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Lamella Silicon Solar Cell under Both Temperature and Magnetic Field: Width Optimum Determination

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Abstract

This work deals with determining the optimum thickness of the lamella wafer of silicon solar cell. The (p) base region makes up the bulk of the thickness of the wafer. This thickness has always been a factor limiting the performance of the solar cell, as it produces the maximum amount of electrical charges, contributing to the photocurrent. Determining the thickness of the wafer cannot be only mechanical. It takes into account the internal physical mechanisms of generation-diffusion-recombination of excess minority carriers. They are also influenced by external factors such as temperature and magnetic field. Under these conditions, magneto transport equation is required to be applied on excess minority carrier in lamella base silicon solar cell. It yields maximum diffusion coefficient which result on Lorentz law and Umklapp process. Then from photocurrent, back surface recombination velocity expressions are derived, both maximum diffusion coefficient and thickness dependent. The plot of the back surface recombination calibration curves as function of lamella width, leads to its maximum values, trough intercept points. Lamella optimum width is then obtained, both temperature and magnetic field dependent and expressed in relationships to show the required base thickness in the elaboration process.

Keywords

Silicon Vertical Junction, Back Surface Recombination Velocity, Magnetic Field, Temperature, Lamella Width

1. Introduction

The manufacturing architecture silicon solar cells evolves to improve photovoltaic conversion efficiency, at lower cost [1] [2] [3] [4].

Many architectures have been achieved, such as, monofacial solar cells (front or rear illumination), bifacial (simultaneous illumination both sides), vertical junction (series or parallel), in order to absorb maximum incident flow and generate excess minority carriers allowing to be collected, before undergoing recombination (in the bulk or on surfaces) [5] [6].

Lifetime (τ) [7] [8] [9], diffusion coefficient (D) [10], diffusion length (L) [11] [12] [13] [14] [15] and surface recombination velocity [16] [17] [18] [19] [20], at junction (Sf) [21]-[26], on back (Sb) [27] [28] [29] [30], at grain boundaries (Sg) [31] are intrinsic parameters in development of silicon material and of solar cells manufacturing [32].

Quality control of manufacturing solar cell is done by measuring these parameters, under light optical excitation [33], or electric [34]. The solar cell can be placed under different regimes, *i.e.* static [35] [36], transient dynamics [37] [38] [39] [40] [41] or frequency [42] [43] [44]. The operating points can be short circuit or open circuit, or any other point of the illuminated (or dark) current-voltage characteristic [45] [46].

However solar cell base thickness (H) is a geometric parameter to consider, compared to minority carriers diffusion length, to ensure a high probability collection of photocreated carriers [47] [48] [49] [50] [51].

The vertical multi-junction silicon solar cells (VMJ) [52] [53] [54] [55], use materials having charge carriers with short diffusion length, but its architecture gives the advantage of excess minority carriers to be collected, without traveling great distances. Indeed the low thickness base can be combined with two emitter allowing the collection of minority carrier (PVMJ) [56] [57], or by existence a rear field (junction p/p^+) who drives them back, thus reducing the distance to be covered (SVMJ) [58]. This rear field induces a recombination velocity minority charge carriers (Sb) that characterize the back surface of solar cell (BSF or ohmic contact) and then gives the rate of charge carrier loss [27] [28] [29] [30] [48] [49].

Our study is interested in the lamella thickness determination, through the new expression of recombination velocity at the back side. This allows extending the life of minority charge carriers in lamella and promotes the solar cell performance, under the effect of both external magnetic field and temperature.

2. Theory

Figure 1 shows the structure of vertical multi-junction silicon solar cells connected in series [52] [53] [58]. It is composed a succession of junctions (**n^+-p-p^+**) joined together with metallic (Al) contacts. Incidental illumination occurs parallel to junctions *i.e.* space charge region plane (SCR) [59] [60]. The elaboration of junction (**p-p^+**) produces the back field effect, that induces excess minority carriers back surface recombination velocity (Sb), that straugths back them towards the junction (SCR) and thus avoids their recombination [28].

Figure 2 shows a section of vertical junction silicon solar cell unit, with the different regions (emitter, junction, base, rear field area). The axis (**Ox**), to origin

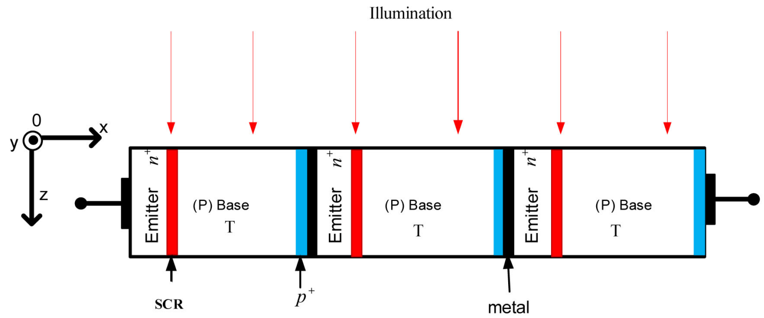

Figure 1. Vertical multi junction solar cells connected in series.

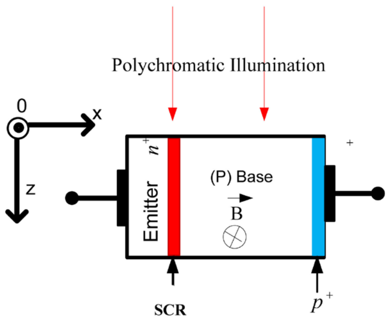

Figure 2. Unit (n^+-p-p^+) cell under illumination and under the effect of an external magnetic field.

from the junction (front side of the base). The base is a thickness H lamella, seat of rear electric field (**p-p**$^+$). The Oz axis, gives the illumination sense and depth z, place of creation of monority charge carriers in solar cell. The magnetic field which plays a deflecting role (Lorentz law) on minority charge carriers,is perpendicular to the plane (**O, x, z**), *i.e.*, along Oy axis.

2.1. Magneto Transport Equation

Excess minority carrier's density $\delta(x)$, generated on the abscissa x and at depth z, in the base of solar cell in steady regime, undergo the law magneto-transport, presented through the following continuity equation [61]:

$$\frac{\partial^2 \delta(x,z,B,T)}{\partial x^2} - \frac{\delta(x,z,B,T)}{L^{*2}(B,T)} + \frac{G(z)}{D^*(B,T)} = 0 \quad (1)$$

Diffusion length $L^*(B,T)$ minority carriers in the base of solar cell under magnetic field B at temperature T is:

$$L^*(B,T) = \sqrt{\tau \cdot D^*(B,T)} \quad (2)$$

$D^*(B,T)$ The diffusion coefficient of minority carriers in the base under influence of temperature T and the magnetic field B applied is given by the relation [21] [62]:

$$D^*(B,T) = \frac{D_0(T)}{\left[1 + (\mu(T) \times B)^2\right]} \quad (3)$$

where $D_0(T)$ is the diffusion coefficient versus temperature T, in the solar cell without magnetic field. It is given by the Einstein-Smoluchowski [63] [64]:

$$D_0(T) = \mu(T) \times \frac{k_b \times T}{q} \tag{4}$$

With $\mu(T)$ is the minority carriers mobility temperature dependent in the base and expresses as [38]:

$$\mu(T) = 1.43 \times 10^9 T^{-2.42}\ \mathrm{cm}^2 \cdot \mathrm{V}^{-1} \cdot \mathrm{s}^{-1} \tag{5}$$

q is the electron elementary charge.

k_b is Boltzmann's constant given as: $k_b = 1.38 \times 10^{-23}\ \mathrm{m}^2 \cdot \mathrm{kg} \cdot \mathrm{s}^{-2} \cdot \mathrm{K}^{-1}$.

The generation rate of minority charge carriers generated at depth z in the base is modeled and expressed by the following relation [65]:

$$G(z) = \sum_{i=1}^{3} a_i \exp(-b_i z) \tag{6}$$

The coefficients a_i and b_i are obtained from the tabulated values of the radiation.

2.2. Solution

The solution of magneto transport equation is given by the following expression of the minority charge carrier density as:

$$\delta(x, z, B, T) = A_1 \cosh\left(\frac{x}{L^*(B,T)}\right) + A_2 \sinh\left(\frac{x}{L^*(B,T)}\right) + \sum_{i=1}^{3} K_i(B,T) \cdot \exp(-b_i z) \tag{7}$$

With

$$K_i(B,T) = \frac{a_i \times L^{*2}(B,T)}{D^*(B,T)} \tag{8}$$

2.3. Boundary Conditions

The previous relationship is fully defined, by determining the coefficients A_1 and A_2, using base boundary conditions, what are junction (SCR) and back side:

1) At the junction (n^+/p), $x = 0$, it is given by [66]

$$\left.\frac{\partial \delta(x, z, B, T)}{\partial x}\right|_{x=0} = \frac{Sf}{D^*(B,T)} \delta(x, z, B, T)\Big|_{x=0} \tag{9}$$

2) At back surface (p/p^+), $x = H$, it is given by [28] [67]:

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

Sf is excess minority carrier junction recombination velocity. It has two components, one defines the operating point, thus, it is imposed by the external load resistor, and the other is the intrinsic recombination velocity, which is related to the solar cell shunt resistance in electric equivalent model [66] [68].

Sb is back surface recombination velocity ($x = H$), where there is an electric field (p/p^+), allowing repel the minority charge carriers towards junction (n^+/p) and avoid their back side recombination [28]. Thus the collection rate of minority carries participating in the photocurrent increases.

3. Results and Discussions

3.1. Photocurrent Density

The excess minority carriers collected through junction give photocurrent density Jph obtained from the following Fick relation:

$$J_{ph}(Sf, H, z, B, T, Sb) = q \cdot D \cdot \left.\frac{\partial \delta(Sf, H, z, B, T, Sb)}{\partial x}\right|_{x=0} \quad (11)$$

3.2. Back Surface Recombination Velocity

Solving Equation (12), leads to two expressions of excess minority carrierback surface recombination velocity in the base as, Sb_1 and Sb_2:

$$\left.\frac{\partial J_{ph}(Sf, H, z, B, T, Sb)}{\partial Sf}\right|_{Sf \geq 10^5} = 0 \quad (12)$$

$$Sb_1(H, B, T) = -\frac{D(B,T) \cdot sh\left(\frac{H}{L(B,T)}\right)}{L(B,T) \cdot \left(ch\left(\frac{H}{L(B,T)}\right) - 1\right)} \quad (13)$$

$$Sb_2(H, B, T) = -\frac{D(B,T)}{L(B,T)} \cdot th\left(\frac{H}{L(B,T)}\right) \quad (14)$$

The maximum values of diffusion coefficient as a function of optimum temperature for different values of magnetic field were determined by comparisons of two different methods according to relationship [69]:

$$D_{\max}(B) = 2.1 \times 10^5 \left[T_{opt}(B)\right]^{-1.58} \quad (15)$$

Other authors, using the same approach, proposed in 3D study or in frequency modulation the following expressions:

- Optimum temperature depending magnetic field [70] is given as:

$$T_{opt}(B) = \sqrt[4.85]{2.56\left[1.43 \times 10^9\right]^2 B^2} \quad (16)$$

- Maximum diffusion coefficient as a function of cyclotronic frequency for different values magnetic field [71]

$$D_{\max}(\omega, B) = 1.717 \times 10^6 \left[T_{opt}(\omega, B)\right]^{-2.065} \quad (17)$$

These relationships show that the choice of values of parameters like the temperature, the magnetic field and the frequency must obey certain conditions for obtaining solar cell good performance.

In **Figure 3**, we represent the profiles of two back surface recombination velocity of excess minority carriers depending on thickness base solar cell for different diffusion coefficient maximum values as a function of optimum temperature and magnetic field.

For each value of maximum diffusion coefficient, the optimum thickness H_{op} of base is determined by projection on abscissa-axis of the intercept point of Sb_1 and Sb_2 curves. Thus the different values are presented in **Table 1**.

Figure 4 shows the lamella optimum width (H_{op}) as function of maximum diffusion coefficient.

We note that lamella optimum thickness increases linearly according to maximum diffusion coefficient. Considering the best fit, we can write the following relation:

$$H_{op} = a \cdot D_{\max} + b \tag{18}$$

The constants a and b are respectively the slope and the ordinate at origin of line. We get the following equation:

$$H_{op} = 0.00012 D_{\max} + 0.01430 \tag{19}$$

Figure 5 shows the lamella optimum thickness (H_{op}) versus magnetic field.

The best fit gives the following modeling equation for mean curve in the form:

$$H_{op}(B) = -3.4 \times 10^3 B^3 + 9.7 \times 10^3 B^2 - 10B + 0.018 \tag{20}$$

The base optimum thickness decreases depending on the applied magnetic field. Indeed, when the magnetic field increases, mobility and diffusion of minority carriers decrease with the increase in the intensity of Lorentz force slowing down the movement of charge carriers [21]. There is thus a decrease in the diffusion coefficient resulting in the decrease of base optimum thickness.

Figure 6 shows the lamella optimum thickness H_{op} as a function optimum temperature.

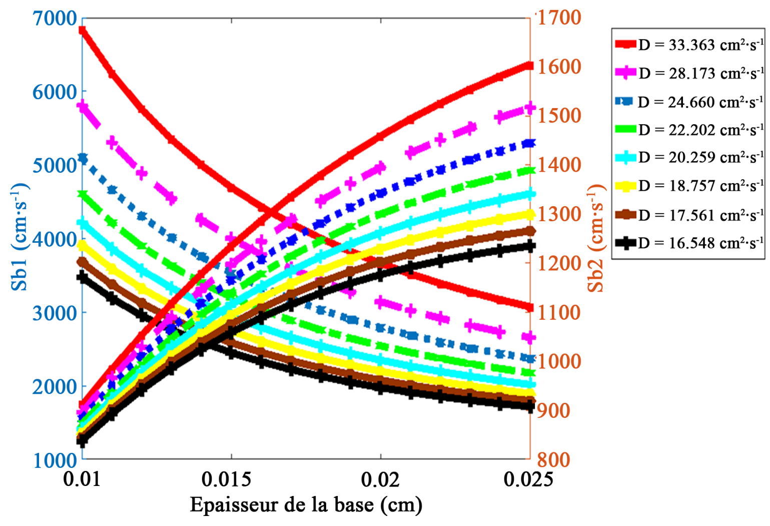

Figure 3. Back surface recombination velocity of excess minority carries versus solar cell base thickness for different maximum diffusion coefficient values.

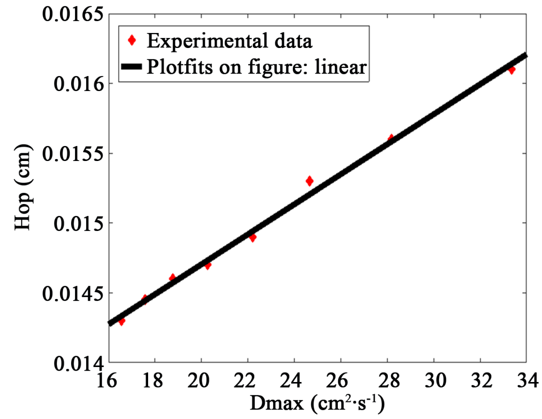

Figure 4. Profile lamella optimum thickness H_{op} versus maximum diffusion coefficient.

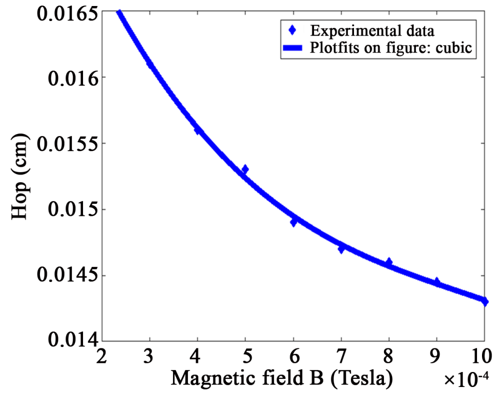

Figure 5. Profile of lamella optimum thickness H_{op} versus magnetic field.

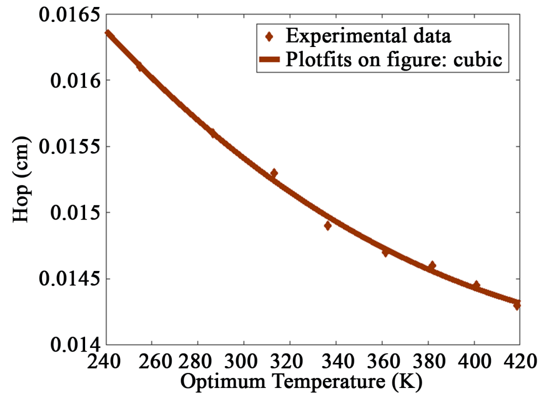

Figure 6. Profile of lamella optimum thickness (H_{op}) versus optimum temperature.

Table 1. Base optimum thickness (H_{op}) for different magnetic field B and optimum temperature values.

B (Tesla)	0.0003	0.0004	0.0005	0.0006	0.0007	0.0008	0.0009	0.001
Optimum temperature (Kelvin)	254.7	286.6	313	336.5	361.4	381.9	401.0	418.8
D_{max} (cm^2/s)	33.368	28.173	24.66	22.202	20.259	18.757	17.561	16.548
H_{op} (cm)	0.0161	0.0156	0.0153	0.0149	0.0147	0.0146	0.01445	0.0143

The average curve modeling equation is in the form:

$$H_{op}(T) = -3.2\times10^{-11}T^3 + 7\times10^{-8}T^2 - 4.5\times10^{-5}T + 0.024 \qquad (21)$$

The lamella optimum thickness H_{op} decreases according to optimum temperature. Indeed, when the temperature is high, the phonons are excited and material resistivity decreases with Umklapp processes [72] [73] which limit thermal conductivity. Thermal agitation reduces excess minority carrier's mobility and obviously diffusion coefficient, that explains the decrease in lamella optimal thickness according to the modeling relation found.

4. Conclusions

This thickness optimization technique plays an important role in the case of vertical solar cell junction, which uses low quality materials, whose minority carriers have low diffusion lengths. It makes the back surface recombination velocity at (p-p$^+$) more efficient by a judicious choice of lamella thickness.

That's why, the two expressions of back surface recombination of excess minority carriers are required to determine the lamella optimum thickness for different values of diffusion coefficient as a function of optimum temperature for different magnetic field values. So the different relationships found justify the choice of the lamella optimal thickness either as a function of temperature or magnetic field. Consequently these results can be used as a tool for selecting lamella elaboration process.

Conflicts of Interest

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

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