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Influence of Wavelength on the Diffusion Capacitance of a Serial Vertical Junction Silicon Solar Cell in Frequency Regime

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Abstract In this paper we have carried out a theoretical study on influence of the illumination wavelength on the diffusion capacitance of a silicon solar cell under constant magnetic field. We solved the continuity equation that is related to the minority carrier's density. Then we established the expression of the solar cell diffusion capacitance in function of the wavelength, the magnetic field, the frequency resonance, the thickness of the base and the junction recombination velocity. The space charge zone (SCZ) of the solar cell has been considered as a plane capacitor which capacitance corresponds to the diffusion capacitance. The expression of the diffusion capacitance is determined. The wavelength range [λ=0.6 µm ;λ=0.86 µm] is the optimum range of illumination wavelengths for good conversion efficiency, for an n+-p-p+ series vertical junction solar cell under constant magnetic field in frequency modulation.

Keywords: *solar cell, wavelength, diffusion capacitance, frequency modulation*

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1. Introduction

The solar cell market is dominated by the use of silicon as a semiconductor, due to the low cost and easy access. However, laboratories data show that the efficiency of silicon solar cells is currently around 26% [1,2]. Semiconductors are materials that become electrically conductive when they receive light or heat. The study wavelength is a fundamental aspect and allows us to pronounce on the yield of conversion. The diffusion capacitance of the solar cell is considered to be the capacitance resulting from the change in charge during the diffusion process within the cell. This capacitance is mainly due to the fixed ionized charges at the junction boundaries and the diffusion process (diffusion capacitance). Several researches have been carried out on the diffusion capacitance of the solar cell [3,4] with the aim of improving the conversion efficiency of the solar cell. The influence of magnetic field [3], temperature [5]; and eclectic field [6] on the diffusion capacitance; and the variation of the diffusion capacitance [7] versus the base thickness have been studied. These studies focus in particular on the photovoltaic effect, the operating principle of solar cells as a function of internal optical parameters and macroscopic parameters (series and shunt resistances). This study aims to define and optimize the performance of solar cells under monochromatic illumination (wavelength) to improve their photovoltaic conversion efficiency. The magnetic field is related to frequency by the equation: $\omega = \frac{q}{2\pi . m} B$.

Each frequency value corresponds to a specific magnetic field. The frequency (and magnetic field) are fixed, and we'll study the effect of the wavelength. In order to determine the optimal wavelength range for the best conversion efficiency, the influence of wavelength on the diffusion capacitance of n+-p-p+ type serial vertical junction silicon solar cell under constant magnetic field (B= 10^{-4} T and ω_r = 1.75×107rad/s) in frequency modulation is studied.

2. Theoretical Study

2.1. Model and Assumptions

The considered cell is designed so that the incident light rays are parallel to the space charge region. In this paper, we assume that the thickness of the space charge region and the emitter are very small compared to the base thickness, and their contributions are then neglected. Figure 1 [3] shows an n+-p-p+ serial vertical junction silicon solar cell [8] under monochromatic illumination and applied magnetic field.

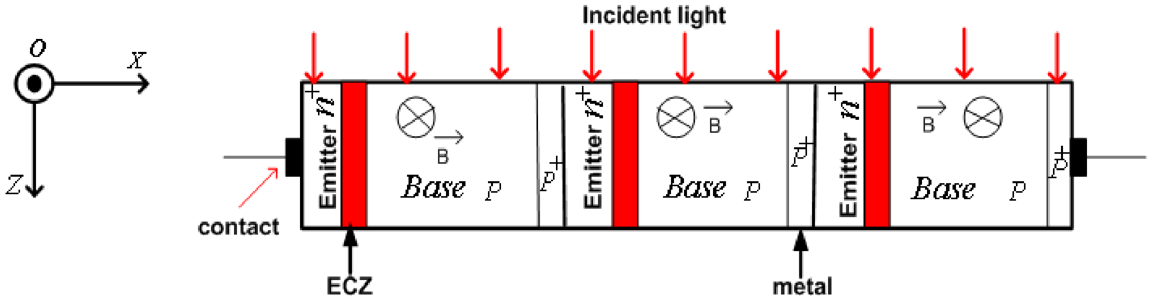


Figure 1. n+-p-p+ type of a vertical junction solar cell under incident illumination

2.2. Mathematical Problem Formulation

When the solar cell is exposed to light excitation, there is an interaction between the incident light (sufficiently energetic photon) and the semiconductor.The phenomena of generation, recombination and diffusion are governed by the continuity equation related to the minority carrier's density [9].

$$\mathbf{D}^*.\frac{\partial^2\boldsymbol{\delta}(\mathbf{x},\mathbf{z},\mathbf{t})}{\partial\mathbf{x}^2}-\frac{\boldsymbol{\delta}(\mathbf{x},\mathbf{z},\mathbf{t})}{\boldsymbol{\tau}}=-\mathbf{G}(\mathbf{z},\mathbf{t})+\frac{\partial\boldsymbol{\delta}(\mathbf{x},\mathbf{z},\mathbf{t})}{\partial\mathbf{t}} \quad (1)$$

Where x and z, are the spatial variables, along the (ox) and (oy) axes respectively. D* is the complex diffusion coefficient as a function of magnetic field and modulation frequency, t is time; τ is the average lifetime of minority carriers in the base; δ(x,z,t) the minority carrier's density in the base and G(z,t) the total generation rate of minority carriers. The expressions for the total generation rate and the minority carriers' density, are given respectively:

$$\mathbf{G}(\mathbf{z},\mathbf{t})=\mathbf{g}(\mathbf{z}).\mathbf{e}^{\mathbf{i}\boldsymbol{\omega}\mathbf{t}} \quad (2)$$

And

$$\boldsymbol{\delta}(\mathbf{x},\mathbf{z},\mathbf{t})=\boldsymbol{\delta}(\mathbf{x},\mathbf{z}).\mathbf{e}^{\mathbf{i}\boldsymbol{\omega}\mathbf{t}} \quad (3)$$

Where: $e^{i\omega t}$ is the time component; δ(x, z) is the spatial component and g (z) is the generation rate. The expression for the generation rate g (z) is given by:

$$g(z)=\alpha\phi(1-R)e^{-\alpha z} \quad (4)$$

Where: ϕ is the monochromatic incident photon flux; α is the monochromatic absorption coefficient of the material and R the monochromatic reflection coefficient of the material. Substituting equations (2) and (3) into equation (1), we obtain:

$$\frac{\partial^2\boldsymbol{\delta}(\mathbf{x},\mathbf{z},\boldsymbol{\lambda},\boldsymbol{\omega},\mathbf{B})}{\partial\mathbf{x}^2}-\frac{\boldsymbol{\delta}(\mathbf{x},\mathbf{z},\boldsymbol{\lambda},\boldsymbol{\omega},\mathbf{B})}{\mathbf{L}^2(\boldsymbol{\omega},\mathbf{B})}=-\frac{\mathbf{g}(\mathbf{z})}{\mathbf{D}(\boldsymbol{\omega},\mathbf{B})} \quad (5)$$

L (ω, B) is the complex diffusion length. It depends on the excitation frequency and the magnetic field.

We pose:

$$\mathbf{L}^2(\boldsymbol{\omega},\mathbf{B})=\boldsymbol{\tau}.\mathbf{D}(\boldsymbol{\omega},\mathbf{B}) \quad (6)$$

With

$$D^* = D(,\ B) \quad (7)$$

The solution of equation (5) is:

$$\boldsymbol{\delta}(\mathbf{x},\mathbf{z},\boldsymbol{\lambda},\boldsymbol{\omega},\mathbf{B})=\mathbf{K}_1.\mathbf{e}^{\frac{\mathbf{x}}{\mathbf{L}(\boldsymbol{\omega},\mathbf{B})}}+\mathbf{K}_2.\mathbf{e}^{-\frac{\mathbf{x}}{\mathbf{L}(\boldsymbol{\omega},\mathbf{B})}}+\frac{\mathbf{L}^2(\boldsymbol{\omega},\mathbf{B})}{\mathbf{D}(\boldsymbol{\omega},\mathbf{B})}.\phi.\boldsymbol{\alpha}.(1-\mathbf{R})\mathbf{e}^{-\boldsymbol{\alpha}.\mathbf{z}} \quad (8)$$

Where the coefficients K_1 and K_2 are determined by the boundary conditions [10,11].

- at the emitter-base junction (x=0):

$$D(\omega,B).\left.\frac{\partial\delta(x,z,\lambda,\omega,B)}{\partial x}\right|_{x=0}=Sf.\delta(x,z,\lambda,\omega,B)\big|_{x=0} \quad (9)$$

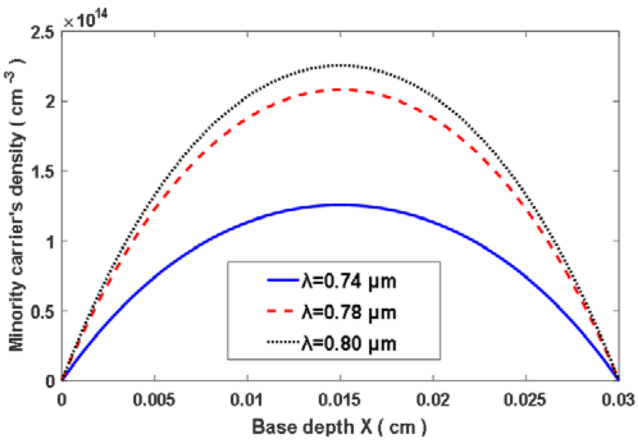
- in the middle of the base in x=H/2:

$$\left.\frac{\partial\boldsymbol{\delta}(\mathbf{x},\mathbf{z},\boldsymbol{\lambda},\boldsymbol{\omega},\mathbf{B})}{\partial\mathbf{x}}\right|_{\mathbf{x}=\frac{H}{2}}=0 \quad (10)$$

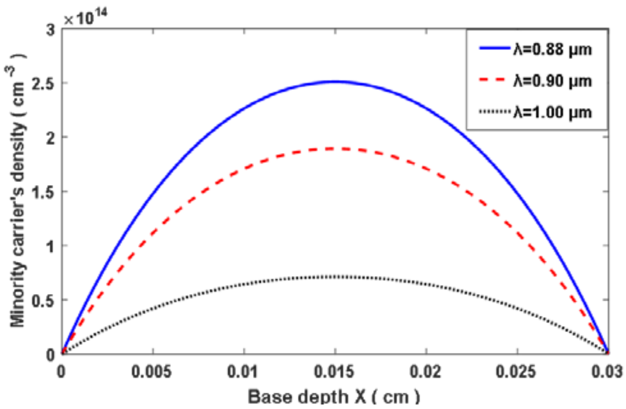
Where: H is the thickness of the solar cell base along the (ox) axis; Sf is the junction recombination velocity [12,13,14,15,16].These calculations allowed us to simulate the parameters presented below.

3. Results and Discussion

In this part, the profiles of the minority carriers' density in the base and the diffusion capacitance are presented. Wavelength effect of the minority carrier's density. In figure 2, the profile of the minority carrier's density versus the base depth is represented:



a). in short wavelengths



b). in long wavelengths

Figure 2. Minority carriers' density versus base depth
a) Short wavelengths b) Long wavelengths
z=0.002 cm; B= 10-4 T; $\boldsymbol{\omega_r}$= 1.75×107 rad/s; Sf = 2×102cm/s

The minority carrier's density curves in figures 2(a) and 2(b) show the same gaits and the maximum corresponds to the base thickness x=0.015 cm. The minority carrier's density increases with wavelength in the short wavelength range.The short wavelengths ($\lambda \leq 0.86$ µm) correspond to strong absorption of incident photons in the base; which leads to increasing photogeneration of minority carriers. In contrast, the minority carrier's density decreases when the wavelength increases. This decrease of the minority carrier's density is explained by the fact that when the wavelength is large ($\lambda \geq 0.86$ µm), the incident light becomes almost weak, the photons do not have enough energy to extract the charge carriers, resulting in low charge carrier generation, and the photon losses associated with recombination effects in the base volume become considerable. In the figure 2, some minority carriers' density values are given in Table 1:

Table 1. some values of the maximum minority carriers' density ($\boldsymbol{\delta_{max}}$) *in* the middle of the base for short and long wavelengths.

	wavelength $\lambda(\mu m)$	Maximum minority carriers 'densitty $\delta_{max}\,(cm^{-3})$
Short wavelength $\lambda < 0{,}86\ \mu m$	0.74	1.3×10^{14}
	0.78	2.1×10^{14}
	0.80	2.3×10^{14}
Short wavelength $\lambda > 0{,}86\ \mu m$	0.88	2.5×10^{14}
	0.90	1.9×10^{14}
	1.00	7.1×10^{13}

This table, shows the evolution of the maximum minority carriers' density δ_{max} for a given wavelength. We note that, whatever the wavelength range, the minority carrier's density is greater when the illumination wavelength is near to the value of the particular value (λ=0.86 µm).

3.2. Wavelength Effect On Diffusion Capacitance

The space charge region of a solar cell can be considered as a planar capacitor [17,18] called diffusion capacitance.

This diffusion capacitance of the solar cell is considered as the resulting capacitance of the charge variation during the diffusion process within the solar cell [19,20]. The capacitance is mainly due to the fixed ionized charge (dark capacitance) at the junction boundaries and the diffusion process (diffusion capacitance). Its expression is given by the relation:

$$\mathbf{C}(\mathbf{Sf},\boldsymbol{\lambda},\boldsymbol{\omega},\mathbf{B},\mathbf{x}=0)=\frac{\mathbf{dQ}(\mathbf{Sf},\boldsymbol{\lambda},\boldsymbol{\omega},\mathbf{B},0)}{\mathbf{dV}(\mathbf{Sf},\boldsymbol{\lambda},\boldsymbol{\omega},\mathbf{B},\mathbf{x})} \tag{11}$$

with

$$\mathbf{Q}(\mathbf{Sf},\boldsymbol{\lambda},\boldsymbol{\omega},\mathbf{B},\mathbf{x})=\mathbf{q}.\boldsymbol{\delta}(\mathbf{Sf},\boldsymbol{\lambda},\boldsymbol{\omega},\mathbf{B},\mathbf{x}) \tag{12}$$

Then equation (10) becomes:

$$\mathbf{C}(\mathbf{Sf},\boldsymbol{\lambda},\boldsymbol{\omega},\mathbf{B},\mathbf{x}=0)=\mathbf{q}.\frac{\mathbf{d}\boldsymbol{\delta}(\mathbf{Sf},\boldsymbol{\lambda},\boldsymbol{\omega},\mathbf{B},0)}{\mathbf{dV}} \tag{13}$$

$$\mathbf{C}(\mathbf{Sf},\boldsymbol{\lambda},\boldsymbol{\omega},\mathbf{B},\mathbf{x}=0)=\mathbf{q}.\frac{\mathbf{d}\boldsymbol{\delta}(\mathbf{Sf},\boldsymbol{\lambda},\boldsymbol{\omega},\mathbf{B},0)}{\mathbf{dSf}}\frac{1}{\frac{\mathbf{dV}}{\mathbf{dSf}}} \tag{14}$$

Equation (13) can be written as:

$$\mathbf{C}(\mathbf{Sf},\boldsymbol{\lambda},\boldsymbol{\omega},\mathbf{B},0)=\frac{\mathbf{q}.\mathbf{n_i^2}}{\mathbf{N_b}.\mathbf{V_T}}+\frac{\mathbf{q}.\boldsymbol{\delta}(\mathbf{Sf},\boldsymbol{\lambda},\boldsymbol{\omega},\mathbf{B},0)}{\mathbf{V_T}} \tag{15}$$

We pose:

$$C_O(T)=\frac{\mathbf{q}.\mathbf{n_i^2}}{\mathbf{N_b}.\mathbf{V_T}} \tag{16}$$

And

$$\mathbf{C_d}(\mathbf{Sf},\boldsymbol{\lambda},\boldsymbol{\omega},\mathbf{B},\mathbf{x}=0)=\frac{\mathbf{q}.\boldsymbol{\delta}(\mathbf{Sf},\boldsymbol{\lambda},\boldsymbol{\omega},\mathbf{B},\mathbf{x}=0)}{\mathbf{V_T}} \tag{17}$$

C_O is the dark capacitance, C_d is the diffusion capacitance under illumination; n_i is the intrinsic concentration; N_b is the doping concentration and V_T is the thermal voltage. Thus, the final expression of the capacitance is given by equation (17):

$$\mathbf{C}(\mathbf{Sf},\boldsymbol{\lambda},\boldsymbol{\omega},\mathbf{B},0)=\mathbf{C_O}(\mathbf{T})+\mathbf{C_d}(\mathbf{Sf},\boldsymbol{\lambda},\boldsymbol{\omega},\mathbf{B},0) \tag{18}$$

In figure 3, the profile of the diffusion capacitance versus junction recombination velocity in short wavelengths is represented:

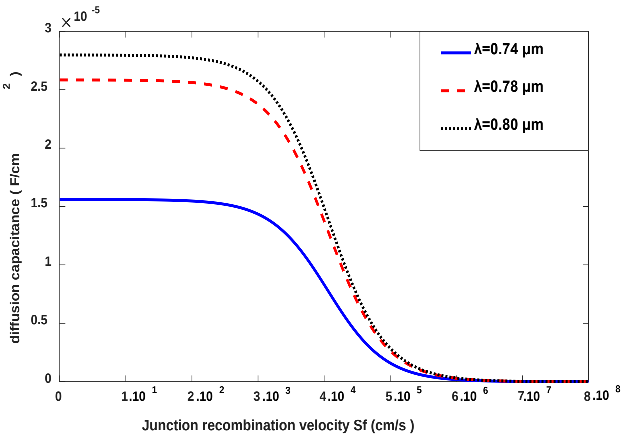


Figure 3. Diffusion capacitance versus junction recombination velocity Sf in short wavelengths. z=0.002 cm; B= 10^{-4} T; $\boldsymbol{\omega_r}$= $1.75.10^{7}$ rad/s

The diffusion capacitance is maximum and almost constant near the open circuit, (Sf tends to 0). This diffusion capacitance corresponds to the open circuit capacitance (Cco). This is explained by the fact that the maximum of minority charge carriers is stored near the emitter-base junction resulting in a narrowing of the space charge zone (SCZ), therefore the diffusion capacitance becomes significant.

On the other hand, for high recombination rates at the junction near the short circuit, the diffusion capacitance is minimal and very low. This diffusion capacitance corresponds to the short circuit capacitance (Ccc). This decrease of the diffusion capacitance is due to the significant number of minority carriers of charge in the base that cross the junction emitter-base to participate in the generation of the photocurrent, causing a widening of the space charge zone.

The capacitance increases in the short wavelength range. This increase of the capacitance corresponds to a shrinking of the space charge zone. The space charge zone is assimilated to a planar condensator [20,21].

Then the reduction of the space charge zone corresponds to a charging of the condensator. Figure 3 has allowed us to obtain some values of the capacitance in open circuit (Cco) and that in short circuit (Ccc).

These values allow us to obtain the expression of the solar cell capacitance efficiency η, given by the following equation:

$$\eta = 1 - \frac{Ccc}{Cco} \tag{19}$$

Thus, we have the following table.

Table 2 gives the value of solar cell capacitance efficiency for a given illumination wavelength. The solar cell capacitance efficiency increases with wavelength in the short wavelength range. The short wavelengths $(\lambda < 0.86\mu m)$ generate more carriers, resulting in increased photogeneration of carriers at the base of the solar cell. In figure 4, the profile of diffusion capacitance versus junction recombination velocity in the long wavelengths is represented:

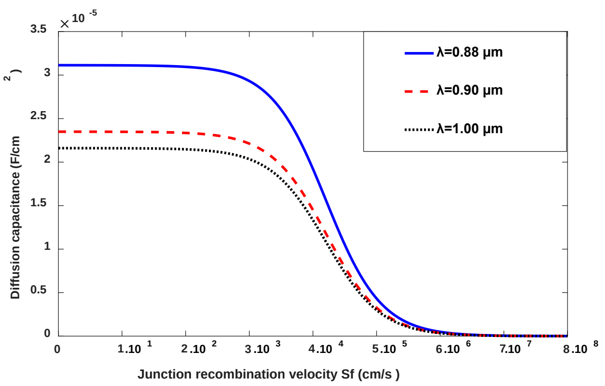


Figure 4. Diffusion capacitance versus junction recombination velocity Sf for different values of the long wavelength. z=0.002 cm; B= 10^{-4} T $\omega_r = 1.75\times10^{7}$ rad/s

Table 2. some values of Cco, Ccc and the capacity efficiency of the solar cell η, for the range of short wavelengths

$\lambda(\mu m)$	Cco (F.cm^{-2})	Ccc (F.cm^{-2})	η
0.74	1.560×10^{-5}	9.976×10^{-6}	0.360
0.78	2.349×10^{-5}	1.583×10^{-5}	0.387
0.80	8.848×10^{-6}	1.739×10^{-5}	0.390

For small values of the junction recombination velocity, the diffusion capacitance is maximal and almost constant. The diffusion capacitance gradually decreases when the junction recombination velocity Sf becomes large.

This decrease of the capacitance corresponds to an extension of the space-charge region. The space charge region is assimilated to a planar condensator. Thus, the extension of the space charge zone corresponds to a discharge of the capacitor. Then the capacitor is assimilated to a current generator. From this figure we obtained some values of Cco, Ccc and η, which are presented in the following table:

Table 3. some values of Cco, Ccc and the efficiency of the solar cell η, for the range of long wavelengths

$\lambda(\mu m)$	Cco (F.cm^{-2})	Ccc (F.cm^{-2})	η
0.88	3.113×10^{-5}	1.948×10^{-5}	0.374
0.90	2.349×10^{-5}	1.481×10^{-5}	0.369
1.00	8.848×10^{-6}	5.502×10^{-5}	0.361

Table 3, gives an overview of the efficiency of the solar cell for a given illumination wavelength. The capacitance efficiency of the solar cell decreases when the wavelength increases, in the long wavelength range. In Table 2 and Table 3, the capacitance efficiency of the solar cell is more considerable for any illumination wavelength near 0.86 µm.

4. Conclusion

In this paper, we have carried out a theoretical study of the influence of wavelength on the diffusion capacitance of a serial vertical junction silicon solar cell under frequency modulation. The emitter contribution is neglected. We were able to obtain two wavelength ranges: the short wavelength range (λ < 0.86 µm), the long wavelength range (λ > 0.86 µm) and a specific illumination wavelength λ = 0.86 µm.

In the short wavelength range, the illumination wavelength increases the minority carriers' density, photocurrent density, photovoltage and diffusion capacitance increase. The opposite phenomenon is observed in the long wavelength range.

The minority carriers' density is significant when the value of the wavelength is near to λ=0.86 µm. For λ≤0.86 µm, we have an overall increased photogeneration of carriers. The short wavelength range (λ<0.86 µm) generates more charge carriers in the base.

This wavelength range $0.6\mu m \le \lambda \le 0.86\mu m$ is optimal for a good conversion yield, for an n+-p-p+ series vertical junction solar cell under constant magnetic field in frequency modulation.

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