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Research Article

Effect of temperature on transient decay induced by charge removal of a silicon solar cell under constant illumination

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Abstract The resolution of the transcendental equation connecting, junction and back surface recombination velocities (Sf, Sb), minority carrier diffusion coefficient (D) and base thickness (H) obtained from silicon solar cell transient decay, has shown theoretical and experimental limits.

This paper deals with transient study, that takes into account the temperature effect trough out, diffusion coefficient D(T) as function of temperature and both, junction and back surface recombination velocities respectively Sf(T) and Sb(T).

The time t_0(T) indicates the moment that fundamental mode predominates over the harmonics is shown.

Keywords Solar cell, Transient decay, Recombination parameters, Temperature

1. Introduction

Transient studies have been performed on semiconductor [1-2] and thermal [3] materials, for characterization. For solar cell characterization, many experimental methods were proposed, with optical [4-5] or electrical [6-7] pulse.

The optical excitations are monochromatic (laser) [8] or white illumination [9]. Constant excitation can be used as back ground and pulse excitation is superimposed, and yields small signal condition that avoids electric parameters influence on solar cell response, i.e. capacitance and resistance effects [10-13].

Some results of transient decay are obtained with solar cell operating under dark condition and submitted to electric excitation [14]. Then emitter contribution can be pointed [15].

Theoretical studies, using the excess minority carrier diffusion equation in the base, provides transient decay constant related to minority carrier lifetime (τ)[1].

Taking in to account the base back surface recombination (Sb) at coordinate x=H, while junction surface is located at x=0, transcendental equation involves variations in the transient decay constant measurement, for the two selected operating points i.e. short-circuit (Sc) and open circuit (Oc). These two cases lead respectively to junction surface recombination Sf taken as infinite for (Sc) and zero for (Oc) conditions [16-17]. Then these two cases give reduced transcendental equation which is govern only by the back surface recombination velocity (Sb), for a given diffusion coefficient (D) at room temperature (T=300K) and fixed doping rate (NB), for a base thickness (H).

The eigein values (ω_n) obtained lead to a series of exponential terms in the transient decay.[18] The fundamental (ω_0)is found to be predominant over the harmonics. The transient is then considered as one exponential decay term with (to) as origin of decay time. The signal turn off time is taken very short to avoid interference on the solar cell response. Many exponential terms have been performed [19] for transient decay modeling. Simultaneous determination of many parameters (τ, L, D, Sb) that are included in the theory was performed [20-21].

Geometrical parameters, in 3 D model [22] and non uniform illumination or shadowing effect [23] associated to solar cell grain size and grain recombination give different constant decay times. In the one dimensional studies, junction recombination is found as a sum with two terms, (Sfo) for intrinsic recombination [11, 24-25] and Sfj, which describes the collection rate of excess carrier throughout the junction to participate for the photocurrent. The suffix (j) indicates the operation point on the well-known I(Sfj)-V(Sfj) characteristic of illuminated solar cell, imposed by variable external load(Rj). Recombination (Sfo) and (Sb) were expressed and determined [25].

The transcendental equation then appears to be influenced by Sf, Sb, D for the electronic parameters and (H) for the geometrical one [11, 26].

Effect of magnetic field on constant diffusion was presented on photovoltage transient decay through eigein value variation [25-28]. Electronic parameters are also shown to be temperature dependent [29-31]. Then our work deals with an experimental study that points out temperature effect on the transient decay curves and deduces conditions of accurate measurement of the decay time constant.

2. Materials and Methods

2.1 Experimental Device

The experimental device (figure 1) includes a square signal generator (BRI8500) which pilots a MOSFET transistor type RFP50N06, two variables resistors R_1 and R_2, an illuminated silicon solar cell under temperature **T**, submitted to a constant multispectral illumination, a digital oscilloscope, and a microcomputer for registered data.

The solar cell is under constant multispectral illumination (Figure 1), and at time t < 0, the MOSFET is turned off and the solar cell is loaded only by resistor R2: this corresponds to operating point **F2** in steady state [32-35]. At t = 0 (Figure 1), MOSFET turning on and after a very short time (600-800ns) it is fully turned on so that resistor R2 is in parallel with R1 this correspond to operating point **F1**.

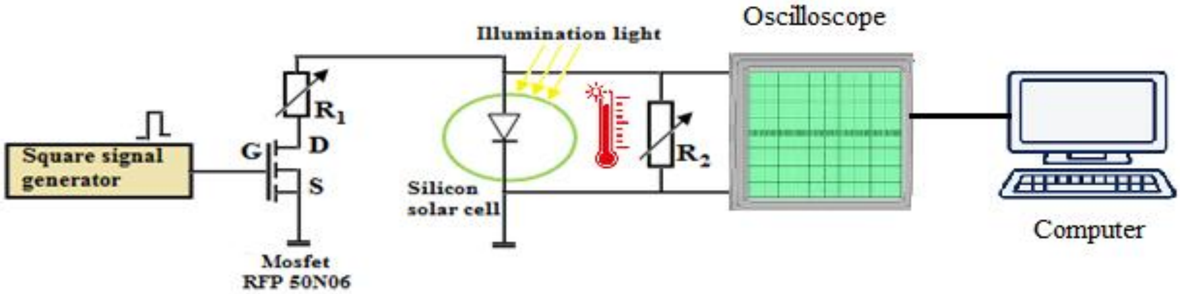

Figure 1: Experimental set up [36]

Figure 2 shows the I-V curve with two operating points.

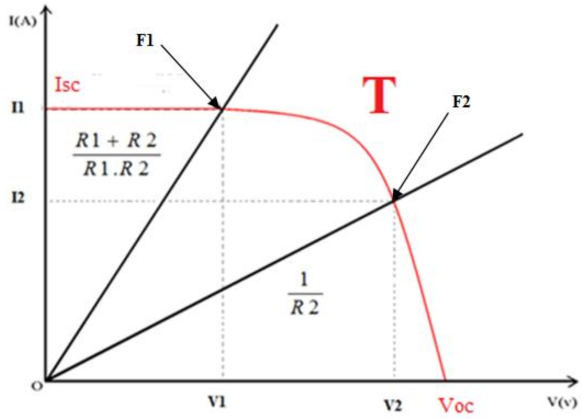

Figure 2: I-V curve with two specific operating points.

2.1 Theory

A schematic diagram of an illuminated silicon solar cell under a given temperature is presented in Figure 3.

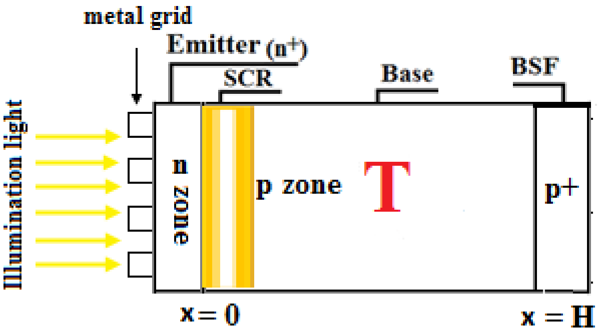

Figure 3: Illuminated silicon solar cell under temperature

The carrier generation rate depth (x) dependent is expressed as:

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

a_i and b_i are the overall tabulated coefficient of the solar radiation spectrum [36].

The contributions of the emitter and the space charge region were also neglected, we consider a low injection level and the analysis was limited to thickness H of the base region.

Hence, the transient excess minority carrier distribution δ(x,t) in the base is obtained by solving the one dimensional continuity equation:

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

The electron diffusion coefficient in the base for a given temperature **T** is given by the well-known Einstein relationship:

$$D(T) = \frac{Kb}{q}\,\mu(T) \tag{3}$$

Both the Diffusion length and the carrier mobility also depend on the temperature. They are then expressed respectively by the following equations [37]

$$(L(T))^2 = \tau . D(T) \tag{4}$$

$$\mu(T) = 1{,}43.10^9 T^{2{,}42} cm^2 V^{-1} s^{-1}; \tag{5}$$

τ is the electrons lifetime in the base. Equation (2) is resolved using boundary conditions

- At the junction[2], x = 0 :

$$D(T) \cdot \left.\frac{\partial \delta(x,t)}{\partial x}\right|_{X=0} = Sf \cdot \delta(0,t) = \frac{J(t)}{q} \tag{6}$$

- At the back side, x = H

$$D(T) \cdot \left.\frac{\partial \delta(x,t)}{\partial x}\right|_{x=H} = -Sb \cdot \delta(H,t) \tag{7}$$

J(t) is the well-known time dependent diffusion current of excess minority carrier trough the junction.

Sf is the excess minority carrier junction recombination velocity [38].

Sf is the sum of two terms sf0 and sfj.

Sf = Sf0 + Sfj; Sfj defines the operating point, it is imposed by the external load resistor and sf0 is the intrinsic recombination velocity.

Sb is the back surface recombination velocity of the excess minority carrier [4-7].

Equations (4) and (5) represent a STURM Liouville's equations system, of which solutions are in two separate variables spatial and temporal, X(x) and T(t) respectively.

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

X(x) and T(t) are given by the following general expressions:

$$X(x) = A\cdot\cos(\frac{x\cdot\omega}{\sqrt{D(T)}}) + B\cdot\sin(\frac{x\cdot\omega}{\sqrt{D(T)}}) \tag{9}$$

And

$$T(t) = T(0)\cdot\exp[-(\omega^2 + \tfrac{1}{\tau})\cdot t] \tag{10}$$

With: $\frac{1}{\tau_c} = \frac{1}{\tau} + \omega^2$, the decay time constant and where ω >0.

The boundary conditions give:

$$\gamma = \frac{\omega\sqrt{D(T)}}{Sf} = \frac{A}{B} \tag{11}$$

And we then obtain the following well-known transcendental equation [11,17] temperature dependant.

$$tg(\frac{H.\omega}{\sqrt{D(T)}}) = \frac{\omega\cdot\sqrt{D(T)}\left(Sf + Sb\right)}{D(T)\cdot\omega^2 - Sf\cdot Sb} \tag{12}$$

With:

$$\frac{\omega\cdot H}{\sqrt{D(T)}} \in \left[0, \frac{\pi}{2}\right[\cup \left](n - \tfrac{1}{2})\pi; (n + \frac{1}{2})\pi\right[\tag{13}$$

n is a natural number and; ω_0 is the eigen value of the fundamental decay mode and ω_n are the harmonic eigen values of n order decay mode, when n >0.

Hence, we can see that A and B have discrete values and were finally calculated by normalization and Fourier transform. Thus, the transient excess minority carrier density appears as the sum of infinite terms $\delta_n(x;t)$. It is expressed as follow:

$$\delta(x,t) = \sum_n \delta_n(x,t) \tag{14}$$

$\delta_n(x;t)$, is the contribution of n order to the transient excess minority carrier density.

When n is equal to zero, we have the first term, $\delta_0(x;t)$, corresponding to fundamental mode which is characterized by ω_0 and. $\delta_n(x;t)$ corresponds to harmonic of n order characterized by ω_n.

$\delta_n(x;t)$ is written as:

$$\delta_n(x,t) = X_n(x)T_n(0)\exp(-\frac{1}{\tau_{c,n}}t) \tag{15}$$

$\frac{1}{\tau_{c,n}} = \frac{1}{\tau} + \omega_n^2$ is discrete decay time constant for the harmonic n. (16)

Transcendental solution:

The right term of Equation 12 contains Sf and Sb obtained by solving the following equations [38].

$$\left(\frac{\partial J}{\partial Sf}\right)_{Sf \succ 10^5 cm.s^{-1}} = 0 \quad \text{And} \quad \left(\frac{\partial J}{\partial Sb}\right)_{Sb \prec 10^3 cm.s^{-1}} = 0 \tag{17}$$

leading respectivey to:

$$Sb = \sum_{i=1}^{3} \frac{D \cdot \left[sh(\frac{H}{L}) + b_i \cdot L \cdot \left(\exp(-b_i \cdot H) - ch(\frac{H}{L}) \right) \right]}{L \cdot \left[b_i \cdot L \cdot sh(\frac{H}{L}) + \exp(-b_i \cdot H) - ch(\frac{H}{L}) \right]} \qquad (18)$$

$$Sf = \sum_{i=1}^{3} \frac{D \cdot \left[b_i \cdot L - \exp(-b_i \cdot H) \cdot \left(sh(\frac{H}{L}) + b_i \cdot L \cdot ch(\frac{H}{L}) \right) \right]}{L \cdot \left[\exp(-b_i \cdot H) \cdot \left(ch(\frac{H}{L}) + b_i \cdot L \cdot sh(\frac{H}{L}) \right) - 1 \right]} \qquad (19)$$

Except geometrical and optical parameters, all these expressions depend on D (T) and hence their curves as a calibration function of temperature T are given in the diagram below (figure 4 and figure 5).

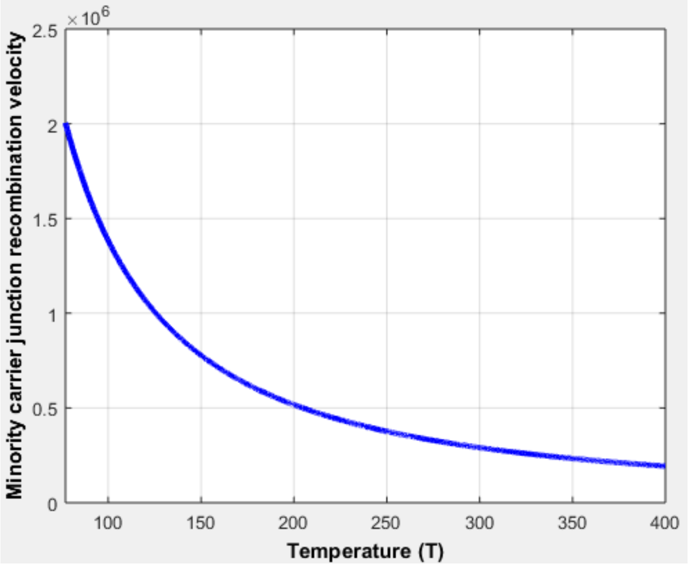

Figure 4: junction recombination velocity of the Minority carriers versus temperature T (K).
H = 200 µm, τ = 4,5 µs.

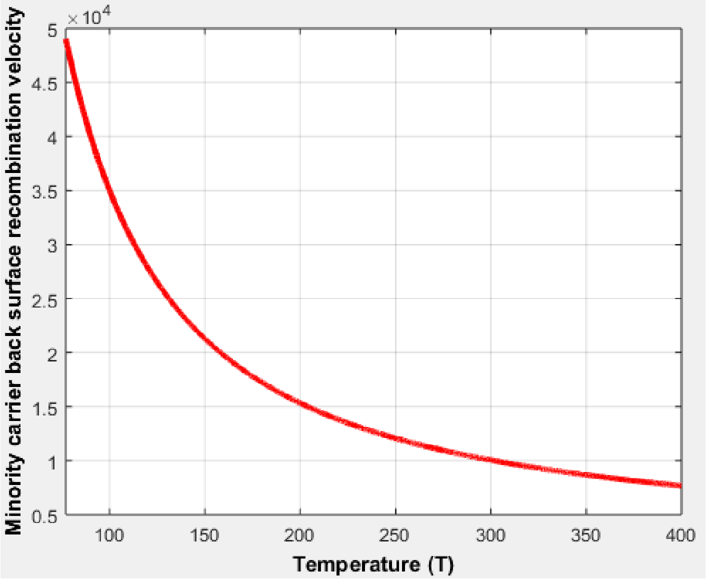

Figure 5: Back surface recombination velocity of the minority carriers versus temperature T (K).
H = 200 µm, τ = 4,5 µs.

Figures 4 and 5 show that recombination velocities Sf and Sb decrease with temperature T.
We present on figure 6, 7, 8 graphical resolution of transcendental equation (equation 12). We can observe temperature effects on the fundamental decay mode eigen value and on the harmonics.

Temperature T = 100K.

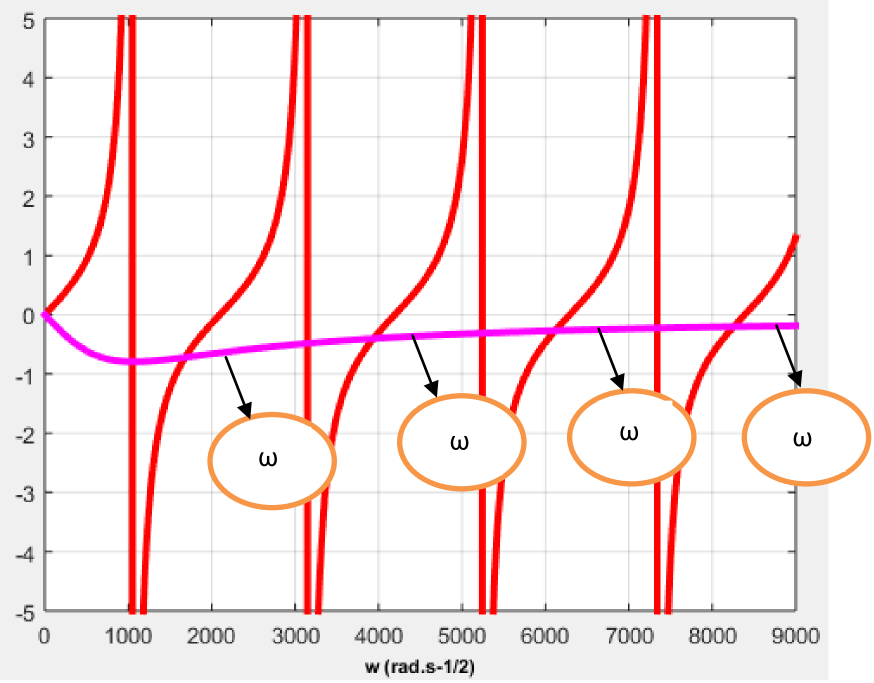

Figure 6**:** Graphical Resolution for T= 100 K.

Temperature T = 223 K.

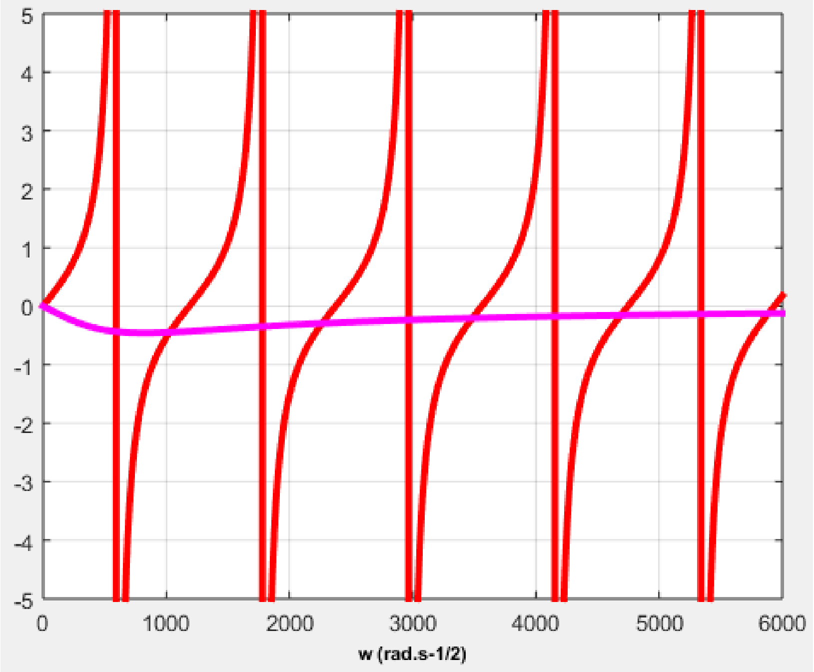

Figure 7**:** Graphical Resolution for T= 223 K

Temperature T = 323 K.

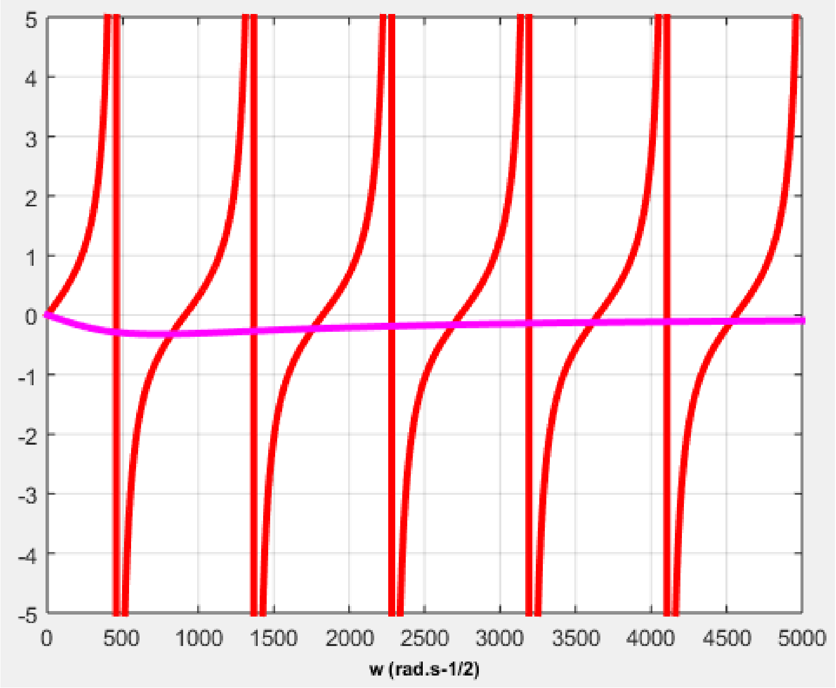

Figure 8: Graphical Resolution for T= 323 K.

We present on Tables 1, 2 and 3 ω_o and ω_n values for different temperatures:

Table 1: T=100 K

n	0	1	2	3
ω_n(rad.s$^{-1/2}$)	2927	5109	7249	9366
$\tau_{c,n}$ (ns)	113.4	37.94	18.94	11.36

Table 2: T= 223 K

n	0	1	2	3
ω_n(rad.s$^{-1/2}$)	1626	2681	4091	5229
$\tau_{c,n}$ (ns)	345.5	134	58.87	36.24

Table 3: T=323 K

n	0	1	2	3
ω_n(rad.s$^{-1/2}$)	1248	2207	3136	4067
$\tau_{c,n}$ (ns)	553.2	195	99.16	59.55

From the previous figures (6, 7, 8) and tables (1, 2, 3) we notice that, the fundamental decay mode eigenvalue ω_0 and the harmonics decay mode eigen values ω_n (n >0) decrease with temperature. The corresponding constant time increases with temperature T as well as surface recombination velocities.

3. Results and Discussion

3.1 Transient excess minority carrier density

For the simulated modeling analyses, the transient excess minority carrier density depends on temperature, minority carrier junction surface recombination velocity (Sf), back surface recombination velocity (Sb), harmonic of n order and time (t). The following figures 9, 10, and 11 plot the excess minority carrier density versus time for various values of temperature.

These figures show that the different terms of the series expansion decrease very fast and after a time t_0, the fundamental mode corresponding to n=0 predominates and is equal to the excess minority carriers $\delta\ (x,t)$ who can be written as:

$\delta\ (x, t > t0)\ =\ X\ (x).T\ (t > t0)$.

We note change in temperature affects the solar cell transient response. For increasing temperature, the carrier density amplitude increases.

The following table gives t_0 for various values of temperature .

Temperature T= 100 K

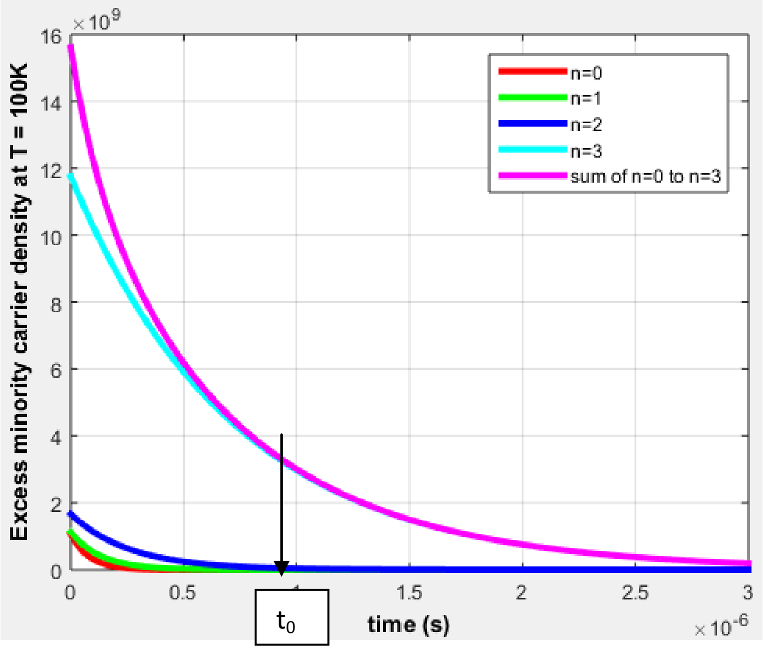

Figure 9: Excess minority carrier density versus time (s) for T = 100 K.
H = 200 µm, τ = 4,5 µs.

Temperature T= 223 K.

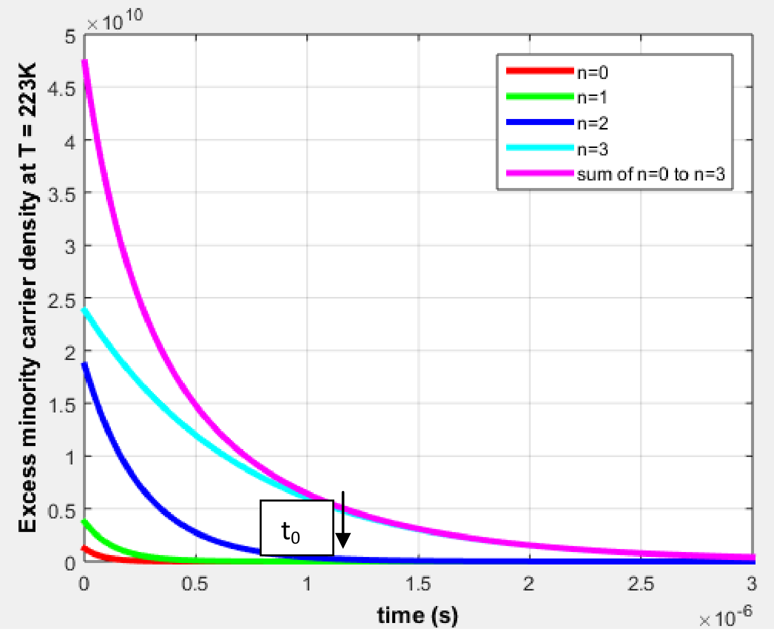

Figure 10: Excess minority carrier density versus time (s) for T = 223K
H = 200 µm, τ = 4,5 µs.

- **Temperature T= 323K**

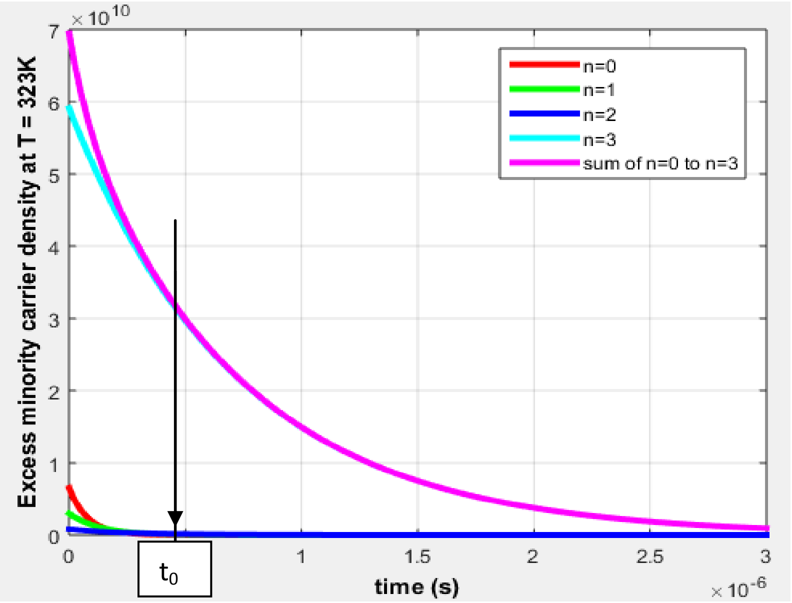

Figure 11: Excess minority carrier density versus time (s) for T = 323 K H = 200 µm, τ= 4,5 µs.

Table 4: t_0 for different values of temperature

T (K)	100	223	323	400
t0 (µs)	0.74	0.95	0.26	0.86

3.2 Transient photovoltage decay:

From excess minority carrier density and the carriers' charge gap (δQ) at the junction we can derive with Boltzmann's relation the transient photovoltage decay across the junction as:

$$V(t) = V_T * \ln\left[\frac{\delta(0,t)}{\delta Q}\right).\exp\left(\frac{\Delta V}{V_T}\right)] \quad (20)$$

$$\Delta V = V1 - V2 \quad (21)$$

With $V_T = \frac{kb*T}{q}$ is a variable thermal voltage (22),

$kb = 1.38 * 10^{-23}$ J.K^{-1} is the Boltzmann constant (23)

δQ is the gap of population charges at the junction [36].

Figures 12, 13, and 14 plot the transient photovoltage for various ΔV.

Temperature T = 100 K

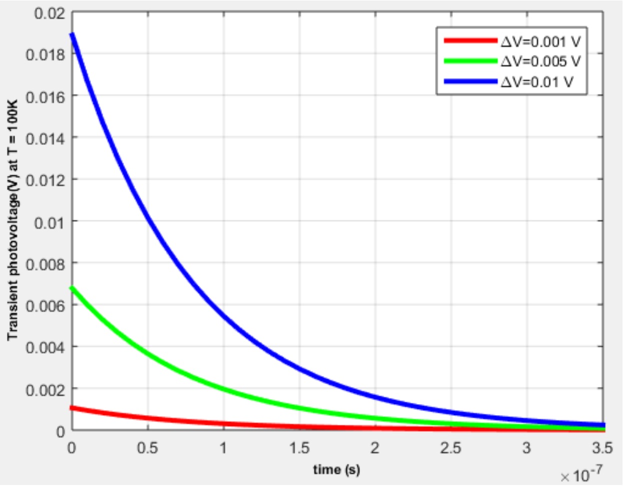

Figure 12: Profile of transient photovoltage for various ΔV. H=200µm, τ = 4.5 µs.

Temperature T = 223 K

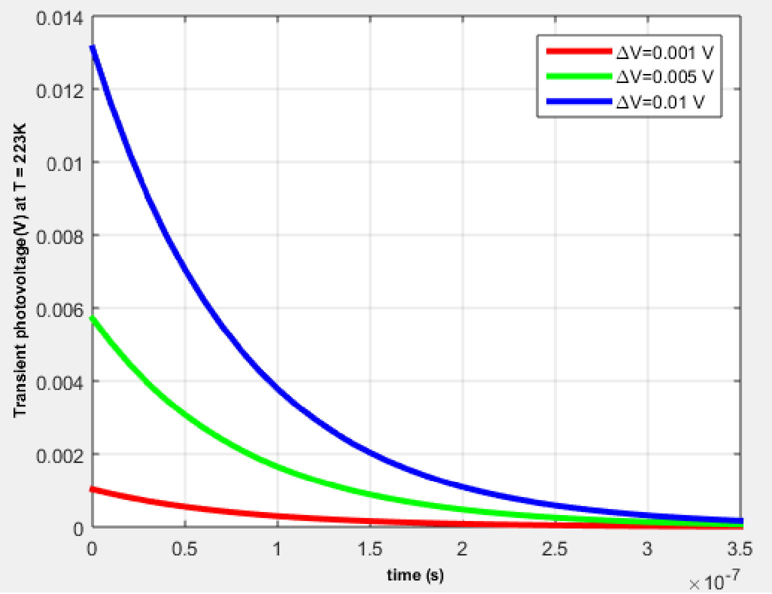

Figure 12: Profile of transient photovoltage for various ΔV H=200µm, τ = 4.5 µs.

Temperature T = 323 K

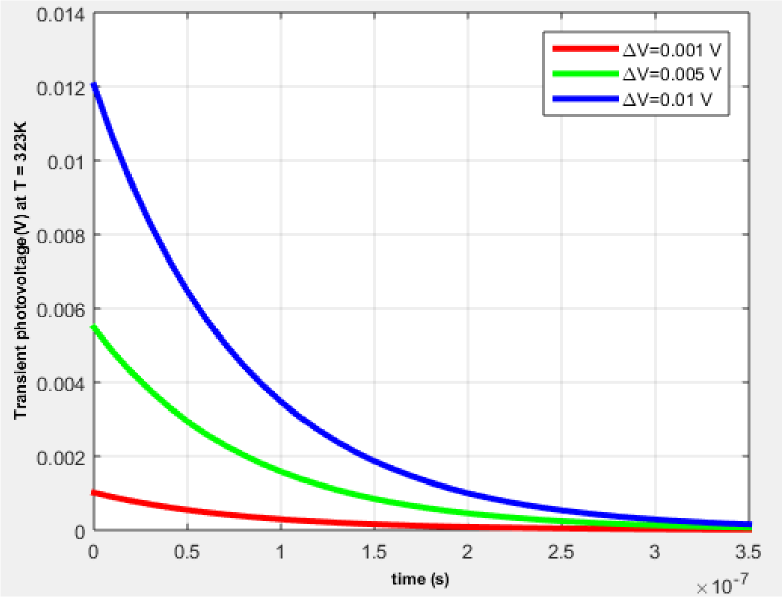

Figure13: Profile of transient photovoltage for various ΔV
H=200µm, τ = 4.5 µs.

We can observe in figures 11, 12 and 13 that transient voltage increases with the potential difference ΔV, this means that carriers are increasingly blocked at the junction.

4. Conclusion.

This study based on the influence of temperature on a silicon solar cell under illumination gives with the help of the continuity equation a new transcendental equation depending on temperature. We have shown in this work the impact of temperature on solar cell transient photovoltage response.

Thus, we have shown that from a graphical resolution, we obtain different eigen values for various temperatures. The study showed also that at a time t_0, the fundamental mode corresponding to n = 0 prevails over harmonics and density will be only considered as fundamental mode, with a decay time constant temperature dependent. It is important to note that t_0 change with temperature.

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