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Back Illuminated N/P/P$^+$ Bifacial Silicon Solar Cell under Modulated Short-Wavelength: Determination of Base Optimum Thickness

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Abstract

A bifacial silicon solar cell under monochromatic illumination in frequency modulation by the rear side is being studied for the optimization of base thickness. The density of photogenerated carriers in the base is obtained by resolution of the continuity equation, with the help of boundary conditions at the junction surface (n^+/p) and the rear face (p/p^+) of the base. For a short wavelength corresponding to a high absorption coefficient, the AC photocurrent density is calculated and represented according to the excess minority carrier's recombination velocity at the junction, for different modulation frequency values. The expression of the AC recombination velocity of excess minority carriers at the rear surface of the base of the solar cell is then deduced, depending on both, the absorption coefficient of the silicon material and the thickness of the base. Compared to the intrinsic AC recombination velocity, the optimal thickness is extracted and modeled in a mathematical relationship, as a decreasing function of the modulated frequency of back illumination. Thus under these operating conditions, a maximum short-circuit photocurrent is obtained and a low-cost bifacial solar cell can be achieved by reducing material (Si) to elaborate the base thickness.

Keywords

Bifacial Silicon Solar Cell, AC Recombination Velocity-Base Thickness, Short-Wavelength

1. Introduction

The photovoltaic effect is the result of photon-matter interaction in a semiconductor. The semiconductor material widely used in the manufacture of solar cells is silicon [1] [2] [3]. This solar cell is composed of an emitter (n^+ material) attached to an (p) material that is the base and followed by an (p^+) material. The emitter and base are separated by the Space Charge Region (SCR), where an electric field arising from the Helmozt principle prevails [4] [5] [6].

The physical mechanisms [7] that take place there are:

1) The absorption of monochromatic [8] or polychromatic [9] light, at a depth x, is related to the monochromatic absorption coefficient $\alpha(\lambda)$ at the wavelength (λ) and the gap energy (Eg) of the material [10] [11].

2) The generation of electrical charge carriers, at a depth x, is the appearance of electrical charges (electrons and holes) in the material, represented by the relationship of generation rate ($G(x)$) related to the spectral quality of incident light, constant flow [12] or variable *i.e.* modulated frequency [13] [14] [15] [16] [17] or pulsed [18] [19] [20] [21]. Depending on the architecture of the structure, the incident flow may be perpendicular to the front [22] [23] or back [24] [25] surface of the base. It can be also parallel [26] [27] to the surface of the space charge area (SCR). Then the elaborate solar cells are, mono or bifacial (DSSD) [28] [29] [30] [31] [32] or multiple vertical junctions (MVJ) [33] [34] [35] [36].

3) The diffusion lengh (L) giving the distance traveled by the photogenerated carriers [37] [38], for a time (τ) that is their lifetime [39] [40] [41], with the diffusion (D) [42] and mobility (μ) [43] coefficients

4) the excess minority carriers recombination that occurs in the volume is associated with the lifetime (τ) and that on the surfaces [44] are called surface recombination velocity, (Se at the n^+ front, Sf at the junction n^+/p, Sb at the rear p/p^+, and Sg at the grain joints in the 3D model) [45] [46] [47] [48] [49].

The solar cell is therefore a structure from which, the maximum current of electrical charges must be drawn (extracted), while keeping an electrical voltage most removed (open circuit). This involves optimizing the physical mechanisms [50] involved (intrinsic and external) and the size of the geometry of the structure (grain size (g) and orientation, size of different regions) [51] [52] [53] [54] [55].

Thus the determination of phenomelogical parameters [56] [57] in the solar cell, through theoretical and experimental studies, allows to trace the performance of photoconversion. In previous works the solar cell is considered in static or dynamic mode (frequency) [58] [59].

The proposed study involves a bifacial solar cell with crystalline silicon ($n^+/p/p^+$), illuminated by the rear side (p^+) with a monochromatic light (λ) in frequency modulation (ω) in order to determine the thickness of its base, allowing to produce the maximum short circuit photocurrent. The technique used [60] [61] is that which studies the excess minority carriers recombination velocity at the rear-facing (p/p$^+$) [62] [63]. In this work, the surface recombination velocity expressions depend on the frequency (ω) modulation [64] [65] that acts on the relaxation of excess minority carriers, and the monochromatic absorption coefficient [8] [12], which defines the depth of light penetration, are considered for the base optimum thickness (H) determination.

2. Methodology

The structure of the n$^+$/p/p$^+$ bifacial silicon solar cell under monochromatic illumination, in frequency modulation, is given by **Figure 1**.

The excess minority carriers' density $\delta(x,t)$ generated in the base of a bifacial silicon solar cell, back illuminated in frequency modulation, is given by the following continuity equation [13] [16] [17] [52]:

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

The expression of the excess minority carriers' density is written, according to the space coordinates (x) at the time (t), with (j) the complex number, and (ω) the modulation frequency, as:

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

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

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

With the generation rate from the back illuminated surface expressed [7] as:

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

H is the depth in the base. I_0 is the monochromatic incident flow with wavelength (λ), producing reflection and absorption coefficients respectively $R(\lambda)$ and $\alpha(\lambda)$ on the Si material [8] [10] [12] [37].

$D(\omega)$ is the complex diffusion coefficient of excess minority carrier in the base. Its expression is given by the relationship [13] [16] [17] [52]:

$$D(\omega)=D_0\times\left(\frac{1-j\cdot\omega^2\cdot\tau^2}{1+(\omega\tau)^2}\right) \tag{5}$$

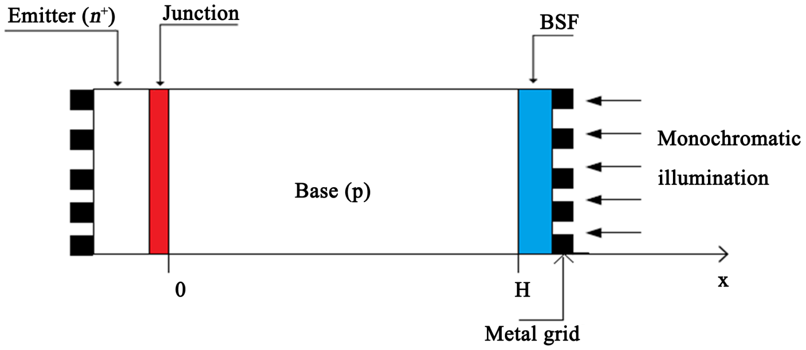

Figure 1. Structure of bifacial silicon solar cell.

τ and D_0 are respectively the excess minority carriers lifetime and diffusion coefficient in the base under steady state.

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:

$$\frac{\partial^2\delta(x,\omega)}{\partial x^2}-\frac{\delta(x,\omega)}{L^2(\omega)}=-\frac{g(x)}{D(\omega)} \quad (6)$$

$L(\omega)$ is the complex diffusion length of excess minority carriers in the base given by Einstein's relation as:

$$L(\omega)=\sqrt{\frac{D(\omega)\tau}{1+j\omega\tau}} \quad (7)$$

Taking into account Equation (4), the solution of Equation (8) is obtained as:

$$\delta(x,\lambda,\omega)=A\cdot\cosh\left[\frac{x}{L(\omega)}\right]+B\cdot\sinh\left[\frac{x}{L(\omega)}\right]+K\cdot\mathrm{e}^{-\alpha(\lambda)\cdot(H-x)} \quad (8)$$

With

$$K=-\frac{\alpha\cdot I_0\cdot(1-R)\cdot\left[L(\omega)\right]^2}{D(\omega)\left[L(\omega)^2\cdot\alpha(\lambda)^2-1\right]} \text{ and } \left(L(\omega)^2\cdot\alpha(\lambda)^2\neq 1\right) \quad (9)$$

Coefficients A and B are extracted from the following boundary conditions respectively:

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

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

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

$$\left.\frac{\partial\delta(x,\lambda,\omega)}{\partial x}\right|_{x=H}=-Sb\cdot\left.\frac{\delta(x,\lambda,\omega)}{D(\omega)}\right|_{x=H} \quad (11)$$

Sf and Sb are respectively the excess minority carrier's recombination velocities at the junction and at the back surface. The recombination velocity Sf is the charge carrier velocity of passage at the junction, in order to participate in the photocurrent. As the solar cell operating point is imposed by the external load, junction recombination is then related [41] [47] [48]. It has an intrinsic component which represents the carrier losses associated with the shunt resistor in the solar cell electrical equivalent model [62] [63] [64]. 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 that pushes the charge carriers back to the junction [4] [22] [40] [48], in order to improve the solar cell efficiency.

3. Results and Discussions

Figure 2 is the plot of the excess minority carrier density (Equation (5)) versus

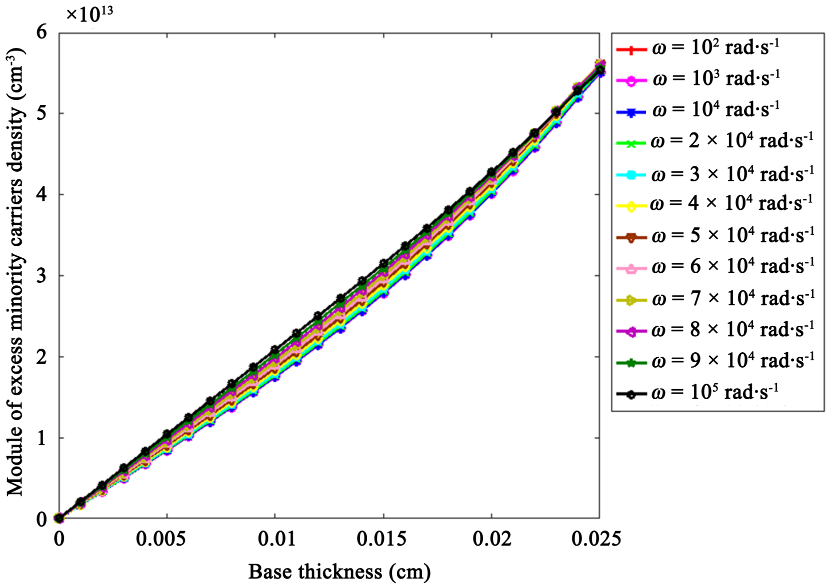

Figure 2. Module of excess minority carriers density versus base thickness ($Sf = 6 \times 10^6$ cm/s), $D_0 = 35\ \text{cm}^2/\text{s}$; $\alpha = 21{,}000\ \text{cm}^{-1}$).

base depth, for different frequencies. As the solar cell is back illuminated with high absorption coefficient (α), the density is high at the incident surface (back) [10] and weak at the junction because of short circuit operating condition (high Sf value) [41] [48].

3.1. Photocurrent

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

$$J_{ph}\left(Sf,\lambda,\omega\right) = qD\left(\omega\right)\left.\frac{\partial\delta\left(x,\lambda,\omega\right)}{\partial x}\right|_{x=0} \tag{12}$$

where q is the elementary electron charge.

Figure 3 gives the plot of AC photocurrent (Equation (12)) versus junction surface recombination velocity for different frequencies (ω), at given absorption coefficient $\alpha(\lambda)$.

At low junction surface recombination velocity values, the photocurrent is low whatever the frequency (open circuit condition). It increases and gives constant value at short circuit condition *i.e.* high junction surface recombination velocity (Sf). At this operating point the short circuit current decreases with the frequency due to the reduction of excess minority carriers' relaxation time [59] [64].

3.2. Optimization

From the representation of **Figure 3**, in this interval of the junction recombination velocity of minority carriers (very large Sf), a constant short-circuit current density (Jphsc) whatever the frequencies appears and allows to write [48]:

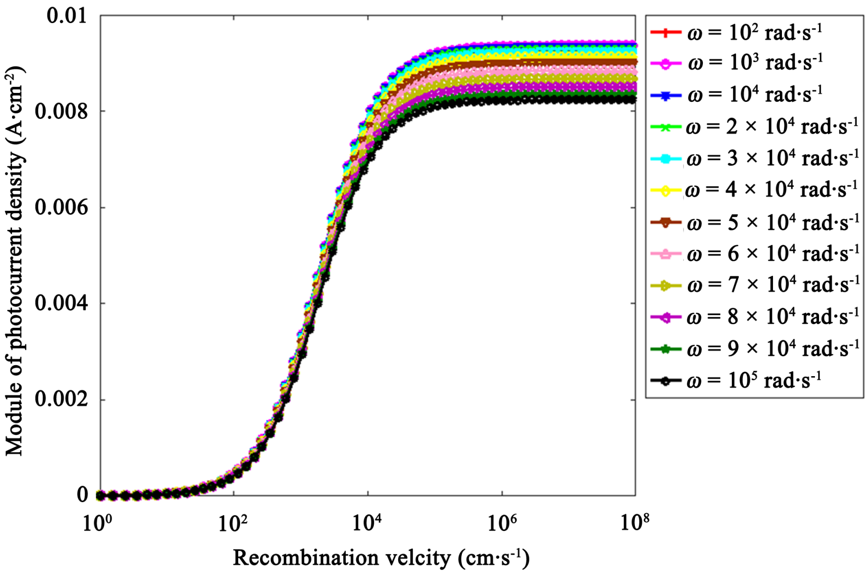

Figure 3. Module of photocurrent density versus junction surface recombination velocity for different frequencies ($D_0 = 35\ \mathrm{cm^2/s}$; $\alpha = 21{,}000\ \mathrm{cm^{-1}}$).

$$\left.\frac{\partial J_{ph}(Sf,\omega,\lambda)}{\partial Sf}\right|_{Sf\geq 10^{5}\ \mathrm{cm\cdot s^{-1}}}=0 \tag{13}$$

The solution of Equation (13) leads to the expressions of the AC back surface recombination velocity [58] [63] [64] given through Equations (14) and (15):

$$Sb_1(H,\omega)=-\frac{D(\omega)}{L(\omega)}\cdot\tanh\left(\frac{H}{L(\omega)}\right) \tag{14}$$

$$\begin{aligned}&Sb_2(H,\lambda,\omega)\\&=\frac{D(\omega)}{L(\omega)}\cdot\left[\frac{L(\omega)\cdot\alpha(\lambda)-\left(L(\omega)\cdot\alpha(\lambda)\cdot ch\left(\frac{H}{L(\omega)}\right)+sh\left(\frac{H}{L(\omega)}\right)\right)\mathrm{e}^{-\alpha(\lambda)\cdot H}}{\left(ch\left(\frac{H}{L(\omega)}\right)+L(\omega)\cdot\alpha(\lambda)\cdot sh\left(\frac{H}{L(\omega)}\right)\right)\mathrm{e}^{-\alpha(\lambda)\cdot H}-1}\right]\end{aligned} \tag{15}$$

Figure 4 representation gives the comparison [34] of the two expressions of back surface recombination velocity versus thickness of the base of the solar cell for different values of frequency. The extracted intercept points, give the base optimum thicknesses (Hopt) [58] [60] relative to frequency values and presented in **Table 1**.

Figure 5 is obtained by help of data from **Table 1**.

From **Figure 5**, we can derive Equation (16) that gives:

$$H_{op}(\mathrm{cm})=-6.9\times10^{-8}\times\omega\left(\mathrm{rad\cdot s^{-1}}\right)+0.0089 \tag{16}$$

Optimum thickness is a decreasing line depending on the frequency. The Equation (16) allows mathematical modelling to be made.

Table 1, combined with Equation (5), allows to plot **Figure 6**, representing the profile of the optimal thickness according to the diffusion coefficient.

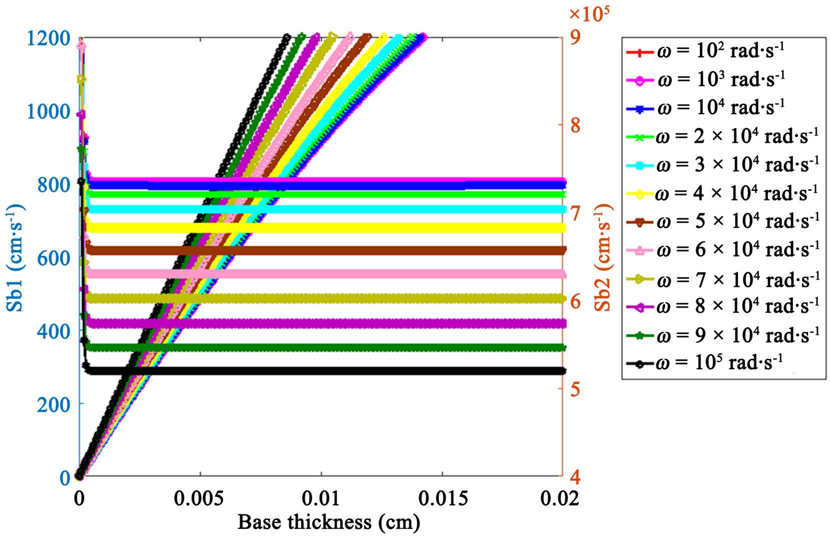

Figure 4. Sb1 and Sb2 versus depth in the base for different frequency ($D_0 = 35$ cm^2/s; $\alpha = 21{,}000$ cm^{-1}).

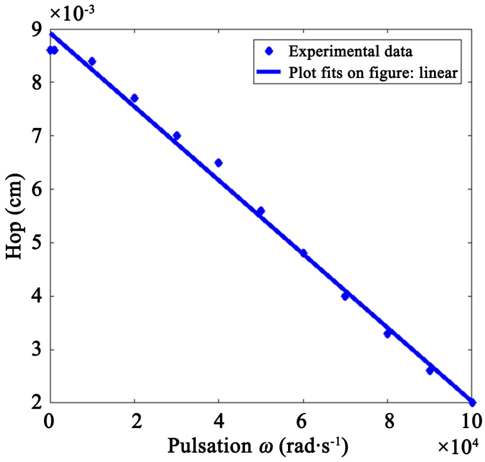

Figure 5. Optimum thickness versus pulsation.

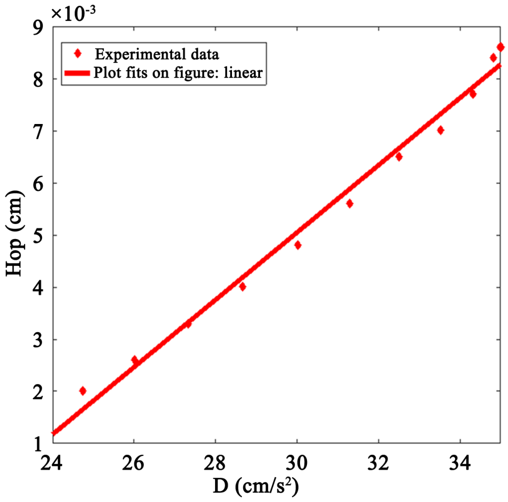

Figure 6. Optimum thickness versus diffusion coefficient.

Table 1. Base optimum thicknesses (Hopt) relative to frequency values.

ω (rad·s^{-1})	10^2	10^3	10^4	2×10^4	3×10^4	4×10^4	5×10^4	6×10^4	7×10^4	8×10^4	9×10^4	10^5
H_{op} (cm)	0.0086	0.0086	0.0084	0.0079	0.0073	0.0065	0.0056	0.0048	0.004	0.0033	0.0026	0.002

Figure 6 provides an equation of correlation between optimal thickness and diffusion coefficient given by:

$$H_{op}\left(\text{cm}\right) = 6.5\times10^{-4}\times D\left(\text{cm}/\text{s}^2\right) - 1.4\times10^{-2} \quad (17)$$

The optimum thickness is large at low frequencies, corresponding to the static regime ($\omega\tau \ll 1$) of the solar cell. In this low frequency interval the relaxation time of the minority carriers is large (large D values from Equation (6)), allowing a great distance of travel (Einstein's relationship), therefore a large base thickness is usable.

At the high frequency values the relaxation time of minority carriers is reduced ($\omega\tau \gg 1$), corresponding to a short distance of travel (Equation (7)), then the optimum thickness needed to collect the maximum carrier must be low [24] [25] [29].

In addition, the generation of carriers by a strong absorption (large $\alpha(\lambda)$) of the incident flow in the rear face [8] [10] [21] hence the need to reduce the distance to be covered (closer junction and back face), in order to collect the maximum carriers. Other works corroborate our results, showing the decrease in the optimum thickness of the silicon solar cell base, when subjected to:

- Monochromatic light with a constant flow of absorption coefficient ($\alpha(\lambda)$) [56]
- Monochromatic light $\alpha(\lambda)$ in frequency modulation (ω) [58]
- Constant magnetic field B[66]
- Flow of charged particles [67]
- Change in the doping rate [60].

Studies of silicon wafers of different thicknesses do not guarantee the reproducibility of opto electronic parameters and only compare the results of macroscopic parameters [14] [57].

4. Conclusions

The bifacial solar cells have a definite advantage by recovering the reflected light flow (albedo) from its rear side and improves performance.

However, the illumination by the rear side presents a disadvantage by creating the charge carriers away from the junction, where they are collected.

The study placed the solar cell in adverse operating conditions, *i.e.* creating minority carriers away from the junction, by strong absorption ($\alpha(\lambda)$) and by a flow of illumination in frequency modulation, which folds the carriers on the incidental rear surface.

Our work, using electronic optoelectronic parameters, including back surface recombination velocities by its intrinsic(diffusion) and generation (absorption $\alpha(\lambda)$), components, we have determined the optimum thickness of the base of the solar cell illuminated by its rear face by a monochromatic light in frequency modulation.

A modelling of the optimum thickness of the base is therefore obtained and can lead to the reduction of the thickness of the material in the development of the silicon solar cell.

Conflicts of Interest

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

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