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Research Article

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Study of the Effect of the Magnetic Field on the Density of Minority Charge Carriers and on the Transient Voltage of a Vertical Junction Photocell Connected in Series Placed in Short Circuit and Under Polychromatic Illumination

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Abstract This work aims to save silicon material, for the realization of the solar cell, by reducing the thickness of the base. For this, the ($n^+/p/p^+$) silicon solar cell at temperature (T) is placed in a variable magnetic field (B) and back illuminated by a monochromatic light of deep penetration into the base.The magneto-transport equation relating to the density of the photogenerated carriers at depth in the base is solved and allows to extract the expressions of the recombination velocity on the rear side. A graphic technique of the study of these expressions in a situation of resonance of minority carriers diffusion, gives the optimum thickness of the base.
The results obtained show a decrease in optimum thickness with both parameters, temperature and magnetic field. Mathematical modeling of these results, shows the possibility of making thin solar cells and saving silicon material

Keywords Silicon Solar Cell, Diffusion Coefficient, Resonance, Temperature, Magnetic field, Recombination Velocity, Absorption Coefficient, Base Thickness

1. Introduction

The manufacture of solar cells has developed in recent years on the basis of several lines of research. It is in this context that after the first conventional structures having a single face to capture the light flux received, new two-sided structures have emerged in the sense of improving the first cells.
Always to make solar energy more competitive, we are moving more and more towards thinner photovoltaic panels. The photovoltaic conversion of a solar cell is linked to the photogenerated minority charge carriers defined from the lifetime of the carriers and the rate of recombination of the charge carriers at the different interfaces of the solar cell (surfaces of the grain boundaries, face front of the transmitter rear face of the base). Thus, various characterization techniques [1] [2] have been developed. These techniques, used for quality control [3] [4], support the manufacturing process.
In order to evaluate their effect on the current or voltage response of the solar cell, the recombination parameters of excess minority charge carriers are studied under different experimental [5] and theoretical [6] conditions and under different operating modes [7] in particular, in static [8], transient dynamic [9] or frequency regime [10] and for different illuminations: monochromatic [11], polychromatic [12], constant multi-spectral [13]. The solar

cell can also be maintained under different experimental conditions as a variant: the temperature [14] [15], the electric field [16] [17], the magnetic field [18] [19] or the irradiation energy of nuclear particles [20] [21]

The phenomenological parameters [22], allowing this quality control and the realization of the solar cell [23] are: In volume [24], defined by the diffusion length (L) [25][26], the diffusion coefficient (D) [27] and the lifetime (τ) [28] of the excess minority carriers.

At the surface [29], defined by the recombination velocity at the (n+-p) emitter-base junction (Sf) indicating the operating point (from open circuit to short circuit) [30][31], the velocity of recombination at the back face of the base (p-p+) (Sb) [32][33] and at the grain boundaries (Sg) in the 3D model [34][35].

To identify these different parameters and indirectly improve the performance of solar cells, lines of research on experimental techniques for measuring cell recombination parameters on the one hand and on the other hand the development of theoretical models for the simulation of solar cells are are developed. To achieve low cost solar cells, vertical multi-junction (VMJ) cells have been fabricated [36]. There are two types of VMJ [37] depending on the connection between the cells, in order to enhance either the photogenerated current or the voltage. Thus, series-connected VMJ [38] and parallel-connected VMJ [39] were treated, which allowed excess minority charge carriers of short diffusion length to be better collected, independent of the crystallinity of the silicon used. (polycrystalline or monocrystalline).

In this work, a transient study of a series vertical junction solar cell obtained by variation of the operating point [40] is proposed. The solar cell is maintained under constant multispectral illumination and under a magnetic field.

The boundary conditions allow us to find the transcendental equation [41,42] from which the eigenvalues are drawn. These eigenvalues allow us to plot the curves of the excess minority charge carrier densities and the curves of the transient voltage.

Experimental apparatus

Figure 1 represents the experimental device used to obtain the transient state by variation of the operating point of the solar cell. [43, 44,45]

This device includes a square signal generator (BRI8500) which supplies an RFP50N06 type MOSFET transistor, two adjustable resistors R1 and R2, a silicon solar cell placed under a magnetic field, a digital oscilloscope, a microcomputer for acquisition and processing of the signal and a multi-spectral light source to illuminate the solar cell.

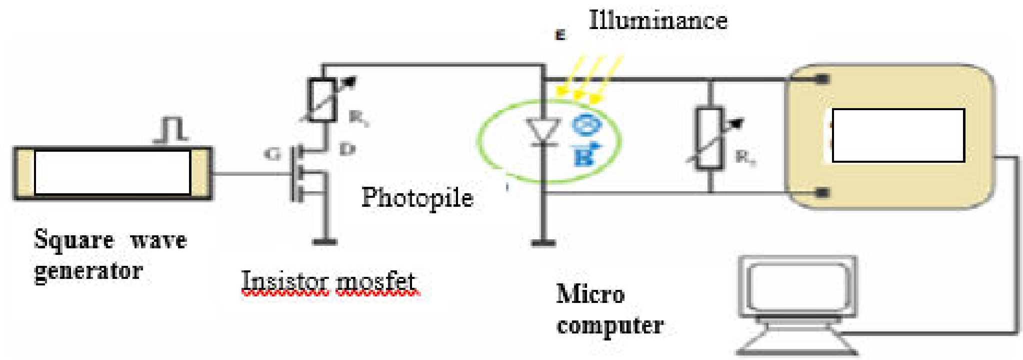

Figure 1: Experimental device for the characterization of the solar cell

Operating principle of the experimental device

At the instant (Figure 2), the solar cell being under constant multispectral illumination, the Mosfet transistor is open and the solar cell is closed in series with the resistor R2 alone: which represents the operating point F2 in steady state [46- 48] (Figure 2).

At t = 0, the closing of the MOSFET T begins and after a very short time (600-800 ns) the MOSFET is totally closed and the resistor R1 is in parallel with R2. This corresponds to the operating point F1 in steady state (Figure 2).

The transient state is obtained between the two operating points in steady state F1 and F2. The transient voltage at the terminals of the solar cell is recorded by a digital oscilloscope (Tektronics) which then transmits it to a microcomputer for processing and analysis.

By varying the resistors R1 and R2, the steady state operating points F1 and F2 move on the current-voltage characteristic of the solar cell (Figure 2), which allows the experiment to be performed at any point of this characteristic. from open circuit to short circuit and record the voltage or current response of the solar cell under constant multispectral illumination. Figure 2 below, gives the I-V characteristic of the solar cell, under different values of the magnetic field.

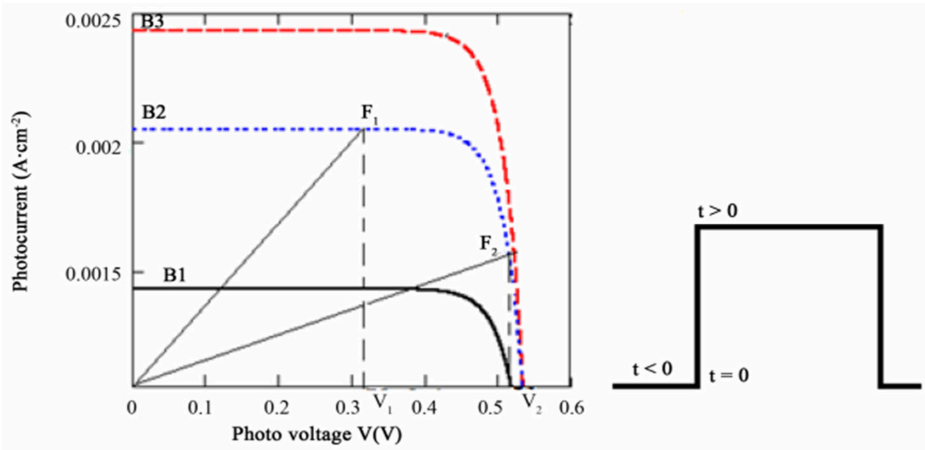

Figure 2: Theoretical I-V characteristic of the solar cell

The straight lines with slopes 1/R2 and 1/R1+1/R2 respectively give the operating points denoted F1 and F2 of the solar cell.

We have represented in the following figure the structure of a series vertical junction solar cell of type n+-p-p+ [49].

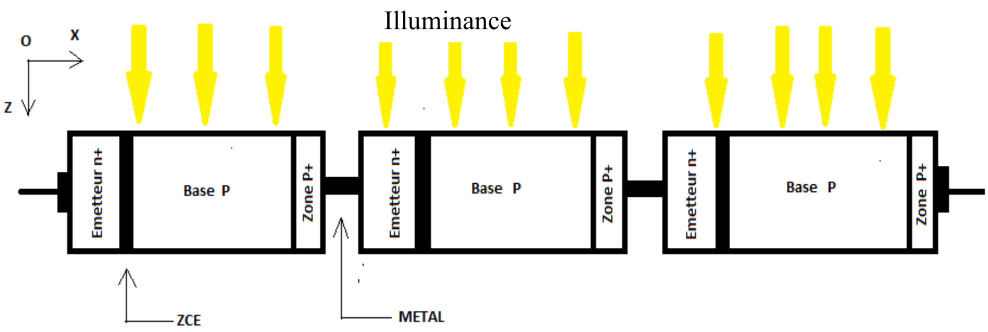

Figure 3: Structure of an n+-p-p+ series vertical junction solar cell [49]

Figure 4 shows the diagram of a series vertical junction unit solar cell under polychromatic illumination and under a magnetic field:

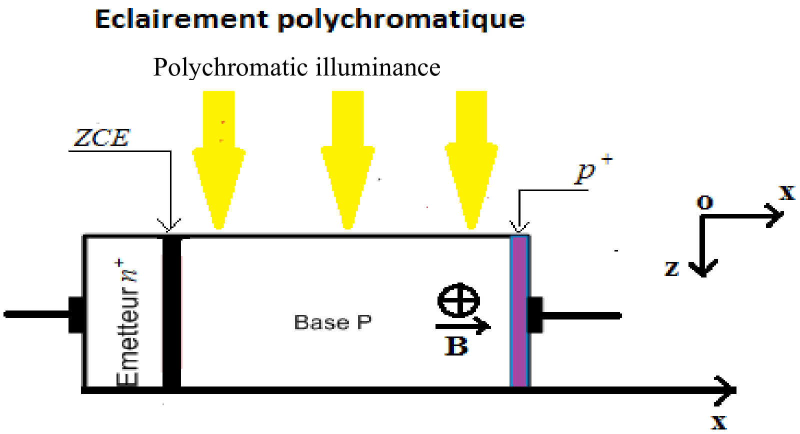

Figure 4 : A unit of the serial vertical junction solar cell under polychromatic illumination and under magnetic field B.

Magneto-transport equation

During the experiment, the level of illumination remains constant, which implies that the level of injection is not modified with respect to time. We obtain the magneto-transport equation in transient dynamic regime relating to the excess of charge carriers in the base.

The continuity equation relating to excess charge carriers [50] in the transient state is as follows:

$$D(B)\cdot\frac{\partial^2\delta(x,t)}{\partial x^2}-\frac{\delta(x,t)}{\tau}=\frac{\partial\delta(x,t)}{\partial t} \quad (1)$$

Equation 1 is solved by considering the following boundary conditions:

- **At the Junction , x=0 :**

$$D(B).\frac{\partial\delta(x,t)}{\partial x}\bigg|_{x=0}=S_f\cdot\delta(0,t) \quad (2)$$

- **At the Rear face** $x=H$:

$$D(B).\frac{\partial\delta(x,t)}{\partial x}\bigg|_{x=H}=-Sb\cdot\delta(H,t) \quad (3)$$

Sf indicates the rate of recombination of charge carriers across the junction [51]

Sb is the recombination velocity [52] at the p/p+ junction where there is an electric field allowing the photogenerated minority charge carriers to be returned near the (n+/p junction) to be collected.

The system of equations 1, 2 and 3 constitutes a problem of Sturn Liouville [53] whose solutions are with separable variables of the type:

$$\delta(x,t)=X(x)\cdot T(t) \quad (4)$$

X(x) represents the spatial part of the minority carrier density and T(t) the temporal part

The boundary condition on the back face leads to the following expression 5:

$$tg\left(\frac{\omega\cdot H}{\sqrt{D(B)}}\right)=\frac{\omega\cdot\sqrt{D(B)}(Sf+S_b(B))}{D(B)\cdot\omega^2-Sf\cdot S_b(B)} \quad (5)$$

Equation 5 is a transcendental equation whose solutions will be determined graphically. It is only set when the following condition is true:

$$\frac{\omega\cdot H}{\sqrt{D(B)}}\in\left[0,\frac{\pi}{2}\right[\cup\left](n-\frac{1}{2})\pi;(n+\frac{1}{2})\pi\right[\quad (6)$$

For large values of Sf namely Sf , the solar cell is placed in short circuit and we obtain the expression of the transcendental equation given by the following relation 7:

$$tan\left(\frac{\omega\cdot H}{\sqrt{D(B)}}\right)=-\frac{\sqrt{D(B)}}{S_b(B)}\cdot\omega \quad (7)$$

The solutions ωn form a discrete sequence: we associate to each of these values the index n. n=0 corresponds to the fundamental mode and n≠0 corresponds to the harmonic of order n.

The general solution of equation 1 is given by the following relation:

$$X_n(x,B)=A_1\cos\left(\frac{\omega_n\cdot x}{\sqrt{D(B)}}\right)+A_2\sin\left(\frac{\omega_n\cdot x}{\sqrt{D(B)}}\right) \quad (8)$$

$$T_n(t)=T_n(0)\cdot\exp(-\frac{1}{\tau_{c,n}}) \quad (9)$$

$$\frac{1}{\tau_{c,n}}=\frac{1}{\tau_0}+\omega^2 \quad (10)$$

With n being an index.

$\tau c,n$ is called the decay time constant.

Given the eigenvalues and equation 1, the definitive expression for the carrier density is written:

$$\delta(x,t)=\sum_n\delta_n(x,t) \quad (11)$$

We will give in tabular form the solutions of the transcendental equation 7 corresponding to each eigenvalue.

The fundamental mode corresponds to n = 0 and if n ≠ 0 we have the harmonic of order n.

The solutions of the transcendental equation 1 are obtained by the points of intersection of the tangential part of the equation and the right-hand side of the equation.

We will however present a graphical resolution of the transcendental equation for different values of the magnetic field in the vicinity of the short circuit.

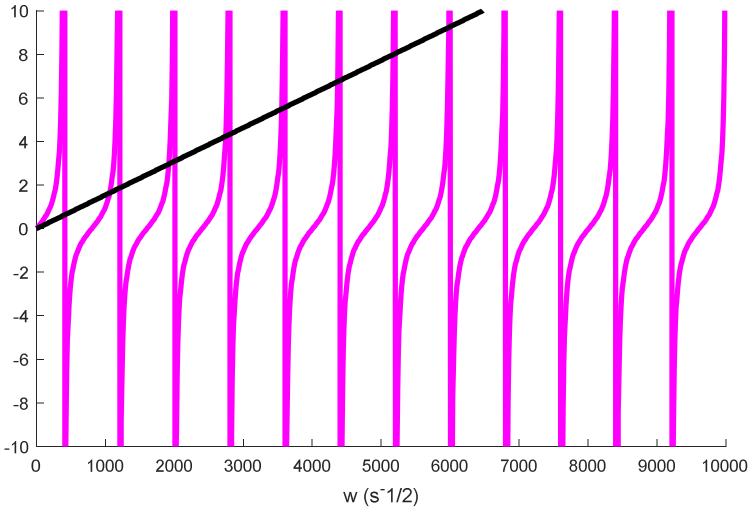

Figure 5: Graphical resolution of the transcendent equation for a Field B=0 T near the Open Circuit;; Sf=5.10^5 cm/s ; H=0.02 cm;

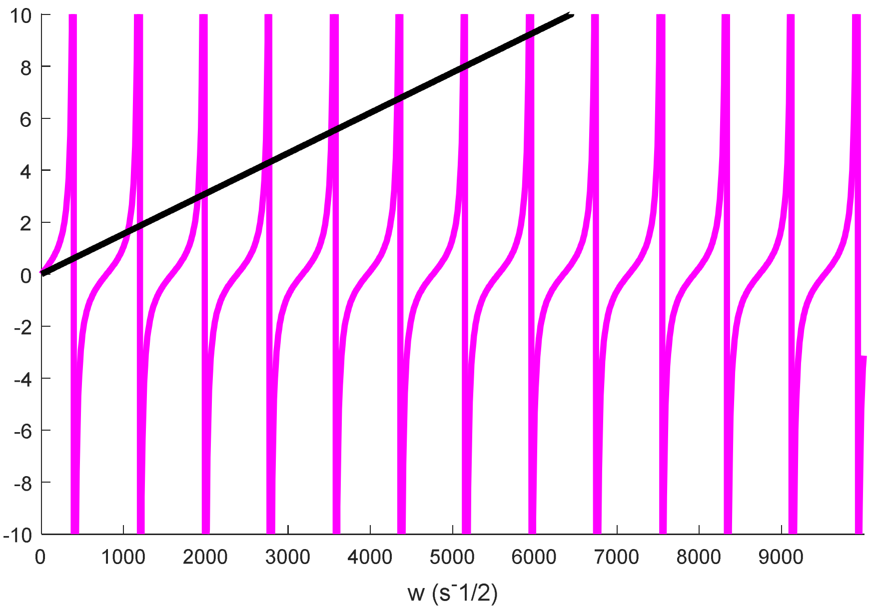

Figure 6: Graphical resolution of the transcendent equation for a Field B=0.0001 T for a short circuit mode of operation ; Sf=5.10^5 cm/s ; H=0.02 cm;

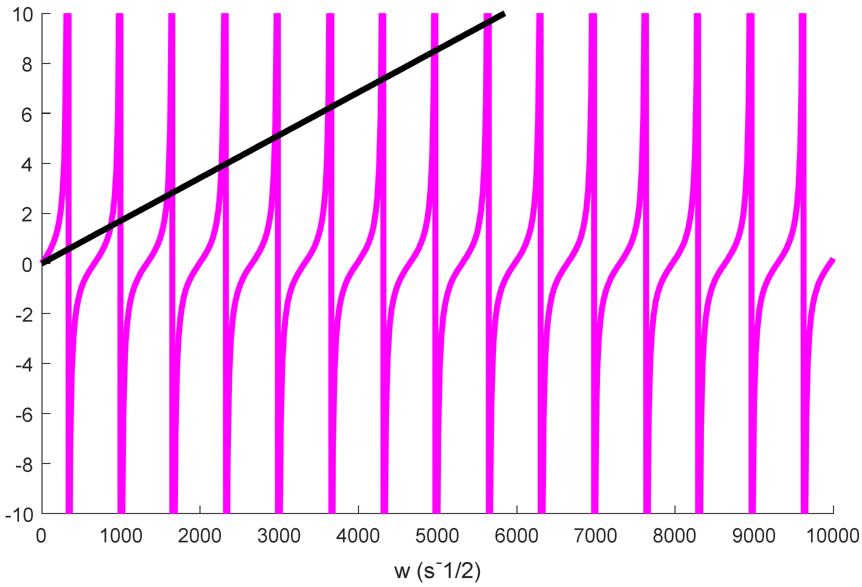

Figure 7: Graphical resolution of the transcendent equation for a Field B=0 T for a short circuit mode of operation Sf=5.10^5 cm/s ; H=0.02 cm;

The tables below give some solutions of the Transcendent Equation obtained from Figures 5, 6 and 7 and the associated lifetime τ values (Decrease Time Constant) for different magnetic field values.

Table 1: Table of eigenvalues n and lifetimes for B=0 T

n	0	1	2	3	4
ω_n($s^{-1/2}$)	1070	1920	2750	3560	4360
$\tau_{c,n}$ (ns)	803.3	264.1	130.50	78.3	53.32

Table 2: Table of eigenvalues n and lifetimes for B=0.0001 T

n	0	1	2	3	4
ω_n($s^{-1/2}$)	1050	1900	2720	3530	4340
$\tau_{c,n}$ (ns)	831.6	269.54	133.36	79.6	52.8

Table 3: Table of eigenvalues n and lifetimes for B=0.0005 T

n	0	1	2	3	4
ω_n($s^{-1/2}$)	870	1590	2270	2950	3620
$\tau_{c,n}$ (ns)	1166.9	380.50	190.37	113.6	75.7

The analysis of the different curves 5, 6 and 7 and the tables of associated values respectively (1,2 and 3) shows that for each case the eigenvalues n increase and the decay constants decrease and this for different eigenvalues of B= 0 T, B=0.0001 T, B=0.0005 T. However, when passing from a weak magnetic field to a larger magnetic field, the eigenvalues decrease and the decay constants increase.
n=0 corresponds to the fundamental mode of decay and n 0 corresponds to the harmonic of order n. We will then write n instead of and all the expressions where the eigenvalue appears will be endowed with this index n. For example: 1, 2 and 3.

Results and Discussions

The solutions of the transcendental equation allowed us to plot the profiles of the densities of minority carriers in the base for different values of the magnetic field.
The following figures represent the profiles of the densities of the minority carriers as a function of time for different values of the magnetic field for the fundamental mode and the different harmonic states in the vicinity of the Short-Circuit.

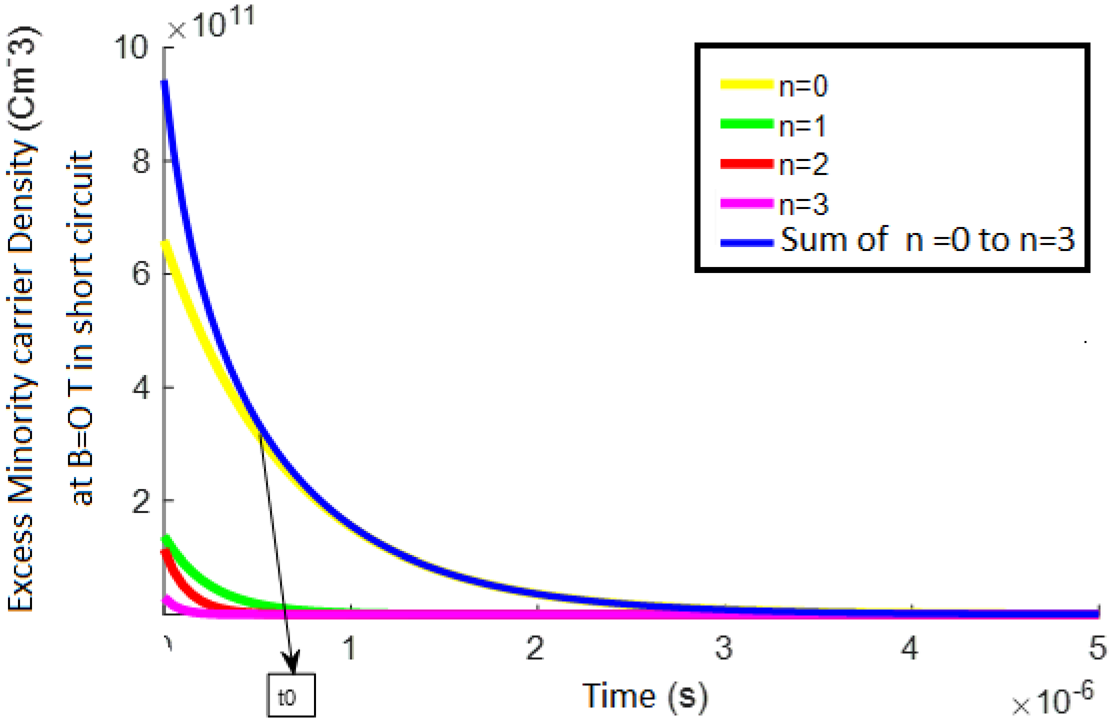

Figure 8: Short Circuit Solar Cell Minority Carrier Density Profile for a Magnetic Field B=0 T

Sf= $5.10^5 cm/s$; ***H=0.02 cm*** ; $\tau = 1 \bullet 10^{-5} s$; $\mu = 1350\ cm^2 . V^{-1} . S^{-1}$

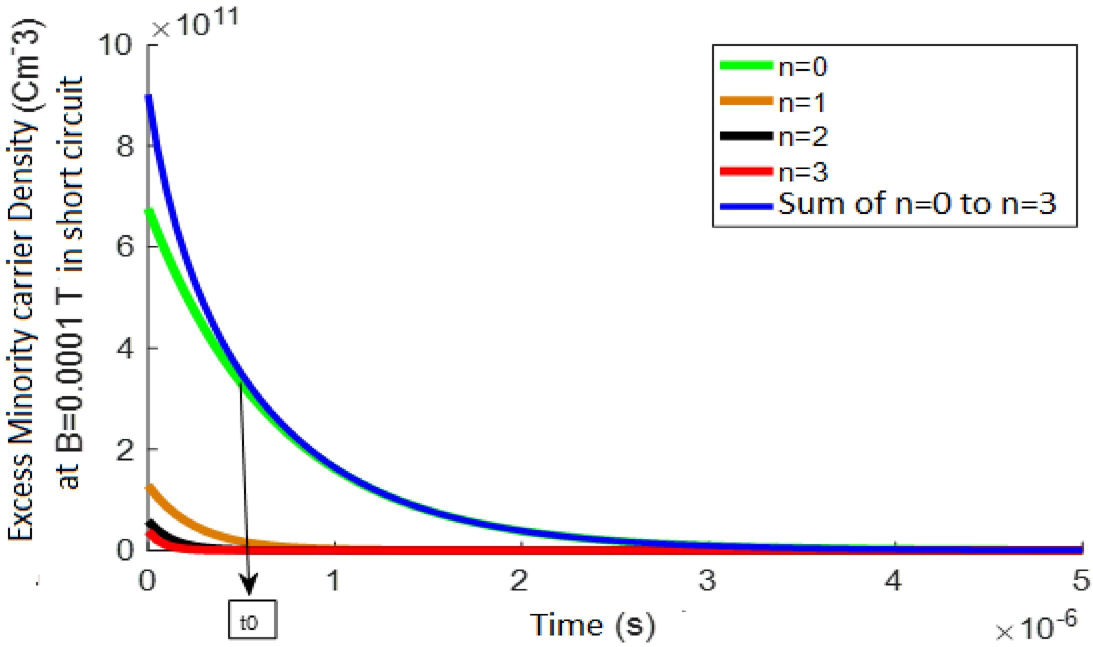

Figure 9: Density profile of Minority Carriers of the Solar Cell in Short Circuit for a Magnetic Field B=0.0001 T

Sf= $5.10^5 cm/s$ ***; H=0.02 cm ;*** $\tau = 1 \bullet 10^{-5} s$ ***;*** $\mu = 1350\ cm^2.V^{-1}.S^{-1}$

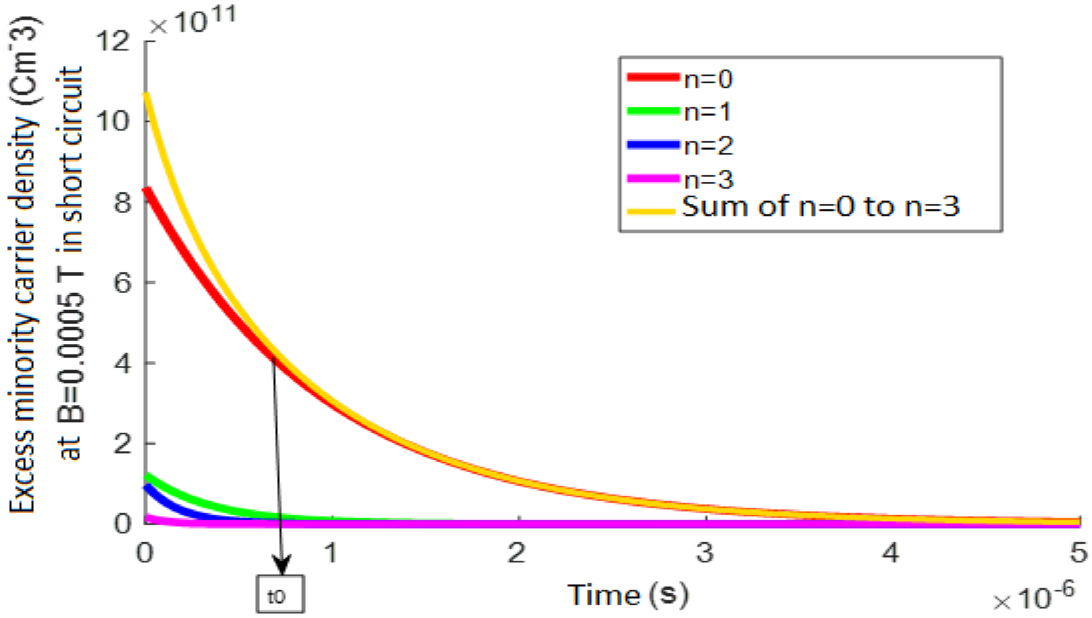

Figure 10: Short Circuit Solar Cell Minority Carrier Density Profile for a Magnetic Field B=0.0005 T

Sf= $5.10^5 cm/s$ *; H=0.02 cm ;* $\tau = 1 \bullet 10^{-5} s$ *;* $\mu = 1350\ cm^2.V^{-1}.S^{-1}$

We can say that to obtain the transient density of minority carriers of excess charges in the base of the solar cell, a graphical resolution of the transcendental equation obtained from the continuity equation was made. This resolution allowed us to study the dependence of the obtained eigenvalues and decay times with the magnetic field. We find that when the magnetic field increases, the carrier density decreases and the transient decay is slower.

We also note in these figures that the densities of the minority charge carriers corresponding to the different values of n, decrease and all tend towards the same limit for a relatively long observation time. However, we notice that the density of the total minority charge carriers merges with that of the fundamental mode from a time that can be noted t0. These figures also show that the carrier density decreases with time and the densities of modes other than the fundamental mode become negligible. The magnetic field under the effect of the Laplace force deflects the photogenerated carriers from their initial trajectory towards the lateral surfaces, thus reducing their mobility, their diffusion and their conduction in the base of the solar cell [54] [55]. The increase in the magnetic field is synonymous with the decrease in the gradient of the carriers at the junction and consequently the reduction of the carriers that can cross it, resulting in a slower decay time. [56]

Transient voltage V(t)

Let's call V(t) the transient photovoltage. Its expression is obtained thanks to the Boltzmann relation

$$V(t)=q_0\cdot F_c(\omega_0)\cdot \exp(-\frac{t}{\tau_{c,0}})$$

With $F_c(\omega_0)=\frac{A_0\cdot T_0(0)}{\delta(0,0)}$

The transient voltage is a decreasing exponential function of time. This during we will show the influence of the magnetic field on the transient voltage.

Transient photovoltage in short circuit

The general shape of the photovoltage V(t) curves depends on the potential difference ΔV between the two points representing the initial and final stationary states.

We will give the different curves obtained for the transient photovoltage as a function of time for different values of the Magnetic Field.

The following curves represent the profiles of transient photovoltages as a function of time for different values of the magnetic field and for different values of ΔV in the vicinity of the short circuit.

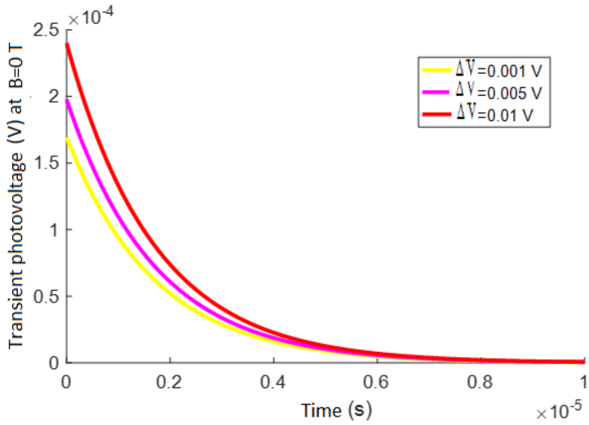

Figure 11: Transient photvoltage Profile of the Photocell at B=0 T in Short-Circuit for different values of ΔV. Sf=5.10⁵ cm/s ; H=0.02 cm ; $\tau=1\bullet 10^{-5}s$

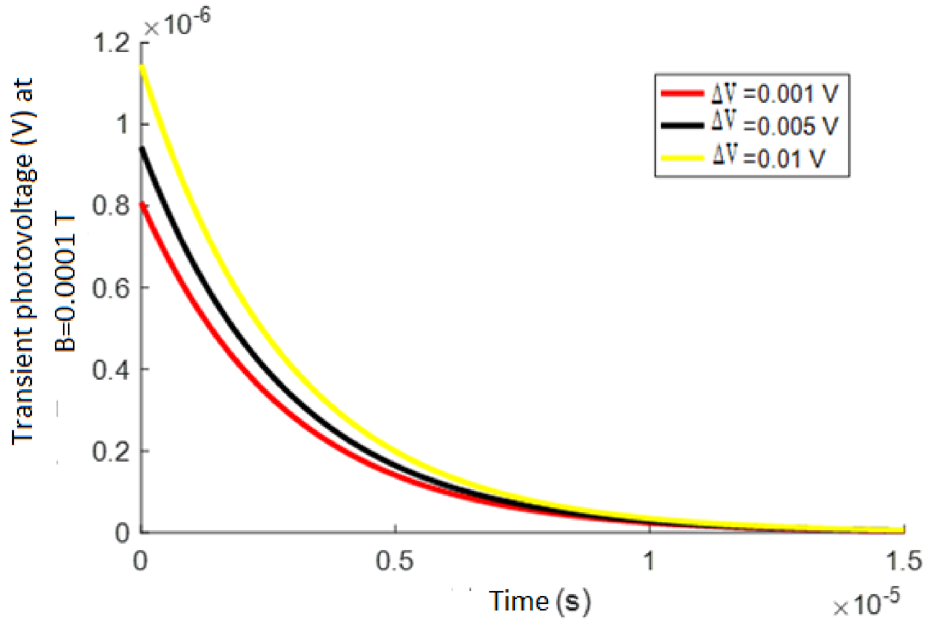

Figure 12: Profile of the Transient photovoltage of the Solar Cell at B=0.0001 T in Short-Circuit for different values of ΔV . Sf=5.10⁵ cm/s ; H=0.02 cm ; $\tau = 1 \bullet 10^{-5} s$

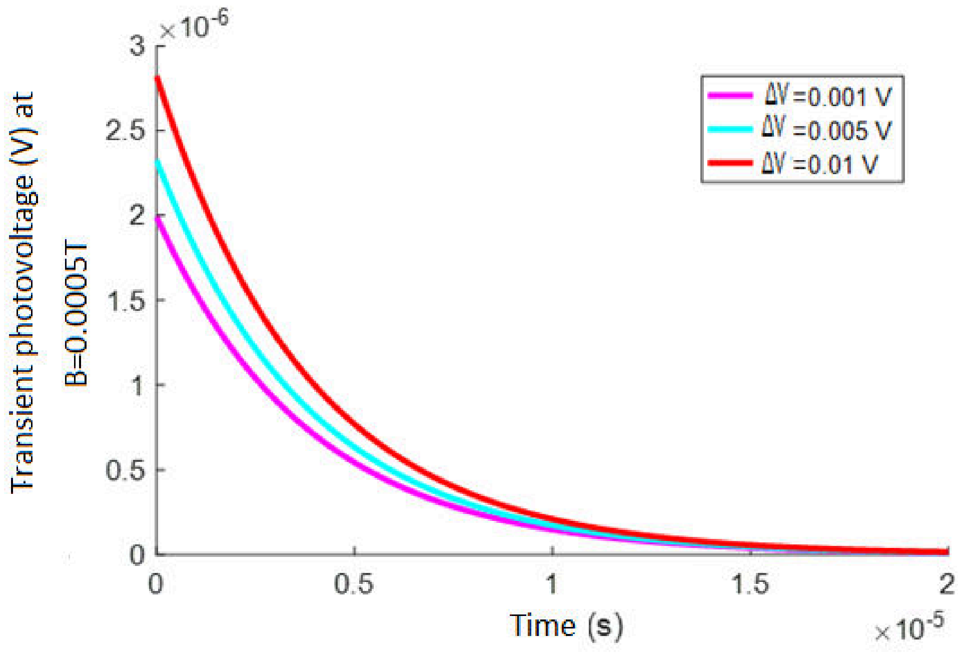

Figure 13: Profile of the Transient photovoltage of the Solar Cell at B=0.0005 T in Short-Circuit for different values of ΔV . Sf=5.10⁵ cm/s ; H=0.02 cm ; $\tau = 1 \bullet 10^{-5} s$

We observe in figures 11, 12 and 13 a decrease in the transient photovoltage. These figures also show that the amplitude of the transient photovoltage increases when the photovoltage difference ΔV=V2-V1 taken between two operating points increases. If ΔV increases, the two operating points move away and in this case the amplitude increases.

However, when passing from a weak magnetic field to a larger magnetic field, the transient photovoltage decreases in amplitude because the magnetic field under the effect of the Laplace force deflects the carriers from their trajectory, thus reducing their mobility, their diffusion, their conduction.

Conclusion

The study of the influence of the magnetic field on a series vertical junction silicon solar cell under polychromatic illumination is studied through the continuity equation. And the boundary conditions allowed us to obtain the transcendental equation from which the eigenvalues are extracted. the eigenvalues and the decay time constants are dependent on the magnetic field. These eigenvalues enabled us to plot the density curves of the excess minority charge carriers and the transient photovoltage curves can be noted t0 the total minority charge carrier density merges with that of the fundamental mode.

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