data in **Table 1**, **Figures 4**, **5** and **6**, represent the optimum thickness of the base of the solar cell as a function respectively of the maximum diffusion coefficient of the minority carriers, the applied magnetic field and the temperature. **Equations 18**, **19** and **20**, represent the mathematical modeling of these curves.

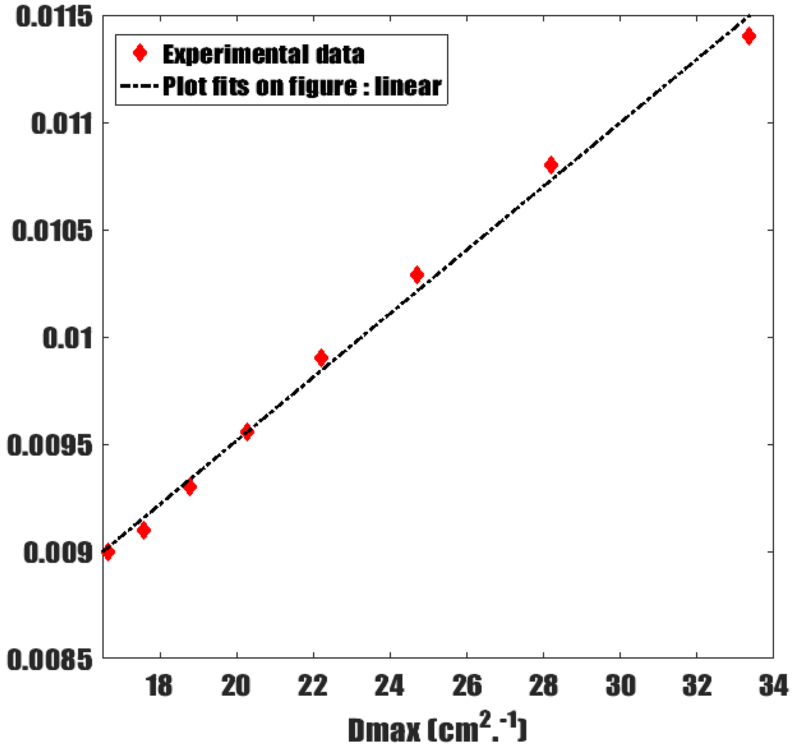

Figure 4: Optimum thickness versus Dmax

Figure .4 shows an increasing linear function of the optimum thickness of the base with the maximum of the diffusion coefficient, expressed by **equation 18** as:

$$Hopt(cm) = 1.5 \cdot 10^{-4} \times D\max + 0.0066 \quad (18)$$

Figures. 5 and **6**, respectively have a decreasing function of the optimum thickness with both, the temperature and the applied magnetic field.

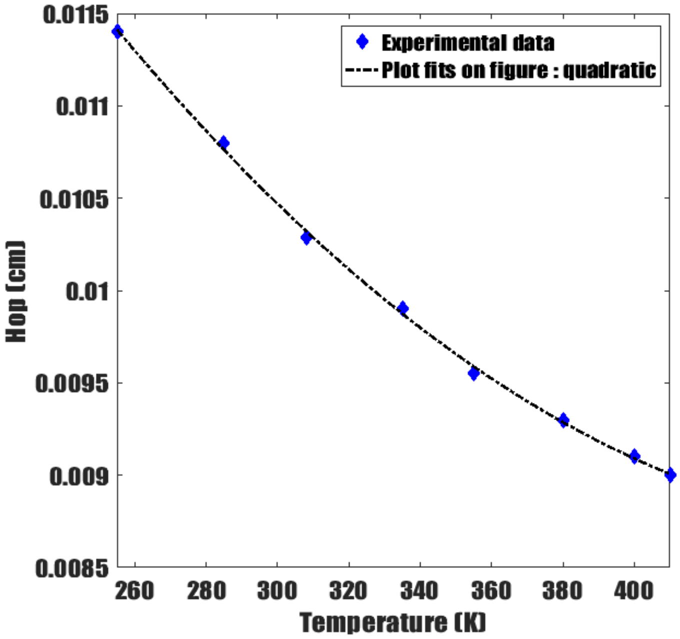

Figure 5: Optimum thickness versus temperature

Equation 19, below, represents the fit of the curve in **Figure 5**.

$$Hopt(cm) = 5 \cdot 10^{-8} \times T^2 - 4.8 \cdot 10^{-5} \times T(K) + 0.021 \quad (19)$$

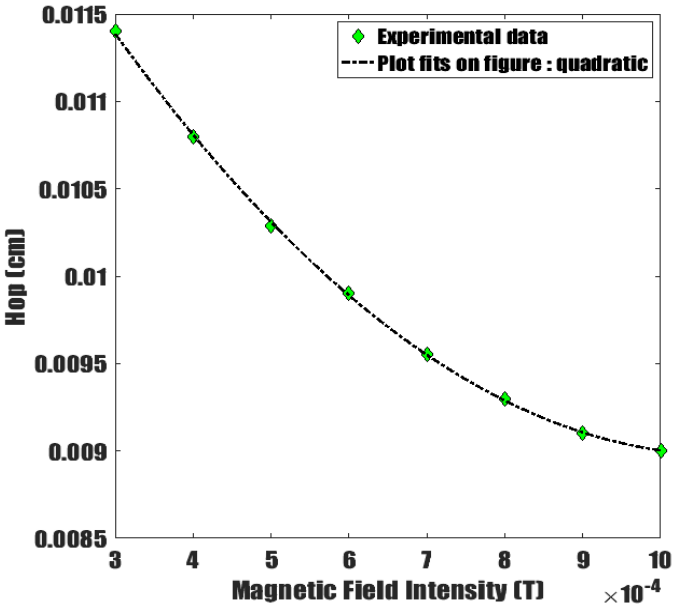

Figure 6: Optimum thickness versus magnetic field

Equation 20 represents the fit of the curve in **Figure 6**.

$$Hopt(cm) = 4 \cdot 10^3 \times B^2 - 8.6 \times B(T) + 0.014 \quad (20)$$

The short-circuit current density, corresponding to the large values of the recombination velocity at the junction, decreases as a function of the maximum diffusion coefficient (**Figure 2**), which itself decreases with the optimum temperature and the applied magnetic field (**Table .1**). The diffusion length of minority carriers (**Eq. 5**), consequently, decreases with the maximum diffusion coefficient, when the optimum temperature and the applied magnetic field increase. Thermal agitation and deflection, then impose, a short distance of course to the minority carriers, photogenerated from the rear face, in depth towards the junction (low α(λ))[31, 69].The results from the table. 1, confirms the need to produce thin bifacial solar cells [12, 13,74, 75, 76], to improve significant efficiency.

4. Conclusion

This work has pointed out a graphical technique for determining the optimum base thickness of bifacial silicon solar cell back illuminated with monochromatic light of weak absorption coefficient.

Indeed excess minority carriers' maximum diffusion coefficient obtained as mathematical co-relationships with optimum temperature point for given magnetic field, is used. The magneto-transport equation relating to the density of the minority carriers in the base of bifacial solar cell was solved. Boundary conditions, were taken into account through recombination velocity in front and rear face.

Study from the photocurrent density has produced expressions of minority carriers' recombination velocity on the back side. Graphical technique is used to analyze back surface recombination velocity expressions versus thickness, and then, optimum thickness of the base of the silicon bifacial solar cell was deduced and fitted as decreasing functions of both, the temperature and the magnetic field.

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