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Influence of the Magnetic Field on the Transient Decay of the Density of Charge Carriers in a Silicon Photocell with Vertical Multijunctions Connected in Series Placed in Open Circuit

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Abstract

This study investigates the effect of the magnetic field on the transient density of excess minority charge carriers in the base of a series-connected vertical junction silicon solar cell. The solar cell is presented in open circuit transient operation. The magnetic field through the Laplace force which deflects the photogenerated carriers from their initial trajectory towards the lateral surfaces reducing their mobility, diffusion and conduction, will certainly influence the decay time of the transient regime. The transient density of excess minority carriers in the base is a sum of infinite terms whose decay time of the different harmonics is studied.

Keywords

Silicon Solar Cell-Series, Vertical Junction, Recombination Velocities, Magnetic Field, Base Thickness (P), Eigenvalues, Decay Time Constant

1. Introduction

The study of the solar cell dates back centuries but continues to offer interesting results and could in the near future be ahead of the world economy. The solar cell is the exposed semiconductor electronic component that comprises a photovoltaic solar panel and which in the light produces electrical energy. It has many characteristics which differ according to the diet and the type of cell. Thus, there are different techniques allowing the direct conversion of sunlight into electricity, the best known is the photovoltaic conversion carried out using semiconductor materials such as Silicon (Si), Germanium (Ge), Selenium (Se) or semi-conductor compounds such as Gallium Arsenide (GaAs), Cadmium Telluride (CdTe). When the solar cell is exposed to light, electron-hole pairs are generated. The existence of an electric field that results from the bringing into contact of two differently doped materials at the junction makes it possible to separate these electric charges of opposite signs and obtain a current. These photogenerated carriers succumb to different recombination processes during their diffusion within the solar cell; these recombination phenomena indicate the collection of charge carriers and consequently the efficiency of the solar cell which is linked to the capacity of the solar cell to convert solar energy into electricity. There are several parameters that contribute to this improvement. Among the most important parameters, there are the phenomenological parameters [1] [2] [3] allowing quality control which are the coefficient of Diffusion (D) [4] [5], the Length (L) of diffusion [6] [7], the lifetime [8], and the recombination velocities at the Sf junction [9] and on the rear face Sb [10] [11] of the minority charge carriers and the electrical parameters [12] [13] which are the series and shunt resistances as well as the space charge area capacitance. 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 [14] and theoretical [15] conditions and under different operating modes [16] in particular, in static regime [17], in dynamic frequency regime [18] [19] [20] and in transient dynamic regime [14] [21] [22] [23]. Crystalline silicon solar cells can come in different architectures, including vertical multi-junction (VMJ) solar cells [24] [25] [26]. Allowing, on the one hand, an incident illumination parallels to the space charge zone, uniform and constant over all the regions and on the other hand, the minority charge carriers in excess of short diffusion length to be better collected. These vertical multi-junction solar cells are of two types depending on the connection between the cells (n/p or n/p/p^+) base, in order to improve either the photogenerated current if the cells are connected in parallel [25] [27] or voltage if connected in series [28]. In this work, a transient study of a series vertical of junction solar cells obtained by variation of the operating point [29] 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 [30] [31] from which the eigenvalues are drawn. These eigenvalues will make it possible to plot the curves of excess minority carrier densities in the base.

2. Theorical Studies

2.1. Experimental Apparatus

Figure 1 presents the experimental device used to obtain the transient state by

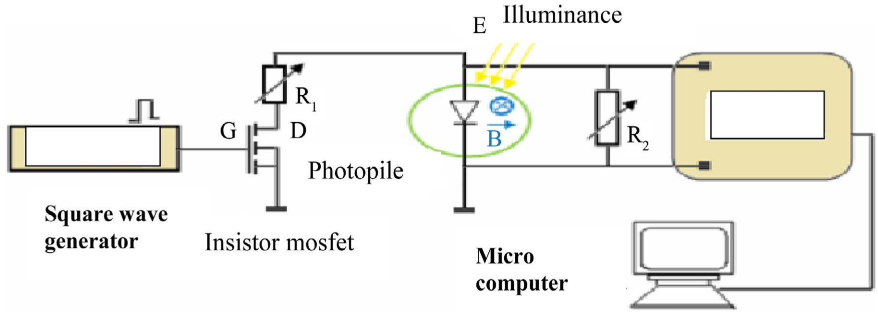

Figure 1. Experimental device for the characterization of the solar cell.

variation of the solar cell's operating point [11] [32] [33]. 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, and a microcomputer for acquisition and processing of the signal and a multi-spectral light source to illuminate the solar cell.

2.2. Operating Principle of the Experimental Device

For the time smaller than zero (**Figure 2**) the solar cell 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 [34] [35] [36] (**Figure 2**), refractive indices very close to the optimal index of silicon. This leads to massive absorption of light flux in the TCO layer, causing almost zero reflections.

For the time equals to zero, begins the closing of the MOSFET T 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 over 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.

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 **Figure 3** the structure of a series vertical junction solar cell of the type n^+-p-p^+ [39].

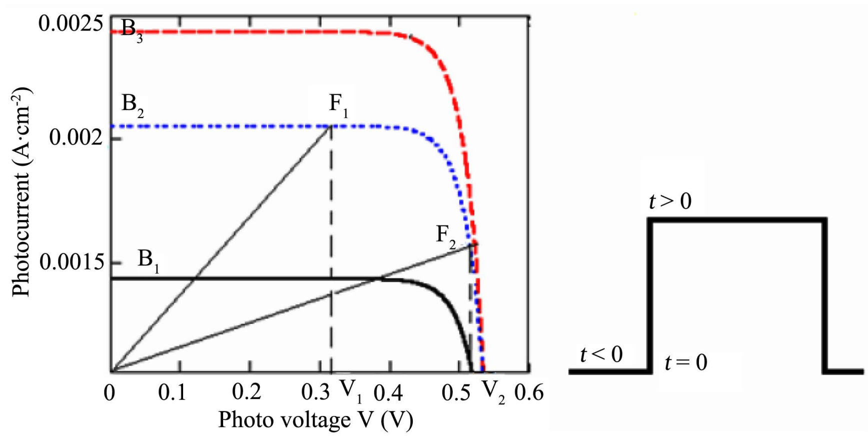

Figure 2. Theoretical I - V characteristic of the solar cell [37] [38].

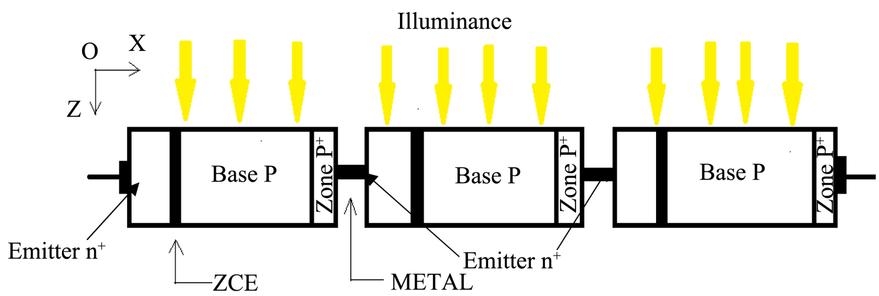

Figure 3. Structure of an n^+-p-p^+ series vertical junction solar cell.

Figure 4 shows the diagram of a series vertical junction unit solar cell under polychromatic illumination and under a magnetic field [39]:

Magneto-transport equation

The illumination arrives parallel to the plane of the junction under the influence of the magnetic field. Thus, there is absorption of photons, generation of electron-hole pairs which can diffuse or recombine on the surface or in volume. All of these recombination and generation diffusion phenomena are governed by the following continuity equation [40]:

$$D(B)\cdot\frac{\partial^2\delta(x)}{\partial x^2}-\frac{\delta(x)}{\tau}=-G(Z) \tag{1}$$

τ: is the lifetime of excess minority carriers in the base of the solar cell.

$\delta(x)$: represents the density of excess minority charge carriers photogenerated in the base of the solar cell at position x.

$G(z)$: is the generation rate of excess minority carriers in the base. Its expression is given by

$$G(z)=\sum_{i=1}^{3}a_i\exp(-b_i z) \tag{2}$$

a_i and b_i are tabulated coefficients of solar radiation is the diffusion coefficient [41] of the minority charge carriers in the base under magnetic field [42]. Its expression is given by the following relationship.

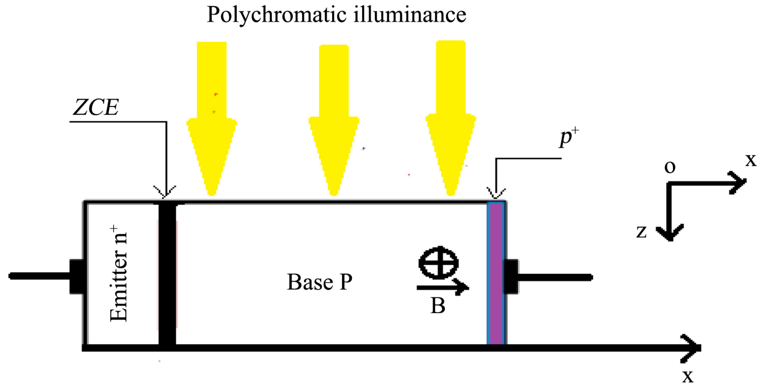

Figure 4. Texturing of the silicon surface in pyramidal form.

$$D(B) = \frac{D_0}{1+(\mu \cdot B)^2} \tag{3}$$

The solution of the continuity Equation (1) is given by the following relation:

$$\delta(x,B,z) = C1 \cdot \exp\left(\frac{x}{L(B)}\right) + C2 \cdot \exp\left(-\frac{x}{L(B)}\right) + \sum_{I=1}^{3} \frac{a_i \cdot L^2}{D(B)} \cdot \exp(-b_i \cdot z) \tag{4}$$

$L(B)$ being the diffusion length of the excess minority carriers.

The coefficients $C1$ and $C2$ are determined from the following boundary condition.

At the junction

$$x = 0: \quad D(B) \cdot \left.\frac{\partial \delta(x,z,B)}{\partial x}\right|_{X=0} = -Sf \cdot \delta(0,z,B) \tag{5}$$

Sf indicates the rate of recombination of charge carriers across the junction [43].

In the Back Zone:

$$D(B) \cdot \left.\frac{\partial \delta(x,z,B)}{\partial x}\right|_{X=H} = -Sb \cdot \delta(H,z,B) \tag{6}$$

Sb is the recombination velocity [44] 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.

3. Photocurrent Density

The photocurrent density of a solar cell is obtained from the gradient of the minority carrier density at the junction. Its expression is given by Fick's law:

$$J_{ph}(Sf,Sb,H,z,B) = q \cdot D \cdot \left.\frac{\partial \delta(Sf,z,x,B)}{\partial x}\right|_{x=0} \tag{7}$$

4. Recombination Rate in the Back Zone

The current photo density, of excess charge minority carriers in the base, being constant for large values of the recombination velocity at the junction ($Sf \geq 10^5\,\mathrm{cm \cdot s^{-1}}$), this corresponds to the short-circuit photocurrent of the solar cell, its derivative is canceled [45].

$$\left.\frac{\partial J_{ph}\left(Sf,Sb,z,B\right)}{\partial Sf}\right|_{Sf \geq 10^5\,\mathrm{cm \cdot s^{-1}}} = 0 \tag{8}$$

Solving this equation leads to two expressions for the recombination rate of excess minority charge carriers in the base in the back region Sb1 and Sb2 [46] [47] [48].

$$Sb1\left(H,B\right) = -\frac{D\left(B\right)}{L\left(B\right)} \cdot \tanh\left(\frac{H}{L\left(B\right)}\right) \tag{9}$$

$$Sb2\left(H,B\right) = -\frac{D\left(B\right) \cdot \sinh\left(\frac{H}{L\left(B\right)}\right)}{L\left(B\right) \cdot \left(\cosh\left(\frac{H}{L\left(B\right)}\right) - 1\right)} \tag{10}$$

The continuity equation relating to excess charge carriers $\delta\left(x,t\right)$ [49] in the transient state is as follows:

$$D\left(B\right) \cdot \frac{\partial^2 \delta\left(x,t\right)}{\partial x^2} - \frac{\delta\left(x,t\right)}{\tau} = \frac{\partial \delta\left(x,t\right)}{\partial t} \tag{11}$$

Equation (11) is solved by taking into account the following boundary conditions:

At the junction, *x* = 0:

$$D\left(B\right) \cdot \left.\frac{\partial \delta\left(x,t\right)}{\partial x}\right|_{x=0} = S_f \cdot \delta\left(0,t\right) \tag{12}$$

At the Back zone, *x* = *H*:

$$D\left(B\right) \cdot \left.\frac{\partial \delta\left(x,t\right)}{\partial x}\right|_{x=H} = -Sb \cdot \delta\left(H,t\right) \tag{13}$$

The system of Equations (10)-(12) constitutes a problem of Sturn Liouville [50] whose solutions are with separable variables of the type:

$$\delta\left(x,t\right) = X\left(x\right) \cdot T\left(t\right) \tag{14}$$

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

The general solution of Equation (19) is given by the following relation:

$$X_n\left(x,B\right) = A_1 \cos\left(\frac{\omega_n \cdot x}{\sqrt{D\left(B\right)}}\right) + A_2 \sin\left(\frac{\omega_n \cdot x}{\sqrt{D\left(B\right)}}\right) \tag{15}$$

$$T_n\left(t\right) = T_n\left(0\right) \cdot \exp\left(-\frac{1}{\tau_{c,n}}\right) \tag{16}$$

$$\frac{1}{\tau_{c,n}} = \frac{1}{\tau_0} + \omega^2 \tag{17}$$

With n being an index.

$\tau_{c,n}$ is called the decay time constant.

Taking into account the eigenvalues and Equation (17), the definitive expression of the carrier density is written:

$$\delta(x,t) = \sum_{n} \delta_n(x,t) \tag{18}$$

5. Results and Discussions

The solutions of the transcendental Equation (16) are obtained by the points of intersection of the tangential part of the equation and the right-hand side of the equation.

A graphical resolution of the transcendental equation for different values of the magnetic field in the vicinity of the open circuit is shown.

With

$$Sb1(H,B) = -\frac{D(B)}{L(B)} \cdot \tanh\left(\frac{H}{L(B)}\right) \tag{19}$$

Tables 1-3 below give some solutions of the transcendent equation obtained from Figures 5-7 and the decay time constants for different values of the magnetic field.

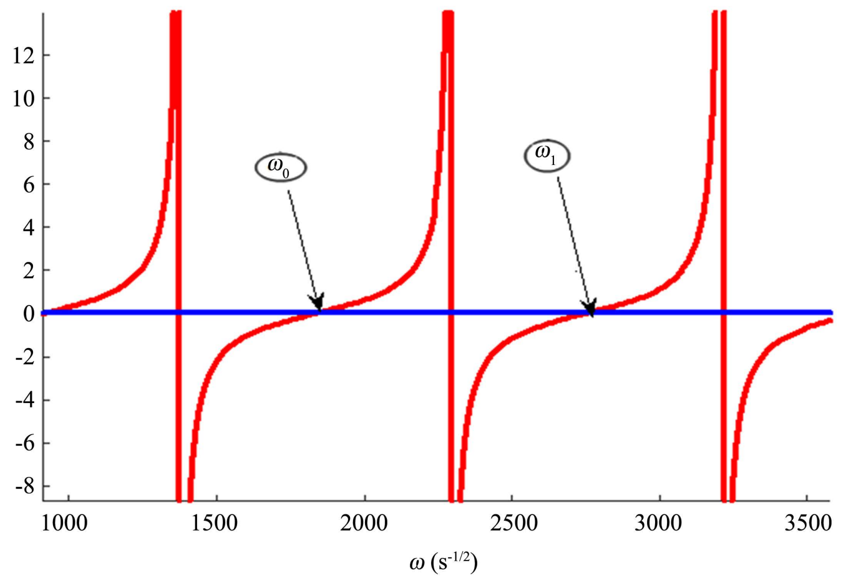

Figure 5. Graphical resolution of the transcendent equation for a Field B = 0 T for an open circuit mode of operation Sf = 10 cm/s; H = 0.02 cm; D = 26 cm^2/s.

Table 1. Table of eigenvalues ω_n and decay time constants $\tau_{c,n}$ for B = 0 T.

n	0	1	2	3	4
ω_n ($s^{-1/2}$)	700	1600	2400	3200	4000
$\tau_{c,n}$ (ns)	1694.9	375.93	170.64	96.70	62.10

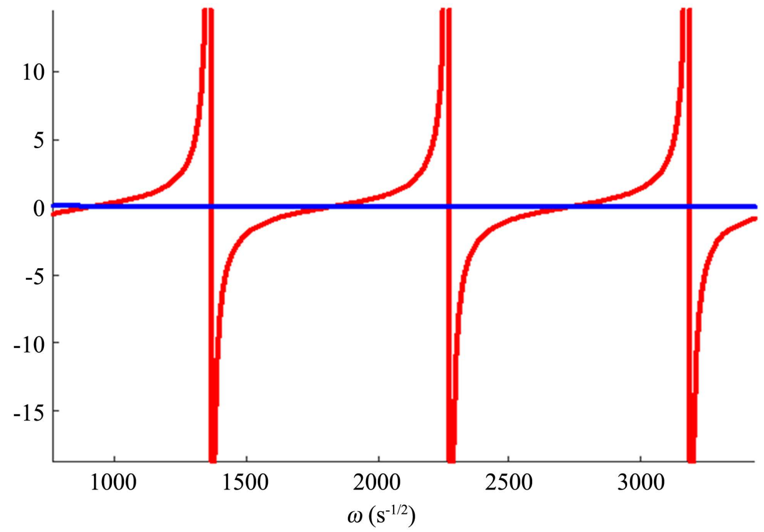

Figure 6. Graphical resolution of the transcendent equation for a Field $B = 0.0001$ T for an open circuit mode of operation $Sf = 10$ cm/s; $H = 0.02$ cm; $D = 26$ cm^2/s; *Sb*1.

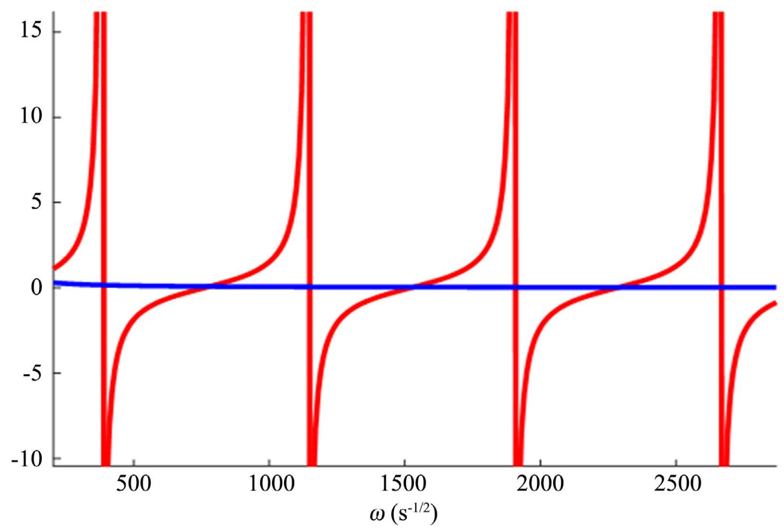

Figure 7. Graphical resolution of the transcendent equation for a Field $B = 0.0005$ T for an open circuit mode of operation $Sf = 10$ cm/s; $H = 0.02$ cm; $D = 26$ cm^2/s; *Sb*1.

Table 2. Table of eigenvalues ω_n and decay time constants $\tau_{c,n}$ for $B = 0.0001$ T.

n	0	1	2	3	4
ω_n (s$^{-1/2}$)	500	1300	2000	2600	3300
$\tau_{c,n}$ (ns)	2857.1	558.7	243.9	145.8	91.00

Table 3. Table of eigenvalues ω_n and decay time constants $\tau_{c,n}$ for $B = 0.0005$ T.

n	0	1	2	3	4
ω_n (s$^{-1/2}$)	400	900	1400	1900	2400
$\tau_{c,n}$ (ns)	3846.2	1098.9	485.4	269.54	170.64

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 ω_n increase and the decay constants decrease $\tau_{c,n}$ 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 also.

$n = 0$ corresponds to the fundamental mode of decay and $n \neq 0$ corresponds to the harmonic of order n. We will then write ω_n instead of ω and all the expressions where the eigenvalue appears will be endowed with this index *n*. For example: ω_1, ω_2 and ω_3.

Figures 7-9 represent the profiles of the densities of the minority carriers as a function of time for a magnetic field $B = 0$ T, $B = 0.0001$ T and $B = 0.0005$ T for the fundamental mode and the various harmonic states in the vicinity of the Circuit Open.

Table 4 gives the values of t_0 for different values of the magnetic field.

Figure 10 shows that as the magnetic field increases, the carrier density decreases and the transient decay are slower.

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 t_0. These figures also show that the density of the carriers decreases with time and after a time (to >1.8 μs), the densities of the modes other than the fundamental mode become negligible.

This results from the fact that 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 [51]. The increase in the magnetic field is

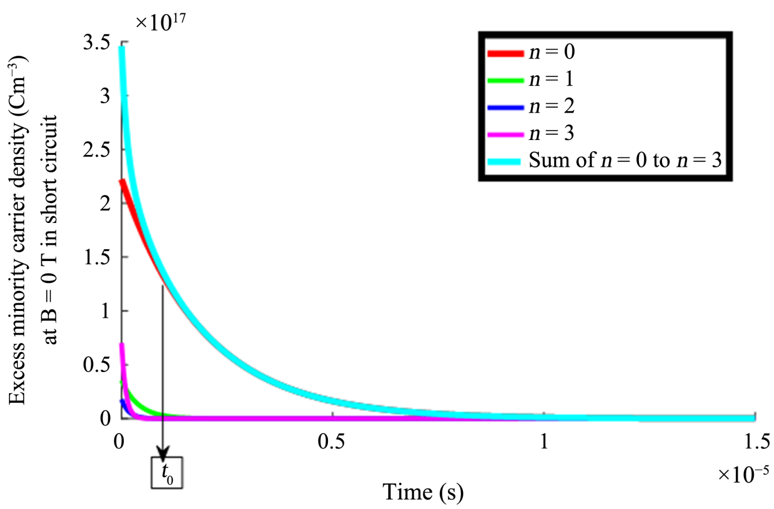

Figure 8. Open circuit solar cell minority carrier density profile for a magnetic field $B = 0$ T $Sf = 1 \times 10^1$ cm/s; $H = 0.02$ cm; $\tau = 1 \times 10^{-5}$ s; $\mu = 1350$ cm^2·V^{-1}·S^{-1}.

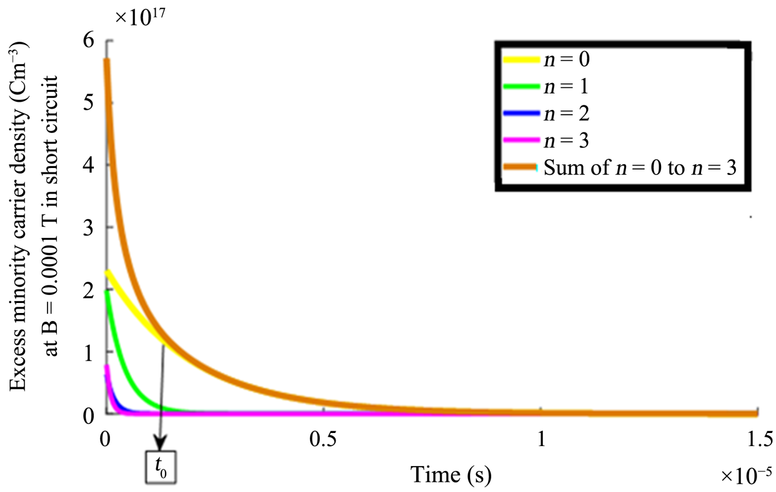

Figure 9. Open circuit solar cell minority carrier density profile for a magnetic field $B = 0.0001$ T $Sf = 1 \times 10^1$ cm/s; $H = 0.02$ cm; $\tau = 1 \times 10^{-5}$ s; $\mu = 1350$ $cm^2 \cdot V^{-1} \cdot S^{-1}$.

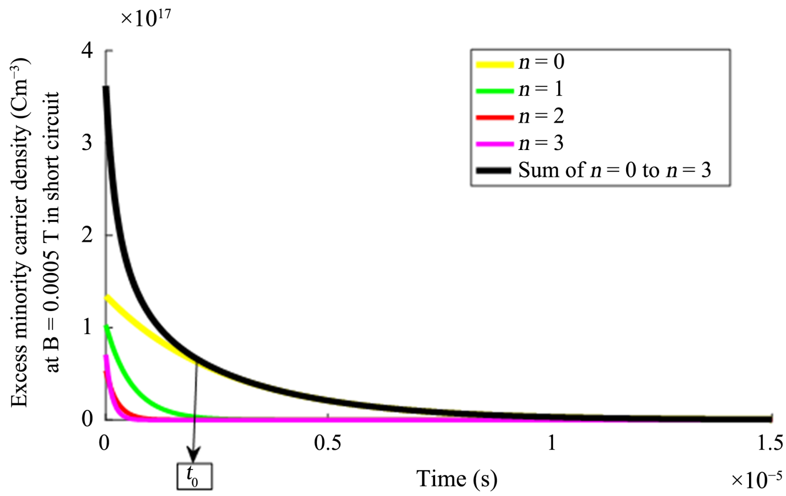

Figure 10. Open circuit solar cell minority carrier density profile for a magnetic field $B = 0.0005$T $Sf = 1 \times 10^1$ cm/s; $H = 0.02$ cm; $\tau = 1 \times 10^{-5}$ s; $\mu = 1350$ $cm^2 \cdot V^{-1} \cdot S^{-1}$.

Table 4. Magnetic field values for different time values.

B (T)	0	0.0001	0.0005
t_0 (µs)	0.12	0.14	0.18

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 [52].

6. Conclusion

This study of the transient regime obtained from a series of vertical junction silicon solar cells was carried out through the transient density of excess charge minority carriers in the base. The graphical resolution of the transcendent equation has been carried out. From this resolution, we obtained the eigenvalues and the decay time constants which are dependent on the magnetic field. Thus, the more the magnetic field increases, the more the eigenvalues decrease and this will have an impact on the transient decrease in the density of the carriers which will inevitably decrease because it depends on these eigenvalues.

Conflicts of Interest

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

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