

Study in Transient Regime of the Electrical Parameters of a Silicon Solar Cell with Multi Vertical Junctions Connected In Parallel and Placed In Short-Circuit: Influence of Temperature and Magnetic Field

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Abstract - A study of the effect of temperature and magnetic field on the electrical parameters of a parallel vertical junction solar cell, in transient dynamic regime operation, and under polychromatic illumination is presented. The transient voltage, the photocurrent density and the transient capacitance of the solar cell are deduced from the expression of the transient density of minority carriers of excess charges in the base. Indeed, the influence of the optimum temperature on the amplitudes and on the transient decrease of these electrical parameters is also studied. This optimum temperature is obtained by determining the optimum thickness of the solar cell from a given magnetic field. Indeed, as the temperature increases, there will be thermal agitation resulting in an accumulation of carriers at the junction and therefore a reduction in carrier mobility. If there is thermal agitation, the minority carriers will take longer to cross the junction. The stationary regime will therefore be reached late, hence t_0 increases with the increase in temperature. This work allowed us to observe that in the first moments of decay, the diffusion capacity is minimal, which leads to a rapid but brief drop in amplitudes because with a recombination velocity in short-circuit, a large number of Minority charge carriers in the base pass through the space charge region to participate in photocurrent generation.

Keywords: Solar Cell, Vertical Parallel Junction, Magnetic Field, Temperature, Time Constant, Base Thickness, Transient Voltage, Photocurrent and Transient Capacity

1. Introduction

The Silicon solar cells being under different technologies [1], present in different architectures, such as solar cells with vertical junctions (connected in series or parallel) where the illumination takes place parallel to the junction plane [2] and [3].

By taking into account certain physical mechanisms, modeling work [4], [5], [6], [7], [8], [9], [10] and [11] has been done for the search for geometric dimensions, thus leading to a better efficiency of the solar cell. Two types of vertical Multi Junction (MJV) silicon solar cells [12] and [13] have been developed: (n/p) cells connected in parallel to increase the electric current (MJVP) and (n/p) cells p/p+ connected in series to increase the electrical output voltage (MJVS).

These solar cells can be under different operating regimes, which are: the transient dynamic regime [14], [15], [16] and [17]. Under these operating regimes, the solar cell may be subject to external conditions, which may be: electromagnetic field variations [18], [19], [20], [21] and [22], temperature variations [23] and [24], etc...

In regards to the transient regime, we can note the influence of the magnetic field [25] and/or the temperature [26] on the transient decay and on the decay time of the minority charge carriers.

This study was done on a silicon solar cell (n/p) with vertical junctions connected in parallel under the double condition of temperature and magnetic field, and in operation of transient dynamic regime which occurs between two stable states from operating points dependent on two variable resistors. We examine the effects of the magnetic field [27] and [28], the temperature [29] and [30] and the optimal thickness [5] and [31] on the eigenvalues ω_n of the different harmonic states and on the time t_0 initiating the exponential decay and on the transient decay of electrical parameters.

2. Materials and Methods

2.1 Experimental Setup and Working Principle of the Transient Decay Occurring Between Two Steady State Operating Points

Figure 1 presents the experimental device used to obtain the transient state by variations of the operating point of the solar cell [16] and [17].

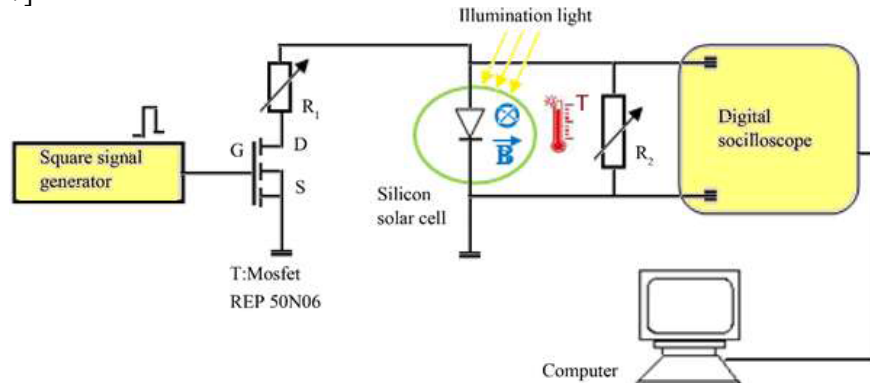


Figure 1: Experimental device for the characterization of the solar cell

This experimental device includes a square signal generator (BRI8500) which supplies an RFP50N06 type MOSFET transistor, two adjustable resistors R_1 and R_2 , a silicon solar cell placed under temperature and magnetic field which submitted to multi-spectral lighting, a digital oscilloscope, a microcomputer for signal acquisition and processing. The transient decay occurs according to the following procedure, described below.

At time $t < 0$ (figure 1), the solar cell being under constant multi-spectral illumination, the MOSFET transistor opened and the solar cell is closed in series with the resistor R_2 alone: this corresponds to the operating point F_2 in steady state [32] and [33] giving the potential V_2 . At $t = 0$ (figure 1), the closing of the MOSFET begins and after a very short time the MOSFET is completely closed, then the resistor R_1 is in parallel with R_2 . This corresponds to the operating point F_1 in steady state, so the voltage V_2 drops from V_2 to V_1 . 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 R_1 and R_2 , the steady state operating points F_1 and F_2 move over the I-V characteristic (Figure 2), to produce a transient state.

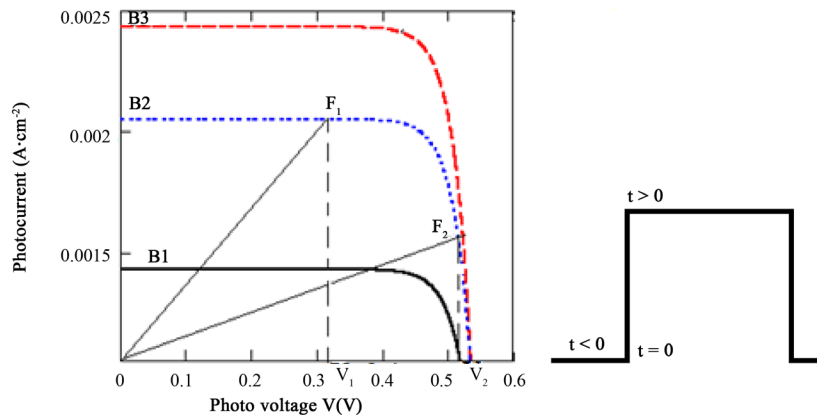


Figure 2: Illuminated I-V curve under constant magnetic field ($B_3 < B_2 < B_1$) with two specific operating points

2.2 Theory

In figure 3, the structure of the (n/p) silicon solar cell with vertical junctions connected in parallel under magnetic field and temperature is presented.

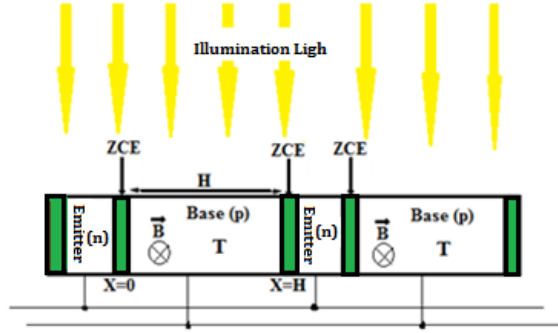


Figure 3: Structure of (n/p) solar cell with vertical vertical junctions connected in parallel

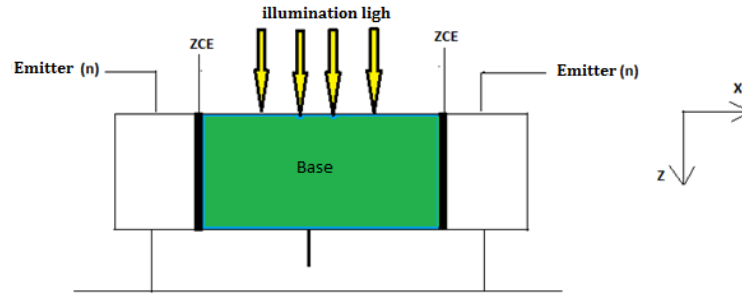


Figure 4: Structure of a junction (n/p) solar cell

The illumination was assumed to be uniform, such that the carrier generation rate depended only on depth (z) in the base and was expressed as:

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

The coefficients a_i and b_i are obtained through tabulated values of the radiation [34].

During the experiment, the level of illumination remains constant, which implies that the level of injection is not modified with respect to time. On the magneto-transport equation [20] and [36] in dynamic regime, related to excess charge carriers $\delta(x, t)$ [3] in the base at temperature (T) [23]:

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

The diffusion coefficient D^* of the minority carriers in the base under the influence of the temperature T and the applied magnetic field B , is given by the relationship [35] and [36]:

$$D^* = D^*(B, T) = \frac{D(T)}{1 + [\mu(T) \times B]^2} \quad (3)$$

B is the magnetic field in the base.

τ is the average lifetime of minority carriers in the base.

$\mu(T)$ is the mobility of excess minority carriers in the base [37].

$$\mu(T) = 1,43 \cdot 10^9 T^{2,42} \text{ cm}^2 \text{ V}^{-1} \text{ S}^{-1} \quad (4)$$

The diffusion coefficient of the minority carriers of charge in the base, dependent on the temperature $D(T)$ without magnetic field is given by the relation of Einstein-Smoluchowski:

$$D(T) = \mu(T) \cdot \frac{K_B \cdot T}{q} \quad (5)$$

Where K_B is the Boltzmann constant $K_B = 1.38 \cdot 10^{-23} \text{ m}^2 \text{ kg s}^{-2} \text{ K}^{-1}$ and q the elementary charge of the electron.

The equation is solved using the following boundary conditions:

- at the junction $x=0$:

$$D^* \cdot \frac{\partial \delta(x,t)}{\partial x} \Big|_{x=0} = S_f \cdot \delta(0,t) \quad (6)$$

- In the middle of the base:

$$D^* \cdot \frac{\partial \delta(x,t)}{\partial x} \Big|_{x=\frac{H}{2}} = 0 \quad (7)$$

S_f is the recombination velocity of the minority charge carriers at the junction [17], [38] and [39] and defines the operating point of the solar cell [32] and [33] on its I-V characteristic.

The system of equations (2), (6) and (7) constitutes a problem of Sturm Liouville [40] whose solutions are with separable variables of the type:

$$\delta(x, t) = X(x) \cdot T(t) \quad (8)$$

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

$X(x)$ and $T(t)$ take the following forms respectively:

$$X(x) = A_1 \cos\left(\frac{\omega x}{\sqrt{D^*}}\right) + A_2 \sin\left(\frac{\omega x}{\sqrt{D^*}}\right) \quad (9)$$

$$T(t) = T(0) \cdot \exp\left(-\left(\omega^2 + \frac{1}{\tau}\right)t\right) \quad (10)$$

$$\text{With } \frac{1}{\tau_c} = \frac{1}{\tau} + \omega^2 \quad (11), \text{ the decay time constant and where } \omega > 0.$$

The application of the boundary conditions (6) and (7) give respectively the relations (12) and (13):

$$\frac{\omega \sqrt{D^*}}{S_f} = \frac{A_1}{A_2} = \gamma \quad (12)$$

$$\tan\left(\frac{\omega H}{2\sqrt{D^*}}\right) = \frac{S_f}{\omega \sqrt{D^*}} \quad (13)$$

Equation (13) is a transcendental equation whose solutions are determined graphically.

$$\text{With: } \frac{\omega H}{2\sqrt{D^*}} \in \left[0, \frac{\pi}{2}\right] \cup \left(n - \frac{1}{2}\right)\pi; \left(n + \frac{1}{2}\right)\pi \left[\quad (14)$$

The first interval $\left[0, \frac{\pi}{2}\right]$ suit for $n=0$ and the second for $n > 0$. n is a natural number

When $n=0$, we have the first term $\delta_0(x, t)$ that corresponds to the fundamental state with the eigenvalue. And for $n > 0$, we have the different $\delta_n(x, t)$ harmonics of order n of eigenvalues .

A_1 and A_2 are calculated using the normalization conditions and the Fourier transformation.

The expression of $T_n(0)$ is calculated using the excess minority carrier density in the static regime.

The expression of $\delta(x, t)$ is therefore written:

$$\delta(x, z, t, T, B) = \sum \delta_n(x, z, t, T, B) = \sum X_n(x) \cdot T_n(z, T, B, 0) \cdot \exp\left(-\frac{1}{\tau_{c,n}}t\right) \quad (15)$$

The excess minority carriers density in the base is given by relation (16).

$$\delta(x, z, t, T, B) = \sum_n \delta_n(x, z, t, T, B) \quad (16)$$

$\tau_{c,n}$ is called decay time constant, its inverse can be written:

$$\frac{1}{\tau_{c,n}} = \frac{1}{\tau_0} + \omega_n^2 \quad (17)$$

After the graphical resolution of the transcendental equation 13, we put on the board the solutions of this equation corresponding to the eigenvalues of the different harmonic states. They are the points of intersection of the tangential part and the non-tangential part of this equation.

Table 1 Table of eigenvalues ω_n for different values of Top, Hop and B

T(K)	254.7	286.6	313	336.5	361.4	381.9	410	418.8
B(T)	0.0003	0.0004	0.0005	0.0006	0.0007	0.0008	0.0009	0.001
Hop (cm)	0.0161	0.0156	0.0153	0.0149	0.0147	0.0146	0.01445	0.0143
ω_0	3077	2944	2832	2774	2704	2619	2565	2517
ω_1	7306	4945	4752	4644	4519	4396	4301	4219
ω_2	9468	6973	6694	6536	6353	6171	6033	5926
ω_3	11650	9024	8651	8444	8206	7962	7786	7642

The transient decay of fundamental mode corresponds to $n = 0$ and that of others correspond to the different harmonics n (with $n \neq 0$).

We find that the eigenvalues ω_n of the different harmonics decrease with increases in the optimum temperature of the magnetic field and the optimum thickness.

3. Results and Discussion

3.1. Transient Voltage

The expression of the voltage collected at the terminals of the solar cell when it submitted to polychromatic illumination is obtained from the Boltzmann relationship; it is expresses in the form:

$$\delta_n(0, t) = n(0) \cdot \left\{ \exp\left(\frac{V(t)}{V_T}\right) - 1 \right\} \quad (18)$$

$V(t)$ is the Transient Voltage.

$$V(t) = V_T \cdot \ln\left(\frac{\delta_n(0, t)}{n(0)} + 1\right) \quad (19)$$

After resolution, the transient voltage becomes:

$$V(t) = q_0 \cdot Fc(\omega_0) \cdot \exp\left(-\frac{t}{\tau_{c,0}}\right) \quad (20) \quad \text{Avec} \quad Fc(\omega_0) = \frac{A_0 \cdot T_0(0)}{\delta(0,0)} \quad (21)$$

The following figures represent the evolution of the transient voltage as a function of (H_{opt}), of the magnetic field (B) and of (T_{opt}).

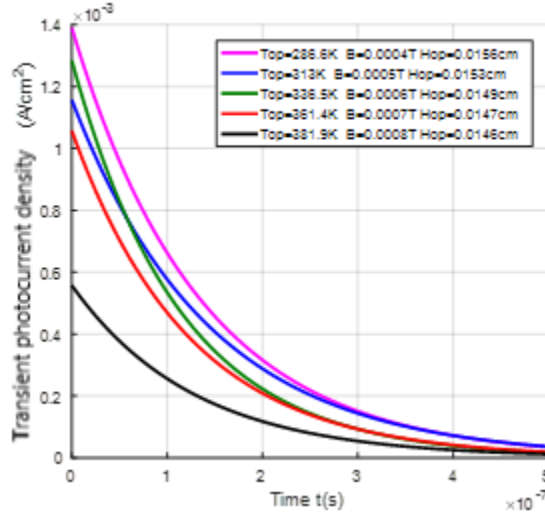


Figure 5: Transient voltage profile between two operating points for different temperature and magnetic field values $Sf=6.10^6$ cm/s; $\Delta V=0.01V$; $\tau=10^5s$; $z=0.017$ cm

Figure 5 shows that the transient voltage decreases in amplitude as the temperature and magnetic field increase respectively. In addition, thermal agitation increases the intrinsic carrier density at the junction, reducing the voltage and increasing the transient decay as the optimum temperature increases.

The voltage amplitude obtained in the vicinity of the short-circuit is much lower than that obtained in the vicinity of the open circuit. Since the velocity recombination at the junction in the vicinity of the short-circuit is greater than that of the open circuit, there will be fewer and fewer carriers near the junction, so the short-circuit voltage will be reduced as the velocity recombination at the junction increases.

3.2 Transient photocurrent density

The photocurrent is due to the diffusion of minority charge carriers at the junction. Knowing the expression for the minority carrier density, we can determine the expression for the photocurrent density using FICK's law.

$$J(t) = 2.D. \left. \frac{\partial \delta(x, z, t)}{\partial x} \right|_{x=0} \quad (22)$$

Figure 6 represents the profile of the transient photocurrent density as a function of time in the vicinity of the short circuit for different values of T_{opt} , H_{op} corresponding to a given magnetic field.

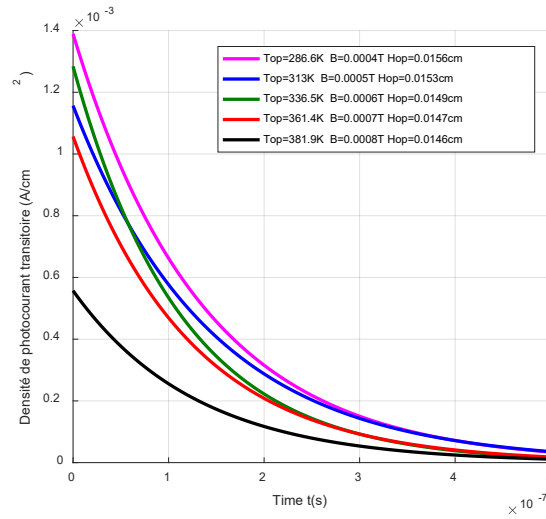


Figure 6: Transient photocurrent density profile for different temperature and magnetic field values; $Sf=6.10^6\text{cm/s}$; $\tau=10^5\text{s}$; $z=0.017\text{ cm}$

By studying the short-circuit photocurrent density profiles, the first instants of decay result in a rapid drop in the amplitude of the current intensity because they are dominated by the diffusion of minority charge carriers. This is followed by a period of slower decay, which is also linked to the recombination of minority carriers photogenerated in the base.

Indeed, the more the temperature increases, the more there is thermal agitation which widens the space charge zone [5]. As a result, with the very high velocity in short circuit recombination, a large number of carriers will be able to cross the junction to participate in the photocurrent so the stationary regime will therefore be reached late unlike the open circuit situation.

3.3 Transient capacity

The space charge region of a solar cell can be considered as a planar capacitor [7, 8] called the transition capacitance. This diffusion capacitance of the solar cell is considered to be the capacitance resulting from the variation in charge during the diffusion process within the solar cell [9, 10]. It is given by the relationship:

$$C(t) = \frac{dQ}{dV} \quad (23)$$

Q is the charge in the vicinity of the emitter-base junction:

$$Q = q \cdot \delta(x=0, z, t)$$

Taking into account the expression for the photovoltage and the density of minority carriers, we obtain the following expression:

$$C(t) = q \times \frac{\delta(0, z, t)}{V_T} + q \frac{n_i^2(T)}{N_B \cdot V_T} \quad (24)$$

The first term in the expression is the diffusion capacity of the solar cell at temperature T and magnetic field B under polychromatic illumination.

The second term in the expression is the capacitance under darkness: it depends on the nature of the material through the intrinsic concentration of minority n_i carriers, the doping of the material (NB), the temperature T and the Boltzmann constant (Kb) in the expression of the thermal voltage V_T .

Figure 7 represents the profile of the Transient Capacity in the vicinity of the short circuit as a function of Time for different values of the Top Temperature, the Hop thickness and the magnetic field.

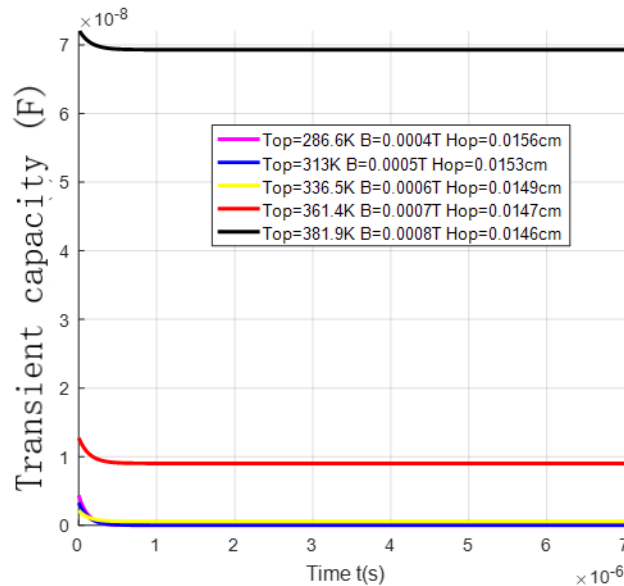


Figure 7: Transient photocurrent density profile for different temperature and magnetic field values; $S_f=6.106\text{cm/s}$; $\tau=10^5\text{s}$; $z=0.017\text{cm}$

We note in the first moments of decay that the diffusion capacity is minimal, which leads to a rapid but brief drop in amplitudes because with a high velocity of short-circuit recombination, a large number of minority charge carriers in the base crosses the space charge zone to participate in the generation of the photocurrent.

There follows a long period where the capacity tends towards the final stationary regime which is linked to the recombination phenomena of the minority carriers photogenerated in the base.

We also observe that the diffusion capacity decreases with increases in the optimum temperature of the magnetic field and the optimum thickness. Increasing the magnetic field leads to a disordered displacement of the carriers, which in turn increases the number of stored carriers. As a result, this minimal diffusion will lead to an increase in the amplitude of the transient capacity as the magnetic field increases.

4. Conclusion

This work allowed us to see the effect of temperature and magnetic field on the eigenvalues, on the transient decay of electrical parameters of a silicon solar cell with vertical junction in parallel placed in short-circuit, in transient operation. The graphical resolution of the transcendental equation has been carried out. It allowed us to find the eigenvalues, then to plot the profile of transient photovoltage, photocurrent density and transient capacitance which are deduced from the expression for the density of minority charge carriers. Under increasing magnetic field and temperature we have derived the following results:

- ✓ The transient voltage and photocurrent density tend rapidly towards stationary regime.
- ✓ The diffusion capacity of minority carriers decreases, leading to an increase in the amplitude of the transient capacity and a very brief decay.

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