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A.C. Recombination Velocity as Applied to Determine $n^+/p/p^+$ Silicon Solar Cell Base Optimum Thickness

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Abstract

This work deals with determining the optimum thickness of the base of an $n^+/p/p^+$ silicon solar cell under monochromatic illumination in frequency modulation. The continuity equation for the density of minority carriers generated in the base, by a monochromatic wavelength illumination (λ), with boundary conditions that impose recombination velocities (*Sf*) and (*Sb*) respectively at the junction and back surface, is resolved. The ac photocurrent is deduced and studied according to the recombination velocity at the junction, to extract the mathematical expressions of recombination velocity (*Sb*). By the graphic technique of comparing the two expressions obtained, depending on the thickness (*H*) of the base, for each frequency, the optimum thickness (Hopt) is obtained. It is then modeled according to the frequency, at the long wavelengths of the incident light. Thus, Hopt decreases due to the low relaxation time of minority carriers, when the frequency of modulation of incident light increases.

Keywords

Silicon Solar Cell, Modulation Frequency, Recombination Velocity, Base Thickness, Wavelength

1. Introduction

Expressions of the recombination velocity of the minority carriers in the back (p/p^+) from the base of the $n^+/p/p^+$ silicon solar cell [1] under constant monochromatic illumination [2] [3] were obtained through the study of the photocurrent versus the carrier's recombination velocity at the junction [4]. These expressions are dependent on the minority carriers diffusion coefficient (D) [5] and diffusion length (L) [6] [7], as well as the monochromatic absorption coefficient $\alpha(\lambda)$ [8] in the silicon material.

Earlier theoretical and experimental works, on semiconductors or on solar cells, using a frequency modulation signal [9]-[15], have helped to determine:

1) phenomelogical parameters (lifetime, diffusion coefficient-mobility, surface recombination velocity) in different regions of the material taking into account the signal penetration depth [16], associated with the distribution of defects [17] [18] [19].

2) the parameters of the equivalent electrical model (conductance and capacitance) through Boode and Nyquist diagram technique [20] [21] [22] [23] [24].

This work is based on the ac technique, through new expressions of minority carrier recombination velocity (ac Sb) [25] [26] [27] [28] [29] at the back surface of the base under monochromatic illumination ($\alpha(\lambda)$) in frequency modulation, depending on the complex parameters, such as $D(\omega)$ and $L(\omega)$ [11] [12] [13] [25] [26] [29].

The thickness of the different parts of the solar cell [30] [31] especially the base, has been the subject of theoretical and experimental investigations on samples of different thicknesses [32] [33] [34] [35] in order to optimize the efficiency of photo conversion [36], by the economy of material entering its industrial development.

The technique of determining the optimum thickness of the base is applied in this study to an $n^+/p/p^+$ silicon solar cell [31] [34] [37] illuminated by the (n^+) surface, and leads to a new expression of Hopt according to the frequency.

2. Theoretical Model

The structure of the n^+-p-p^+ silicon solar cell [1] under modulated monochromatic illumination on the (n^+) side is represented by **Figure 1**.

The excess minority carriers' density $\delta(x,t)$ generated in the base of the solar cell obeying to the continuity equation under modulated monochromatic illumination, is then given by [38] [39]:

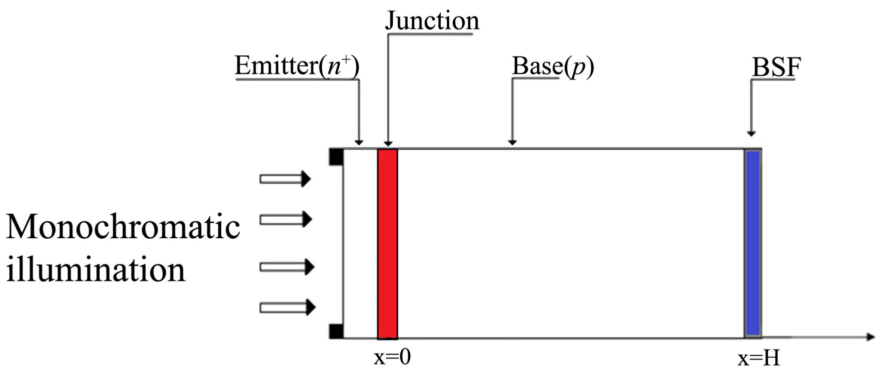


Figure 1. Structure of $n^+/p/p^+$ silicon solar cell.

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

The expression of the excess minority carrier's density is written, according to the space coordinates (x) and the time t, as:

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

The modulated carrier generation rate $G(x,\alpha,\omega,t)$ is given by the relationship:

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

with the coordinate dependent generation rate:

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

where:

- $I_0(\lambda)$ is the incident monochromatic light intensity.
- R and α are respectively the reflection coefficient and absorption coefficient for silicon material at wavelength (λ) [3] [7] [8].

$D(\omega)$ is the complex diffusion coefficient of excess minority carrier in the base. Its expression is given by the relationship [9] [11] [12] [13] [29]:

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

D_0 is the excess minority carrier diffusion in the base under steady.

By replacing Equation (2) and Equation (3) in Equation (1), the continuity equation for the excess minority carriers' density in the base is reduced to the following relationship:

$$\frac{\partial^2\delta(x,\omega)}{\partial x^2}-\frac{\delta(x,\omega)}{L^2(\omega)}=-\frac{g(x)}{D(\omega)} \tag{8}$$

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

$$L(\omega)=\sqrt{\frac{D(\omega)\tau}{1+j\omega\tau}} \tag{9}$$

τ is the excess minority carriers lifetime in the base.

The solution of Equation (8) is:

$$\delta(x,\omega)=A\cdot\cosh\left[\frac{x}{L(\omega)}\right]+B\cdot\sinh\left[\frac{x}{L(\omega)}\right]+K\cdot \mathrm{e}^{-\alpha\cdot x} \tag{10}$$

with $K=\dfrac{\alpha\cdot I_0\cdot(1-R)\cdot\left[L(\omega)\right]^2}{D(\omega)\left[L(\omega)^2\cdot\alpha^2-1\right]}$

$$\text{And}\quad \left(L(\omega)^2\cdot\alpha^2\neq 1\right) \tag{11}$$

Coefficients A and B are determined through the boundary conditions:

- At the junction ($x = 0$)

$$D(\omega)\frac{\partial\delta(x,\omega)}{\partial x}\bigg|_{x=0} = Sf \cdot \frac{\delta(x,\omega)}{D(\omega)}\bigg|_{x=0} \tag{12}$$

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

$$D(\omega)\frac{\partial\delta(x,\omega)}{\partial x}\bigg|_{x=H} = -Sb \cdot \frac{\delta(x,\omega)}{D(\omega)}\bigg|_{x=H} \tag{13}$$

Sf and *Sb* are respectively the recombination velocities of the excess minority carriers at the junction and at the back surface. The recombination velocity *Sf* reflects the charge carrier velocity of passage at the junction, in order to participate in the photocurrent. It is then imposed by the external load which fixes the solar cell operating point [2] [29]. It has an intrinsic component which represents the carrier losses associated with the shunt resistor in the solar cell electrical equivalent model [39] [40]. 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 for throwing back the charge carrier toward the junction [2] [41].

3. Results and Discussions

3.1. Ac Excess Minority Carrier Density

Excess minority carrier density is plotted versus depth in the base, for given illumination modulated frequency (ω) with large wavelength (giving rise to weak $\alpha(\lambda)$ for silicon), while the solar cell is under short circuit condition (large *Sf* values) (**Figure 2**).

3.2. Photocurrent Density

From the density of minority carriers in the base, the ac photocurrent density at the junction is given by the following expression:

$$J_{ph}(Sf, Sb, \omega) = qD(\omega)\frac{\partial\delta(x, Sf, Sb, \omega)}{\partial x}\bigg|_{x=0} \tag{14}$$

where q is the elementary electron charge.

Figure 3 shows ac photocurrent versus the junction surface recombination velocity for different frequency. As junction's recombination velocity indicates solar cell operating point, ac photocurrent is weak for low *Sf* values *i.e.* open circuit. And at large *Sf* values, the ac photocurrent reaches flat region assimilate to short circuit current which decrease decreases with frequency.

3.3. Back Surface Recombination Velocity

Photocurrent density versus minority carriers recombination velocity at the junction, shows a bearing sets up and corresponds to the short-circuit current density (*Jphsc*), for very large Sf. For this junction recombination velocity interval, it then comes [2] [27] [39] [41]:

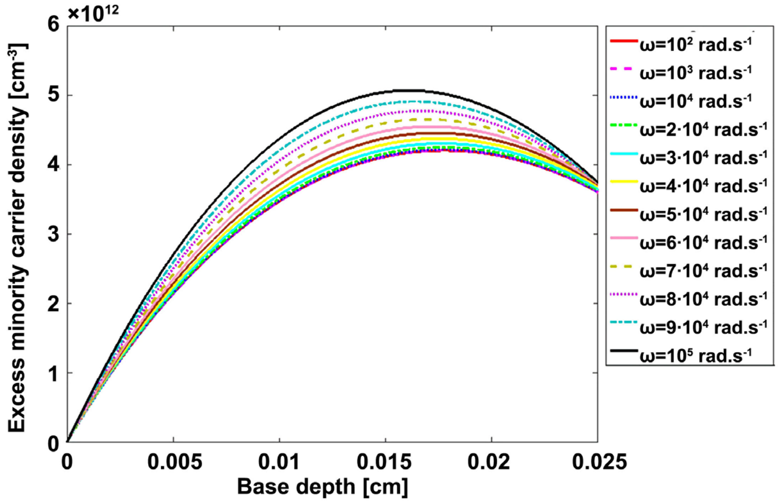


Figure 2. Excess minority carrier density versus base depth for different frequencies (D_0 = 35 cm; α = 6.2 cm^{-1}).

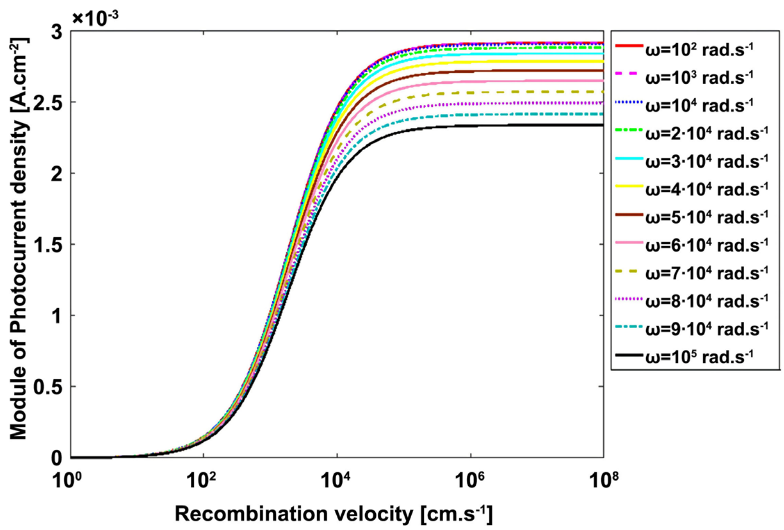


Figure 3. Module of photocurrent density versus recombination velocity for different frequency (D = 35 cm; α = 6.2 cm^{-1}).

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

The solution of Equation (15) gives the ac recombination velocity expressions in the back surface through Equation (16) and Equation (17):

$$Sb1(\omega) = -\frac{D(\omega)}{L(\omega)} \cdot \tanh\left(\frac{H}{L(\omega)}\right) \tag{16}$$

$$Sb2(\omega,\lambda) = \frac{D(\omega)}{L(\omega)} \cdot \left[\frac{\alpha(\lambda)\cdot L(\omega)\cdot\left(\exp\left(-\alpha(\lambda)\cdot H\right) - \cosh\left(\frac{H}{L(\omega)}\right) + \sinh\left(\frac{H}{L(\omega)}\right)\right)}{\exp\left(-\alpha(\lambda)\cdot H\right) - \cosh\left(\frac{H}{L(\omega)}\right) + \alpha(\lambda)\cdot L(\omega)\cdot \sinh\left(\frac{H}{L(\omega)}\right)}\right] \tag{17}$$

3.4. Optimum Thickness Determination Technique

This technique is based on the results of the calculation of the photocurrent through the two emitters of a parallel vertical junction silicon solar cell [42].

Figure 4 gives the representation of the two back surface recombination velocities versus thickness of the base of the solar cell for different frequency, in order to determine the optimum thickness of the base.

Figure 5 allows us to model the optimum thickness through the following mathematical expression, for a low value of $\alpha(\lambda)$:

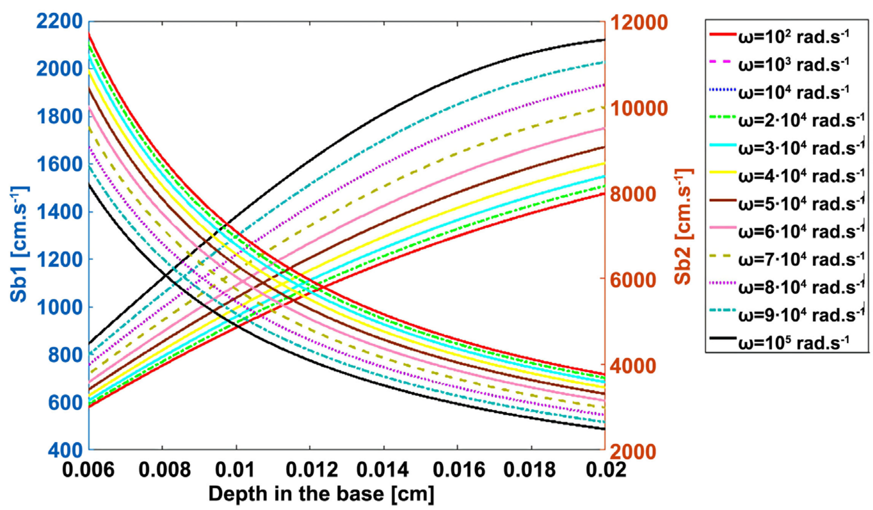
$$H_{op}\left(\text{cm}\right) = -3\times10^{-13}\times\omega^2 - 2.9\times10^{-8}\times\omega\left(\text{rad}\cdot\text{s}^{-1}\right) + 0.015$$

For the large wavelengths of incident light, corresponding to the low values of the silicon absorption coefficient $\alpha(\lambda)$, minority carriers are generated in depth from the base [7] [8]. The optimum thickness (Hopt) obtained in static (low modulation frequency, *i.e.* $\omega\tau \ll 1$) is therefore large. As the modulation frequency increases, the density of the generated carriers decreases and is folded back to the junction [27], the optimum thickness (Hopt) decreases (in dynamic state, *i.e.* $\omega\tau \gg 1$). Figure 6 gives the optimum thickness of the base according to the diffusion coefficient $D(\omega)$ Equation (5) [9] [10] [11] [13]

The optimum thickness is a growing right according to the diffusion coefficient, modeled by the following relationship:

$$H_{op}\left(\text{cm}\right) = 3.1\times10^{-4}\times D\left(\text{cm}\cdot\text{s}^{-2}\right) + 0.004 \tag{19}$$

Several works have produced a relationship giving Hopt thickness, depending on the D coefficient, which in turn can be expressed according to external parameters. These are the works giving Hopt variations with:



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)	0.015	0.015	0.015	0.0146	0.0141	0.0136	0.0129	0.0122	0.0115	0.0108	0.0101	0.0095

Figure 4. *Sb*1 and *Sb*2 versus depth in the base for different frequency (D = 35 cm; α = 6.2 cm^{-1}).

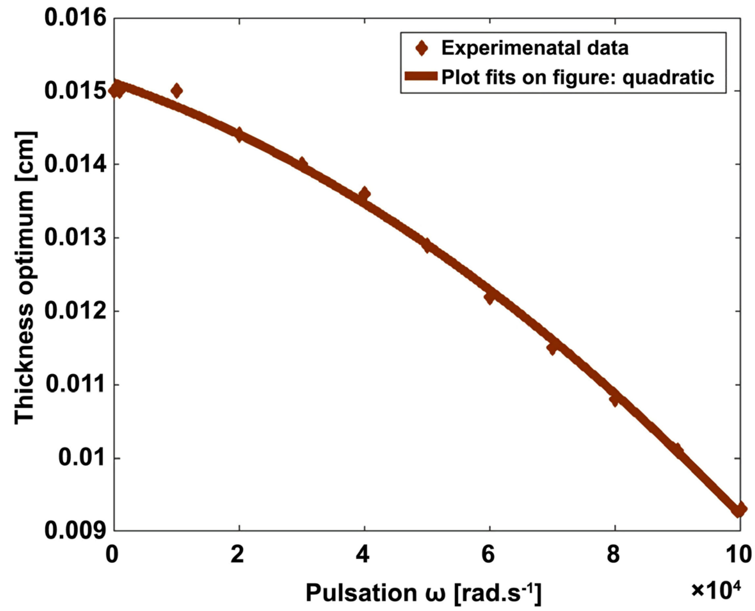


Figure 5. Optimum thickness versus pulsation.

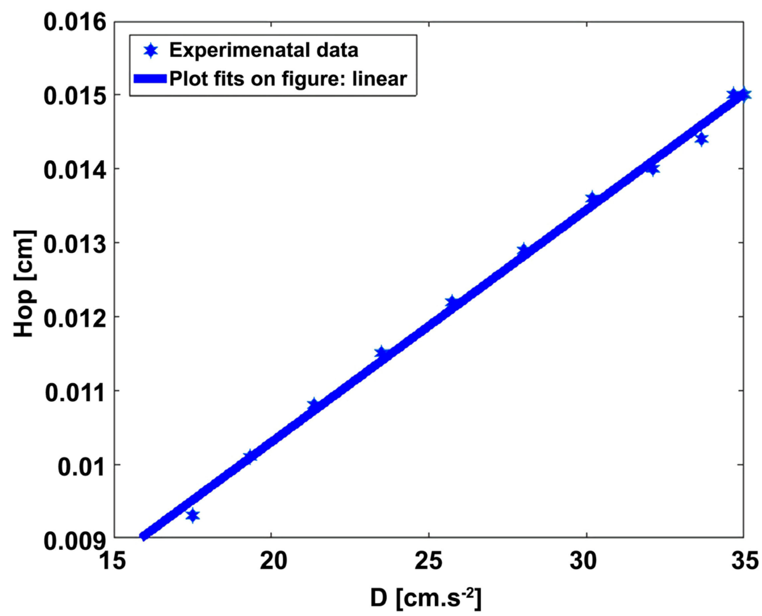


Figure 6. Optimum thickness versus diffusion coefficient.

- The base's doping rate (Nb) [43].
- The magnetic field applied to vertical junction series silicon solar cell [44].
- The magnetic field applied to front illuminated (n^+-p-p^+) silicon solar cell [45].
- The magnetic field and temperature applied to front illuminated (n^+-p-p^+) silicon solar cell [46].
- The temperature [47].
- The flow of electrical charge particles irradiating the (n^+-p-p^+) silicon solar cell [48] [49].

- The monochromatic absorption coefficient of the material (Si) [50].

Each value of the diffusion coefficient must correspond to an elaborated silicon solar cell, with Hopt its base optimum thickness. The diffusion coefficient of the minority carriers then imposes the thickness to be chosen for the manufacture of a high-performance solar cell. Thus low diffusion coefficients require low thicknesses to produce an important photocurrent, therefore a better efficiency.

4. Conclusions

The ac recombination velocity at the back surface of the $n^+/p/p^+$ silicon solar cell was used to determine the optimum thickness of the base for long wavelengths of modulated incident light.

The light penetration depth at low monochromatic absorption coefficient values reduced the relaxation effect of photogenerated carriers, resulting in a small decrease of Hopt with frequency, through the expression of its modeling.

Conflicts of Interest

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

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