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Back Surface Recombination Velocity Dependent of Absorption Coefficient as Applied to Determine Base Optimum Thickness of an $n^+/p/p^+$ Silicon Solar Cell

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Abstract

The monochromatic absorption coefficient of silicon, inducing the light penetration depth into the base of the solar cell, is used to determine the optimum thickness necessary for the production of a large photocurrent. The absorption-generation-diffusion and recombination (bulk and surface) phenomena are taken into account in the excess minority carrier continuity equation. The solution of this equation gives the photocurrent according to absorption and electronic parameters. Then from the obtained short circuit photocurrent expression, excess minority carrier back surface recombination velocity is determined, function of the monochromatic absorption coefficient at a given wavelength. This latter plotted versus base thickness yields the optimum thickness of an n^+-p-p^+ solar cell, for each wavelength, which is in the range close to the energy band gap of the silicon material. This study provides a tool for improvement solar cell manufacture processes, through the mathematical relationship obtained from the thickness limit according to the absorption coefficient that allows base width optimization.

Keywords

Silicon Solar Cell, Absorption Coefficient, Back Surface Recombination, Optimum Thickness

1. Introduction

The solar cell (n^+-p-p^+) or (p^+-p-n^+) has been widely studied [1] [2] [3] [4] for the determination of the phenomenological parameters of minority charge carriers in the base [5] which are: lifetime, diffusion length and surface recombination velocity. The illumination of the solar cell is monochromatic [6] [7] or composite [8] [9] [10], arriving perpendicularly on the front or rear face (bifacial), or laterally for the series vertical multi junctions [11].

The operating modes of the solar cell are:

1) The static regime, through the study of the short-circuit photocurrent (quantum efficiency or incident flux) as a function of the reciprocal absorption coefficient [3] [12] [13] [14] [15] [16].

2) The dynamic frequency regime, by studying the impedance (amplitude and phase) [17], or the phenomenological parameters of recombination (Sb, L, D) in their complex expressions [18] [19] [20] [21] [22] depending on the modulation frequency, leading to Bode and Nyquist representations.

3) The transient dynamic regime which is obtained for photocurrent, photovoltage and diffusion capacitance, as time dependent. The measured time constant is related to life time (τ) and eigen value, which is related to diffusion coefficient, base thickness (H), and surface recombination velocities (at junction and back surfaces in the 1D model, and also grain size and grain boundaries recombination in the 3D model) [23]-[30].

The analysis of the response of the solar cell whatever the regime poses the problem of the contribution of each of its constituent parts (emitter, space charge region, base), and as well as the recombination phenomena which occur there (bulk and surfaces). Thus certain techniques for determining the recombination parameters [31] impose conditions in:

- Comparing the diffusion length with the thickness of the base of the solar cell, and define fields of application [32] (theory of thick or thin base);
- By putting hypotheses on the back surface recombination velocity (Sb = 0 for an ideal Back Surface Field and infinite for an ohmic contact) [28].

The choice of the wavelength ranges to be used is also applied [33] to activate the different zones. Thus the depth of light penetration [34] imposed by the monochromatic absorption coefficient, yield to identify the response in static [35] or frequency dynamic [36] [37] [38], or transient dynamics [39] associated with each of the regions of the solar cell (surface or deep absorption theory).

In this work, the diffusion equation relative to the density of charge carriers photo generated by the monochromatic illumination of a solar cell (n^+-p-p^+), is provided with the conditions imposed on the geometric limits of the base of the solar cell. They are surface (x = H), characterized at the junction (Space Charge Region at x = 0) and on the back by, respectively, the recombination velocity (Sf) and (Sb). The incident illumination on the solar cell with long monochromatic wavelengths generates excess minority carriers in the base. It is then plotted as function of base depth of the solar cell maintained in short circuit (large

Sf) condition. This representation of the density of photo generated carriers clearly shows the extension of SCR [40] [41] [42] [43], and yields to explain the short-circuit photocurrent obtained, by the displacement of the maximum density peak deeply in the base, when the absorption coefficient decreases [43], *i.e.* at long wavelengths [44]. From the expression of the short-circuit photocurrent, two expressions of back surface recombination velocity (Sb) of the charge carriers are obtained [34] [45]. One is the intrinsic component and the second, is monochromatic absorption coefficient dependent traducing the coupling between (p) and (p^+) regions. Using the model of parallel vertical multi-junctions [46], leading to an optimum photocurrent, these two expressions of recombination velocity are compared through a representation as a function of the thickness (H) of the base, and the intercept abscissa leads to the optimum thickness (Hopt) [47] [48] [49] [50] [51], for each monochromatic absorption coefficient. This optimum thickness (Hopt) is represented as a function of the absorption coefficient and modeled (best fit) and yields to account for the choice of the necessary thickness of a solar cell according to the wavelength of the illumination and reduce the use of excess material in the development of the solar cell.

2. Theory

The study concerns an n^+-p-p^+ silicon solar cell illuminated by the front face with a monochromatic light, represented by **Figure 1** below [52].

The solar cell under study consists of:

- A strongly doped n^+ type emitter with phosphorus atoms (10^{17} to 10^{19} atom·cm^{-3}). Its thickness varies from 0.5 to 1 μm. The emitter represents the front face where the incident light arrives through metal grids which collect the photo generated electrical charges.
- A p-type base lightly doped than the emitter with Boron acceptor atoms (10^{15} to 10^{17} atom·cm^{-3}). Its thickness varies from 200 to 400 μm where minority carriers (electrons) are widely generated, and contribute to improve the phocurrent production, and thus justifies the choice of this study
- A Space Charge Region (SCR) which is located between the emitter and the base where there is an intense electric field, built on Helmotz principle, allows to separate the photogenereted electron-hole pairs which arrive at the junction.

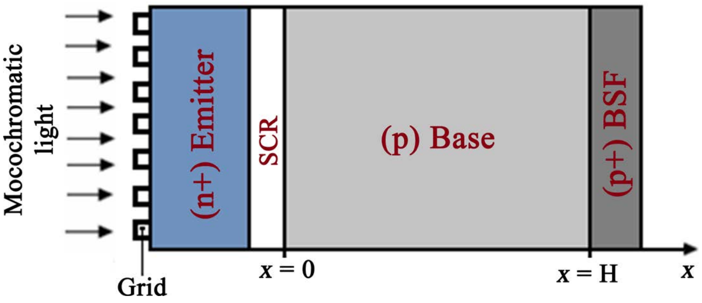

Figure 1. n^+-p-p^+ type solar cell.

- An overdoped (p^+) type rear zone with acceptor atoms (10^{17} to 10^{19} atom·cm^{-3}). There is an electric field, called Back Surface Field (BSF), resulting from the p/p^+ junction. It is used to return the photocreated carriers near the rear face, towards the emitter-base junction (SCR) and thus increases the collected photocurrent.

Taking into account the phenomena of generation, recombination and diffusion within the illuminated solar cell by the front face by a monochromatic light, the excess minority continuity equation in the base under steady state is given by the following expression:

$$D\times\frac{\partial^2\delta(x,\alpha_\lambda)}{\partial x^2}-\frac{\delta(x,\alpha_\lambda)}{\tau}+G(x,\alpha_\lambda)=0 \quad (1)$$

where:

$\delta(x,\alpha_\lambda)$ is the excess minority carrier's density generated in the base,

$G(x,\alpha_\lambda)$ is the electron-hole pairs generation rate at depth x in the base under monochromatic illumination. Its expression is given by:

$$G(x,\alpha_\lambda)=\alpha_\lambda\times\varphi_\lambda\times(1-R_\lambda)\times\exp(-\alpha_\lambda.x) \quad (2)$$

α_λ is monochromatic absorption coefficient of the silicon material for a wavelength λ [53] [54].

R_λ is monochromatic reflection coefficient.

φ_λ is incident flow of monochromatic light.

x is absorption depth in the base of the solar cell.

The electrons diffusion coefficient (D) and diffusion Length (L) in the base are related to the lifetime (τ) by Einstein's relation as:

$$\tau=\frac{L^2}{D} \quad (3)$$

The resolution of Equation (1) gives the expression of minority carrier's density in the following form:

$$\delta(x,\alpha_\lambda)=A\times ch\left(\frac{x}{L}\right)+B\times sh\left(\frac{x}{L}\right)+K(\alpha_\lambda)\times\exp(-\alpha_\lambda\cdot x) \quad (4)$$

With:

$$K(\alpha_\lambda)=\frac{-\alpha_\lambda\times\varphi_\lambda\times(1-R_\lambda)\times L^2}{D\times\left[\alpha_\lambda^2\times L^2-1\right]} \quad (5)$$

The constants ***A*** and ***B*** are determined from the boundary conditions.

1) At the junction emitter-base (*x* = 0)

$$\left.\frac{\partial\delta(x,\alpha_\lambda)}{\partial x}\right|_{x=0}=\frac{S_f}{D}\times\delta(0,\alpha_\lambda) \quad (6)$$

S_f represents the charge carrier's recombination velocity at the junction imposed by both the external and internal (shunt resistance) charge and thus characterizes the operating point of the solar cell, varying from the open circuit to the short circuit condition [27] [54].

2) At the rear face ($x = H$)

$$\left.\frac{\partial \delta(x,\alpha_\lambda)}{\partial x}\right|_{x=H} = \frac{-S_b(\alpha_\lambda)}{D}\times\delta(H,\alpha_\lambda) \tag{7}$$

S_b represents the minority carrier's recombination velocity at the back surface. It is the consequence of the electric field created by the p/p+ junction and characterizes the high-low junction surface [28] [45] [55] [56].

The expression of the photocurrent density is defined by the following relation:

$$Jph(S_f,\alpha_\lambda) = q\times D\times\left[\frac{B(Sf,\alpha_\lambda)}{L} - K(\alpha_\lambda)\times\alpha_\lambda\right] \tag{8}$$

The photocurrent density is constant for the large values recombination velocity of excess minority carriers at the junction [10] [29] [45].

$$\left.\frac{\partial Jph(Sf,\alpha_\lambda)}{\partial Sf}\right|_{Sf\geq 5\times 10^5\ \mathrm{cm\cdot s^{-1}}} = 0 \tag{9}$$

The resolution of this equation leads to two solutions of the minority carrier's recombination velocity at the back surface *i.e.* intrinsic (or electronic) *Sb*1 and *Sb*2 which depends on the absorption coefficient of monochromatic light for a wavelength λ [34] [45] [57].

$$Sb1(H) = -\frac{D}{L}\times th\left(\frac{H}{L}\right) \tag{10}$$

$$Sb2(H,\alpha_\lambda) = D\times\frac{\alpha_\lambda\times\left(ch\left(\frac{H}{L}\right)-\exp(-\alpha_\lambda\cdot H)\right)-\frac{1}{L}\times sh\left(\frac{H}{L}\right)}{ch\left(\frac{H}{L}\right)-\alpha_\lambda\times L\times sh\left(\frac{H}{L}\right)-\exp(-\alpha_\lambda\cdot H)} \tag{11}$$

3. Results and Discussions

3.1. Minority Carrier's Density in the Base

Figure 2 materializes the excess minority carrier's density profiles as function of the depth in the base for different low values of the absorption coefficient.

The **Figure 3** represents the relative density profiles of minority charges carriers as a function of the depth in the base for different low values of the absorption coefficient.

Figure 2 shows that the low absorption coefficients penetrate deep into the base, creating charge carriers far from the junction. These week absorption coefficients give low recombination velocity on the rear face corresponding to a high density of charge carriers on the rear face and therefore leading to thick optimum thicknesses to produce a low photocurrent.

3.2. Photocurrent Density

Figure 4 illustrates the profiles of the photocurrent density as a function of the

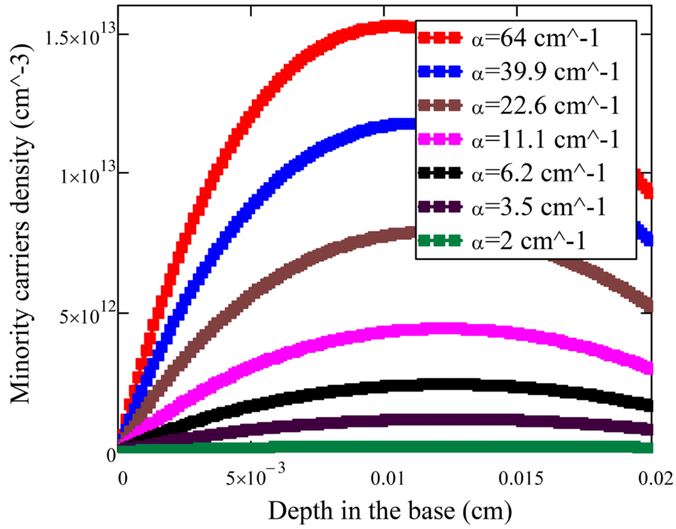

Figure 2. Minority carriers charges versus the depth in the base for different absorption coefficient low values with $Sf = 6 \times 10^6$ cm/s, *Sb*2.

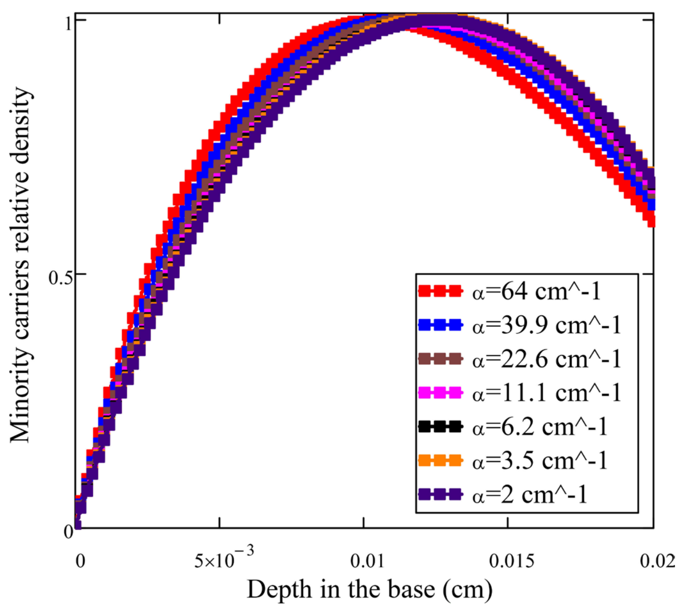

Figure 3. Relative density of minority charges carriers versus the depth in the base for different absorption coefficients low values with $Sf = 6 \times 10^6$ cm/s, *Sb*2.

recombination velocity at the junction for different low values of the absorption coefficient.

We note on **Figure 4**:

- *Sf* less than 2×10^2 cm/s, the photocurrent density is practically zero (open circuit situation).
- *Sf* between 2×10^2 cm/s and 4×10^4 cm/s, the photocurrent density is increasing.
- *Sf* greater than 4×10^4 cm/s, the amplitude of the photocurrent density is maximum and constant (short-circuit situation).

This amplitude increases with increasing absorption coefficient light.

3.3. Influence of Diffusion Coefficient (*D*) on *Sb*2 Recombination Velocity

Excess minority carrier back surface recombination was studied with diffusion coefficient variation [43] [47] [48] [50] [51] [58], while solar cell remained in certain external conditions.

Figure 5, below we represent the profiles of the excess minority carrier recombination velocity at the rear face (*Sb*2) as a function of the thickness of the base for different values of the diffusion coefficient for a given absorption coefficient (α).

3.4. Base Depth Optimization

Figure 6 illustrates the profiles of relative recombination velocities at the rear

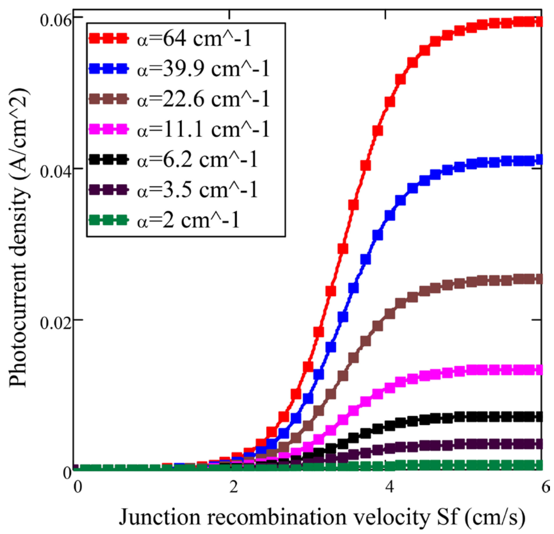

Figure 4. Photocurrent density versus the recombination velocity at the junction for different absorption coefficients low values with *Sb*2.

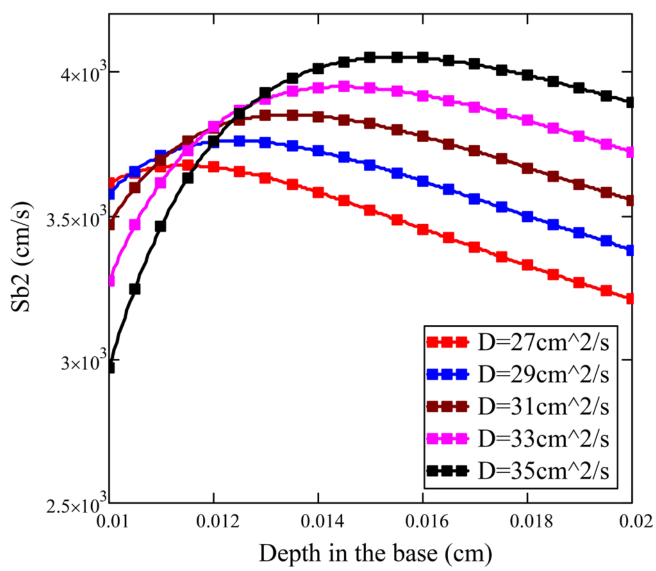

Figure 5. Sb2 versus depth in the base for different diffusion coefficient values with α = 64 cm^{-1}.

face as function of the thickness of the base for different absorption coefficient values.

Table 1 below presents the optimum values of the thickness of the base obtained for various low values of the absorption coefficient and plotted on Figure 7.

The relationship obtained is given as follow:

$$H_{opt}(\text{cm}) = F \times \alpha^2 + G \times \alpha + M \quad (12)$$

With: $F = 2 \times 10^{-7}\,\text{cm} \cdot \alpha^{-2}$; $G = 3 \times 10^{-5}\,\text{cm} \cdot \alpha^{-1}$; $M = 0.0241\,\text{cm}$

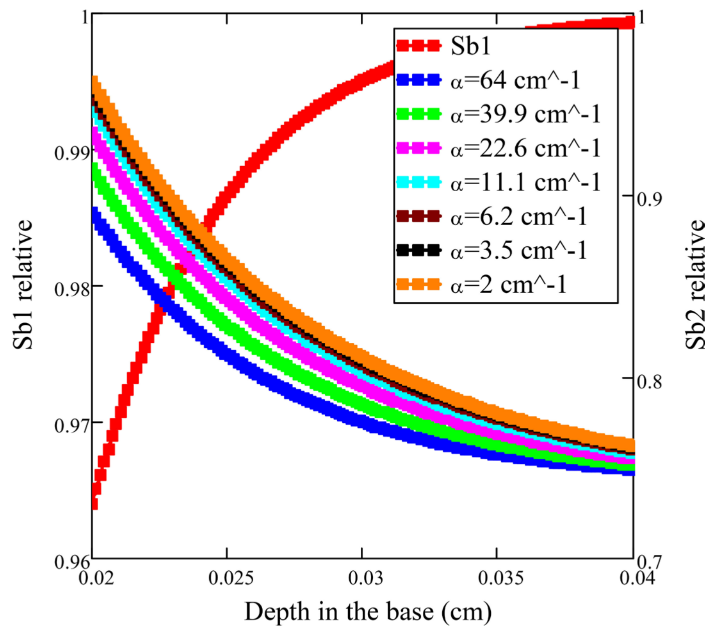

Figure 6. Back surface recombination velocity versus base thickness for different low values of absorption coefficient (L = 0.01 cm and D = 35 cm²/s).

Table 1. Values of the optimum thickness (H_{opt}) as a function of the absorption coefficient.

α (cm^{-1})	64	39.9	22.6	11.1	6.2	3.5	2
H_{opt} (cm)	0.022669	0.023094	0.023458	0.023761	0.023903	0.024004	0.024085

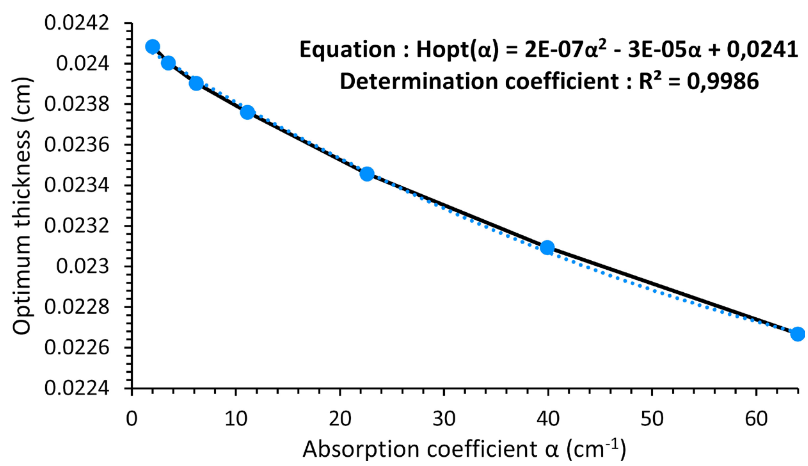

Figure 7. Optimum thickness versus absorption coefficient.

It is then seen, that long wavelength illumination needs large base depth and generates more excess minority charge carriers to be collected.

Some previous studies, using the same technique for solar cells (horizontal junction and vertical junction [51]) placed under different conditions, have produced very important results. These results have linked the optimum thickness to the diffusion coefficient that depends on:

1) the doping rate of the base according to the manufacturing process [30] [47] [52].

2) applied magnetic field [49].

3) temperature and magnetic field [49] [50] for given resonance values

4) the intensity and flow of irradiation of charged particles [48]

In the monochromatic illumination conditions of the solar cell [32] [35] the recombination velocity in the back surface is dependent on the absorption coefficient which varies greatly (from 2 cm^{-1} to 10^5 cm^{-1}). The optimum thickness has been correlated with the large absorption coefficient values corresponding to short wavelengths, which are poorly absorbed, close to the space charge region (SCR) [57].

The interest of our study with the large wavelengths generally used to extract diffusion length [3] [6] [7] [12] [14] [33] [34], allows a generation of minority carriers deeply in the base [24] and therefore justifies determining this thickness in these spectral conditions, for optimum efficiency.

Thus the results obtained in this study giving the optimum thickness, justify the choice of long wavelengths (close to energy band gap), for the optimization of silicon material in the development of the solar cell.

4. Conclusions

This study has shown, the influence of low absorption coefficient values on:

- The minority charge carriers density function base depth.
- Photocurrent as a function of the minority carriers recombination velocity at the junction, which allowed the establishment of expressions recombination velocity on the rear face.
- Recombination velocity on the rear face, and has led to the determination of the optimum base thickness.
- Optimum base thickness that decreases with wavelength.

Thus the base optimization technique presented here, taking into account the penetration depth, would yield to reduce the amount of material (Si) necessary for the manufacture of crystalline solar cells dedicated to a specific lighting application and would also reduce the cost of manufacturing and resale price.

This work, based on mathematical results of determining the minority carrier's recombination velocity at the back surface, will extend to other types of solar cells, the possibility of back surface illumination or simultaneous double-face illumination. The external operating conditions of the solar cell, involving temperature variation, will be studied in future works, in modelling and under experiments. The combination of two to two or three is also envisaged, in particular taking into account the frequency modulated illumination that affects minority carrier's diffusion coefficient.

Conflicts of Interest

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

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