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Research Article

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Surface recombination velocity concept as applied to determinate back surface illuminated silicon solar cell base optimum thickness, under temperature and external magnetic field effects

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Abstract From back surface illuminated silicon solar remained under temperature and external magnetic field, new expressions of back surface recombination velocity of excess minority carriers in the base are expressed dependent of both, the thickness and the diffusion coefficient. This later parameter is in relationship with both, the temperature and the applied magnetic field that express, Umklapt and Lorentz physical phenomena that take place in the base of silicon solar cell. The plot of back surface recombination velocity expressions for given diffusion coefficient, as a function of thickness, yields intercept point, that gives the optimum thickness of the base of the solar cell to be manufactured.

Keywords Silicon solar cell-Umklapt and Lorentz processes- Diffusion coefficient- Surface recombination velocity-base thickness

Introduction

Measurement of both diffusion and mobility coefficients of excess minority carrier goes through spectroscopic techniques [1-4] and current or voltage responses measurement of material or solar cell under specific theoretical and experimental conditions [5-6]. Mathematical correlations are established between the diffusion coefficient and:

a) the doping rate of the emetter and the base [7-9]

b) the operating temperature [10,11]

c) frequency of electrical or light excitation [12,13], with magnetic superimposed [14,15]

d) the magnetic or electrical field [16-19]

e) the excess minority carrier recombination velocity at junction surfaces (n/p, n^+/p, p/p^+), grain boundaries, grain size and structures dimensions [20-27]

f) Irradiation parameters (flux and intensity) [28-34] by charged particles on the solar cell

From the diffusion coefficient, these different parameters influence minority carrier recombination velocity in volume and surfaces [35; 36] of the solar cell.

The current and voltage responses of the solar cell, under these different conditions, are studied as a function of the minority carrier recombination velocity in order to evaluate the quality of the solar cells.

In this work, the minority carriers recombination velocity in volume, (τ) at the emitter-base junction (Sf) and at the back surface (Sb) are studied to determine, optimum thickness (H) bifacial silicon solar cell to the illuminated by the rear face. That leading to the optimum short-circuit current, as a function of the temperature T and the magnetic field B, inducing the diffusion coefficient (D (B , T)) [37].

2. Theory

2.1. Bifacial silicon solar cell

figure 1 represents a n^+-p-p^+ bifacial silicon solar cell type and under polychromatic illumination [35,36], by back side (p^+), through the collector gates. The space charge region, (in x = 0) constitutes the junction (n^+-p), allowing the separation of photogenerated electron-hole pairs, subjected to a junction recombination velocity (Sf) [20-23]. The back surface corresponds to a zone of higher doping rate (p^+), in x = H, and produces an electric field (Back surface Field), which allows the return of the minority carriers towards the junction, and minimizes the recombination velocity (Sb) in this rear face [19, 6, 20]. Metal grids are placed on the back (p^+) and allow illumination by the rear face.

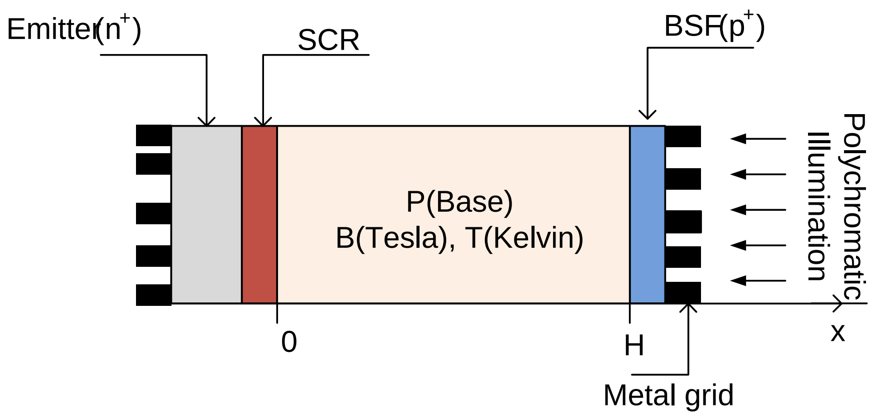

Figure 1: Back side illuminated n^+-p-p^+ silicon Solar cell, under both the magnetic field and the temperature

When the solar cell is under illumination, the minority carrier density δ(x) photogenerated for a low injection in the base, is governed by the following equation

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

τ and D are, respectively, the lifetime and the diffusion coefficient of the minority carrier in the base, connected by the relation of Einstein

$L^2(B,T) = D(B,T)*\tau$ (2)

with L(B,T)the diffusion length of the minority carrier which depends on both, the magnetic field and the temperature. The diffusion coefficient of the excess minority carrier is related to the magnetic field and the temperature by the following relations [10; 37]:

$D(B,T)=\frac{D(T)}{1+(\mu(T)*B)^{□}}$ (χμ□/σ) (3)

$D(T)=\mu(T).\frac{k_b.T}{q}$ (4)

The minority carrier mobility coefficient with temperature is given by [10]:

$\mu(T)=1.43*10^9 T^{-2.42} cm^2V^{-1}.s^{-1}$ (5)

T is the temperature of the solar cell, kb = 1.43 10-23m^2 kg.s^{-2}.K^{-1} is the Boltzmann constant and q is the elementary charge. D (B, T) is therefore the result of the coexistence of the Umklapt and Lorentz processes, describing respectively the thermal agitation and the deflection of the minority charge carriers [**37**].

δ(x) the excess minority carrier density of photogenerated in the illuminated base by the (p +) face, is produced by the generation rate [36, 38], expressed by the following equation:

$$G(x) = \sum_{i=1}^{3} a_i . e^{-b_i(H-x)} \quad (6)$$

Where, ai and bi are coefficients obtained from the modeling of the radiation under A.M1.5

The expression of the excess minority carrier's density at point x in the base is given by the resolution of the continuity equation and is written by:

$$\delta(x, B, T) = A(B, T). \cosh\left(\frac{x}{L(D)}\right) + C(B, T). \sinh\left(\frac{x}{L(D)}\right) + \sum_{i=1}^{3} K_i(B, T). e^{-b_i(H-x)} \quad (7)$$

Where : $K_i(B, T) = \frac{a_i.L(B,T)^2(B,T)}{D(B,T)[1-(L(B,T).b_i)^2]}$ (8)

A(B,T) and C(B,T) are coefficients deduced using boundary conditions of the base. They respectively introduce the junction recombination velocity (Sf) and at the back surface (Sb) of the excess minority carrier.

- At the junction x = 0 (SCR)

$$\left.\frac{\partial\delta(x,B,T)}{\partial x}\right|_{x=0} = Sf * \delta(x = 0, B, T) \quad (9)$$

Sf indicates the minority carrier velocity of passage across the junction. This minority carrier velocity of passage is imposed by the resistance of the external charge of the solar cell which indicates the operating point [20-23]. Thus, the minority carriers that are not collected and not crossing the external load, constitute the losses, and are therefore linked to the electrical model through the shunt resistance [31, 39]. The velocity is associated with the concept of the intrinsic recombination velocity, defining the solar cell under open circuit condition [21].

- At the back surface (x=H)

$$\left.\frac{\partial\delta(x,B,T)}{\partial x}\right|_{x=H} = -Sb * \delta(x = H, B, T) \quad (10)$$

Sb is the excess minority carrier recombination velocity at the rear face [19, 6, 20], at x = H, where there is a rear electric field (p/p^+i.e. low-high junction), which returns electric charges towards the junction (SCR). At this surface where there is a potential barrier, the minority carriers can cross this junction p / p + [19].

2.2. Results and Discussions

2.2.1. Photocurrent Density

The expression of the photocurrent density is given by the following equation:

$$Jph(Sf, B, T, H) = qD(B, T) * \left.\frac{\partial\delta(x,B,T)}{\partial x}\right|_{x=0} = qD(B, T)\left[\frac{C(B,T)}{L(B,T,)} - \sum_{i=1}^{3} b_i K_i(B, T)\right] \quad (11)$$

FIG. 2 gives the profile of the photocurrent density as a function of minority carrier recombination velocity at the junction for different depth values H of the base. At large values of SF (> 10^5 cm / s), the short-circuit current, represented by the plates, decreasing with thickness: reduction of Lorentz forces with thickness.

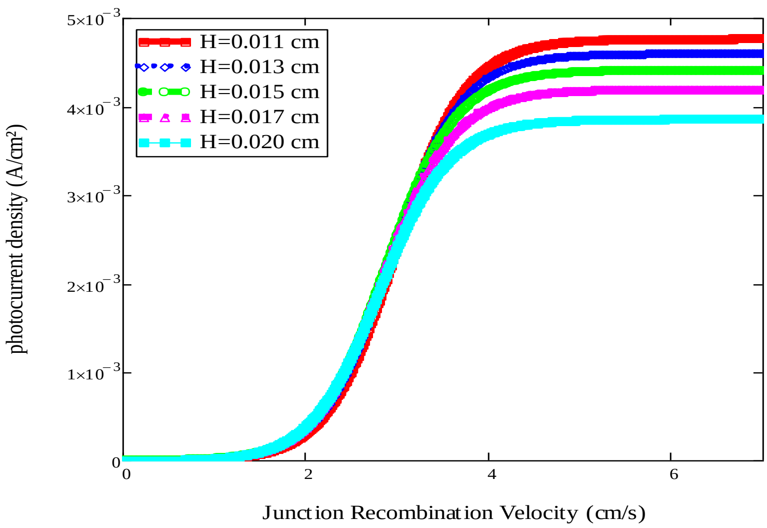

Figure 2: Photocurrent density as a function of the junction recombination velocity for different thicknesses H, $B=10^{-3.45}$Tesla ; T=276K ; D=30.23cm²/s

Figures 3 and 4 represents the calibration curves of the photocurrent density as a function of the minority carrier recombination velocity at the junction. The bifacial silicon solar cell of thickness H is placed under magnetic field and temperature, leading to the D values of the minority carrier diffusion coefficient [25, 37], and for recombination velocity respectively Sb1 and Sb2 [21, 22].

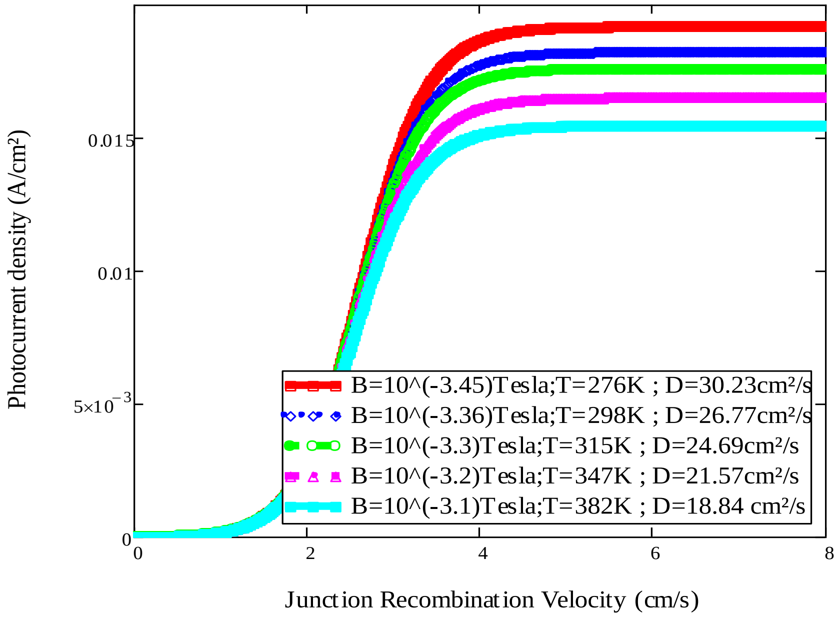

Figure 3: Photocurrent Density versus junction recombination velocity for different values of the magnetic field and the temperature, H=0.02 cm

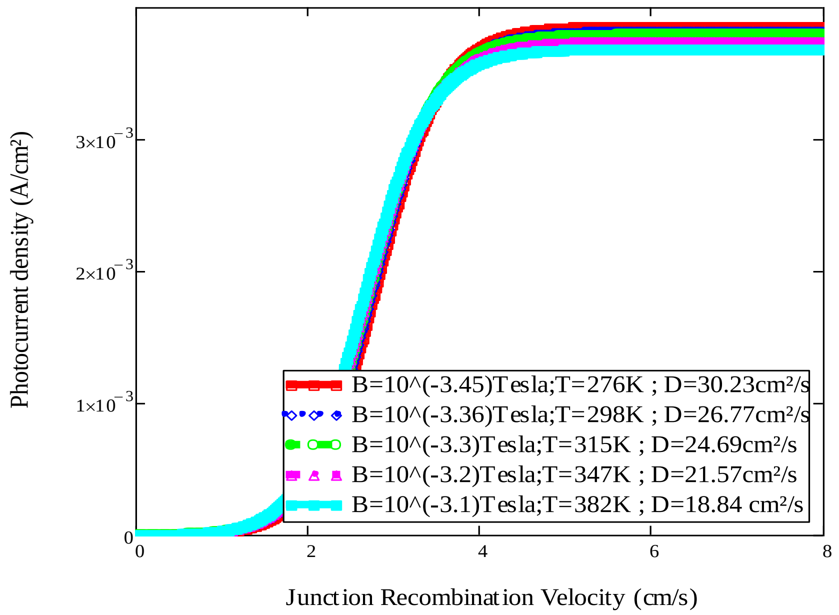

Figure 4: Photocurrent density versus junction recombination velocity for different values of magnetic field and temperature H=0.02 cm

For values of Sf<10^2cm/s, the photocurrent is practically zero (depending on the illumination level), which corresponds to an open circuit operating point of the solar cell. For the junction recombination velocity range from 10^2cm / s to about 10^4 or 10^5cm/s, depending on the diffusion coefficient (D), the photocurrent density is increasing.

Beyond 10^5cm/s, the photocurrent density is almost constant with Sf and corresponds to the short circuit current density Jphsc, which is a plateau.

This short circuit density decreases with D, therefore with increasing thermal agitation and magnetic field (reduction of Lorentz forces). In the case where Sb2 (Figure 3) is smaller than Sb1 (Figure 4), this produces much larger short-circuit photocurrent densities (Jsc2 of Figure 3 is larger than Jsc1 in Figure 4) regardless of the values of T and B.

2.2.2. Back Surface Recombination Velocity Sb(B, T)

Figures 2, 3 and 4 has showed a tray regardless of, D, H, and n, thus the derivative of the expression of the photocurrent density relative to the junction recombination velocity Sf, is zero [10; 13; 17, 26]:

$$\frac{\partial Jph(Sf,B,T,H)}{\partial Sf} = 0 \qquad (12)$$

The resolution of this equation yields to expressions of back surface recombination velocity Sb1 (bi, H, D) and Sb2 (H, D), with D function of B and T:

$$Sb1(B,T,H) = -\frac{D(B,T)}{L(B,T)} * \tanh\left(\frac{H}{L(B,T)}\right) \qquad (13)$$

Sb1 (B, T, H) <0, is the minority charge carrier velocity crossing the junction p / p^+. It is the flux of minority carriers towards the (p) part (FICK law), justifying the potential inducing the electric field on the rear face [6]. It represents the intrinsic recombination velocity of minority carrier at the p/p^+ junction.

$$Sb2(B,T,H) = \sum_{i=1}^{3} \frac{D(B,T)}{L(B,T)} * \frac{\left[\sinh\left(\frac{H}{L(B,T)}\right) + L(B,T)*b_i*\cosh\left(\frac{H}{L(B,T)}\right)\right]e^{-b_iH} - L(B,T)*b_i}{1-\left[\cosh\left(\frac{H}{L(D)}\right) + L(B,T)b_i\sinh\left(\frac{H}{L(D)}\right)\right]e^{-b_iH}} \qquad (14)$$

Where appears the effect of the absorption of the light in the material through the coefficients (bi) and leads to a generation velocity for (bi.H >> 1). Sb1 indicates the velocity of excess minority carrier sent back to the junction n $^+$/p, to participate in the photocurrent.

The recombination velocity expressions i.e. Sb1 and Sb2 give an asymptote under the conditions where H / L >> 1, equal to D / L, who represents a diffusion velocity [10 ; 13 ; 26].

FIG. 3 gives the profile of the recombination velocity at the rear face versus solar cell base thickness, for different values (B, T) leading to the diffusion coefficient values of the minority carrier in the base (table 1).

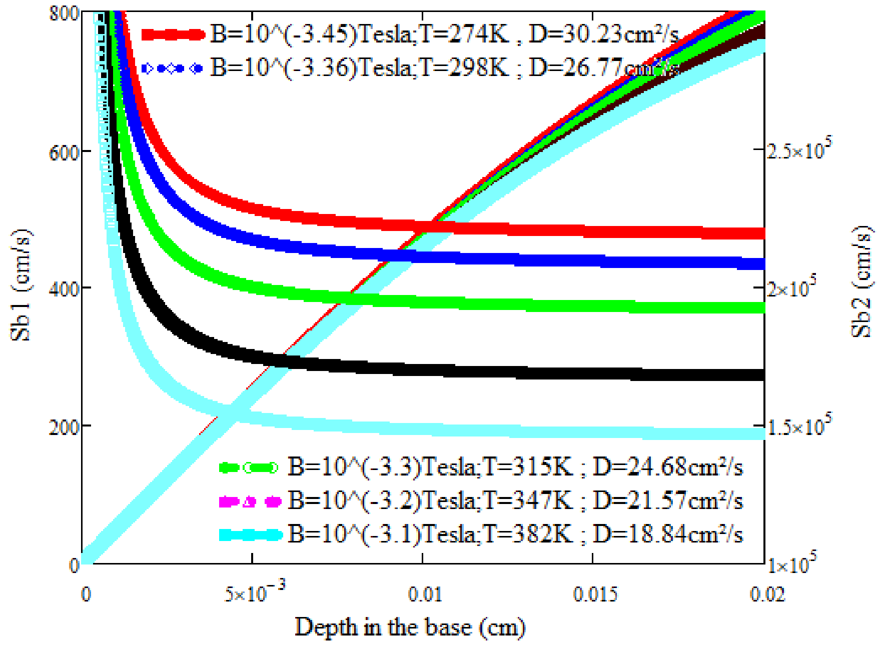

Figure 5: Back surface recombination velocity Sb1 and Sb2 versussolar cell base thickness

The intercept point on the plot of the curves Sb1 and Sb2, for each diffusion coefficient, allows to deduce the optimum thickness of the base of the bifacial silicon solar cell, illuminated by the rear face, et sought by other authors [40, 41, 42] using macroscopic values of current and voltage.

Table 1 summarizes the variation of the thickness of the base of the solar cell illuminated by the rear face and placed under the conditions (B, T) et leading to the specific values of the diffusion coefficient and the respective short-circuit currents Jsc1 and Jsc2. Jsc1 and Jsc2 values remain maximum and constant, corresponding to Sb1 and Sb2.

Table 1: Values of the thickness H for different diffusion coefficients D (B, T)

Magnetic field (Tesla)	$10^{-3.45}$	$10^{-3.36}$	$10^{-3.3}$	$10^{-3.2}$	$10^{-3.1}$
Temperature (K)	276	298	315	347	382
D(cm²/s)	30.23	26.77	24.69	21.57	18.84
H(cm).10^{-2}	0.44	0.58	0.50	0.48	0.47
Jsc1(A/cm^2)	0.028	0.028	0.027	0.027	0.027
Jsc2(A/cm^2).10^{-3}	5.36	5.26	5.15	5.28	5.29
Sb1(cm/s)	217.831	246.181	283.589	235.816	230.513
Sb2(cm/s).10^2	2650	21730	19860	17550	15360

Figure 6 gives the required thickness of the base of the solar cell manufactured for each case of the diffusion coefficient.

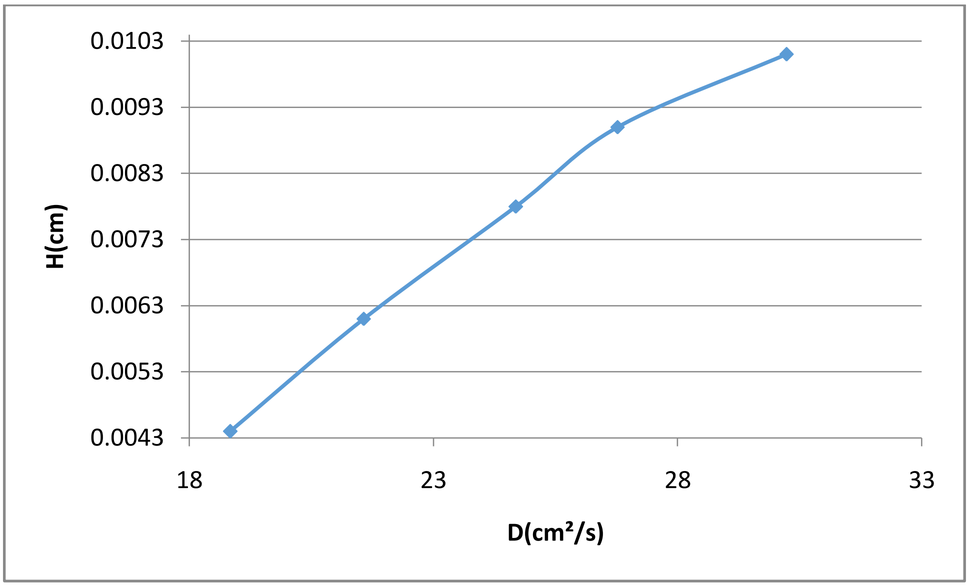

Figure 6: Depth H as a function of diffusion coefficient D.

The correlation between the diffusion coefficient and the optimum thickness of the base is established for 18 $cm^2/s < D < 35\ cm^2/s$, as:

$$H(\text{cm}) = \left[-0.2D^2\left(\frac{cm^2}{s}\right) + 13D\left(\frac{cm^2}{s}\right) - 149\right]10^{-4} \quad (15)$$

It makes it possible to manufacture the bifacial solar cell with a thickness H of the base, illuminated by the rear face, maintained under the conditions of a magnetic field B and at the temperature T. It leads to a minority carrier diffusion coefficient D(B,T), who results from the coexistence of the Umklapt and Lorentz processes, respectively due to the thermal agitation and the deflection of the minority charge carriers.

3. Conclusion

In this work, a technique of the intersection of back surface recombination velocity is proposed for the determination of the optimum thickness of the base of the bifacial solar cell illuminated by the rear face et submitted to temperature and magnetic field variation. The calibration curves of the photocurrent as a function of the excess minority carrier recombination velocity at the junction, are produced under:

i) different thicknesses H of the base

ii) different values (Sb1 and Sb2) of the minority carrier recombination velocity to the rear face of the base

iii) different diffusion coefficients, Dmax (T, B) obtained at the resonance points of the D (T) curves while B is kept constant, lead to recombination velocity obtained in the rear face, depending on both, the thickness and the diffusion coefficient D(B, T) of the minority carrier in the base.

The study of the profile of the minority carrier recombination velocity at the rear face, through the two expressions obtained, made it possible to establish the optimum thickness of the base under magnetic field B, associated with the optimum temperature, leading to an optimum short-circuit current, through a mathematical correlation.

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