Effects of the Average Temperature on the Photocurrent Density of Inorganic Solar Cells Based on Silicon in the Presence of Excitons

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Abstract Exciton dissociation in solar cells, based on inorganic materials, is easily done under the effect of the electric field. They exhibit strong photovoltaic properties, in particular the generation of quantum efficiency of the charge carriers. The electron continuity equations and exciton coupled, governing generation-recombination mechanisms and dissemination after a monochromatic illumination from the front side and a thermal insulation from the back side of the cell and the heat equation were resolved by a numerical approach based on the finite volume method.

These mechanisms are analyzed through the profile of the total photocurrent density, calculated for different values of the average temperature.

The effects of the heating factor, the number of Fourier and the surface conversion velocity on the total photocurrent density were analyzed.

In the end, a comparison between the total photocurrent densities, calculated as functions of these two forms coupling coefficients volume fixed and different in the base, was also proposed. This study allowed us to achieve our objective, namely the development of a numerical model applicable to inorganic solar cells.

Keywords: Excitons, Average temperature, Factor heater, Number of Fourier, photocurrent.

I INTRODUCTION

The conversion of solar energy into electrical energy is a necessary and effective process that can deal with any imbalances between supply and strong demand. Solar cells, based on inorganic materials have been greatly improved and researchers still continue their improvement to meet this need.

The absorption of photons by the cell, generates free charge carriers which form a current under the effect of an applied electric field. It also generates excitons which dissociate into electron-hole pairs.

In order to increase efficiency and reduce the cost of manufacturing solar cells, researchers are still oriented inorganic solar cells based on silicon. Some authors like Mr. Burgelman and B. Minnaer [2] developed a numerical model applicable to organic solar cells in the presence of excitons. Others like S. Zh. Karazhanov [3] has developed an analytical model in the space charge layer of the solar cells in the presence of excitons in the light of the temperature and the doping level.

The objective of our study is to develop a numerical model applicable to inorganic solar cells in the presence of excitons for different values of the average temperature. We performed by considering a solar cell subjected monochromatic illumination from the front side and a thermal insulation from the back side by taking into account inclusion of the space charge layer and the non-uniformity of the dissociation and recombination of excitons in this zone. This model is governed systems of equations coupled non-linear partial derivatives which we do not know the analytical solutions in general. That is why our choices have been focused on the mathematical and numerical models. The equations of continuous domain are integrated by the control volume method and the coefficients of algebraic systems are approached by the scheme of Patankar. Finally, we solve them by using an iterative relaxation line by line type Gauss Siedel.

II POSITION OF THE PROBLEM AND MATHEMATICAL FORMULATION

A) Physical Position of the problem and Assumptions

We will consider a semiconductor of length L (Figure 1), a one-dimensional character, the non-uniform doped regions. They are conductive. The electric field in the space charge layer is not negligible. We recognize that this electric field in the space charge layer is a linear function of the abscissa z that can be expressed in the form

$$E(z)=\frac{E_m}{w}(w-z) \quad \text{and} \quad b(z)=b[E(z)] \quad \text{in} \quad (0\le z\le w)$$

We have also taken into account the absorption due to electron-hole pairs as $f_e + f_x = 1$. With f_e is the fraction of electrons and is the excitons. We consider for an inorganic solar cell and $f_e = 1$ and $f_x = 0$ [2].

The majority carriers are not affected and regarding the minority carriers, their distributions are governed by the continuity equations.

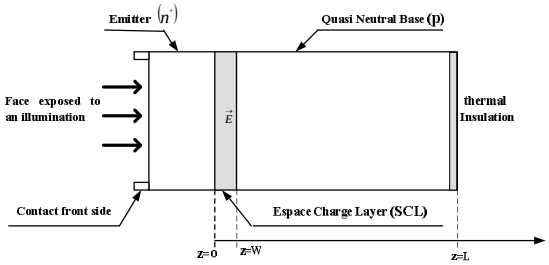

Figure 1: Structure of a solar cell silicon n + p

In addition we assume faces $z = 0$ and $z = L$ are the site of recombination events in volume and surface.

The electron diffusion coefficients and excitons are functions of some variables, particularly the temperature of the material. They are given by the Einstein relation [11].

B) Mathematical formulation

Considering the modeling assumptions above and the following reference physical quantities D_T^* (concentration for carriers), $\Delta T_r = \frac{q_m \times L}{\lambda}$ (for the temperature difference), L and W (for the spatial variables z), G_r (generation rate of carriers and that of excitons), the non-dimensional equations for the coupled system and the heat become:

$$F_{e0}\frac{\partial}{\partial z^*}\left\{D_T^*\frac{\partial n_e^*}{\partial z^*}\right\}+A\frac{\partial}{\partial z^*}\left\{n_e^*\left(w^*-z^*\right)\right\}=\frac{n_e^*n_h^*-n_{in}^{*2}}{n_e^*+n_h^*+2n_{in}^*}+$$
$$B_e\left(n_e^*n_h^*-n_x^*n_1^*\right)-C_e f_e G^* \qquad (1a)$$

$$F_{x0}\frac{\partial}{\partial z^*}\left\{R_\mu D_T^*\frac{\partial n_x^*}{\partial z^*}\right\}=\left(n_x^*-n_{x0}^*\right)-B_x\left(n_e^*n_h^*-n_x^*n_1^*\right)-C_x(1-f_e)G^* \qquad (1b)$$

$$\frac{\partial T^*}{\partial z^*}=\frac{\partial^2 T^*}{\partial z^{*2}} \qquad (2)$$

With

$$z^*=\frac{z}{L},\quad z^*=\frac{w}{L},\quad n_e^*=\frac{n_e}{C_r},\quad n_h^*=\frac{n_h}{C_r},$$
$$n_x^*=\frac{n_x}{C_r},\ n_{in}^*=\frac{n_{in}}{C_r},$$

$$G^*=\frac{G_{eh}}{G_r},\qquad G^*=\frac{G_x}{G_r},\qquad t^*=\frac{a}{L^2}t,$$
$$T^*=\frac{T-T_a}{\Delta T_r}$$

The amount D^0 is the electron diffusion coefficient calculated from the ambient temperature T_a considered constant. The " coefficient of diffusion " dimensionless D_T^* expressed as:

$$D_T^*=1+\frac{\Delta T_r^*}{T_a}T^* \qquad (3)$$

It is therefore a function of the dimensionless temperature. The amount is called heat factor. To complete the system of equations (1) and (2) in the interval [0,1], we associate the initial conditions and boundary conditions dimensionless following:

For the electrons

$$\begin{cases} z^*=0 \ \Rightarrow\ n_e^*(0)=N_D^* \\ z^*=1 \ \Rightarrow\ A_{Le}\frac{\partial}{\partial z^*}\left\{D_T^*n_e^*\right\}_{z=1}=-\left[n_e^*(1)-n_{e0}^*\right]+B_{Le}\left[n_x^*(1)-n_{x1}^*\right] \end{cases} \qquad (4a)$$

For the excitons

$$\begin{cases} z^*=0 \ \Rightarrow\ A_{0x}\frac{\partial}{\partial z^*}\left\{R_\mu D_T^*n_x^*\right\}_{z=0}=\left[n_x^*(0)-n_{x0}^*\right]-B_{0x}\left[n_x^*(0)-n_{x1}^*\right] \\ z^*=1 \ \Rightarrow\ A_{Lx}\frac{\partial}{\partial z^*}\left\{R_\mu D_T^*n_x^*\right\}_{z=1}=-\left[n_x^*(1)-n_{x0}^*\right]-B_{Lx}\left[n_x^*(1)-n_{x1}^*\right] \end{cases} \qquad (4b)$$

For the temperature

$$\begin{cases} t^*=0 \ \Rightarrow\ T^*\left(z^*,0\right)=0 \\ z^*=0 \ \Rightarrow\ \frac{\partial T^*}{\partial z^*}=-g\left(t^*\right) \\ z^*=1 \ \Rightarrow\ \frac{\partial T^*}{\partial z^*}=0 \end{cases} \qquad (4c)$$

III NUMERICAL PROCEDURE

The three differential partial differential equations are solved by the finite volume method.

It is to discretize the computational domain into a number of finite volumes called volume controls (V_c) in which the transport equations are integrated [5].

First we will approach the continuous segment [0, 1] in a series of i_m points (nodes) of x-rated z_i. As different parts of our zone (the space charge layer and the base) are not the same size and are the site of physical phenomena of very different natures should be used a variable mesh. Distributions of electrons and excitons are very sensitive to a fine mesh surface phenomena in the vicinity of $z = 0$ and $z = 1$ is adopted [5].

The discretization of the equations and the boundary conditions, Systems solving method of nonlinear equations obtained and the different steps of the algorithm are already developed, specified and explained in [5].

IV RESULTS AND DISCUSSION

To validate our code, we Compared our results with Those of S. Zh. Karazhanov [3].

The results from the mathematical and numerical modeling of various phenomena are summarized by considering the representation below.

We essentially present the influences of the surface conversion veloccity, of the heating factor and the number of Fourier on the total photocurrent density of electrons and excitons in the junction.

The tests we conducted showed that no time $\delta t^* = 10^{-3}$, the index that tracks the position of the load zone space interface / base $i_w = 81$, the number of nodes $i_m = 201$ the allowable error $\varepsilon = 10^{-3}$ and the relaxation parameter $w = 0.15$; are good compromise between an acceptable amount of calculation and a reasonable calculation time. The volumetric coefficient of coupling which depends on the mean temperature is given by $bv = \left(10^{-2} \times T_{moy}^{-2} + 2.5 \times 10^{-6} \times T_{moy}^{-0.5} + 1.5 \times 10^{-7}\right)$ [2]. With T_{moy} the average temperature.

In this section, we will study the effects of the heating factor, the number of Fourier, the surface conversion velocity and the wavelength of the total photocurrent density of electrons and excitons in function of the average temperature.
Assuming a negligible electric field polarization in the base, the total photocurrent density of electrons and excitons that are given by the gradient of the carriers of electrons and excitons in the junction.

The photocurrent density of electrons at the interface is defined by:

$$J_e = q \times j_e \qquad (5)$$

With

$$j_e = J_r \times J_e^* \ , \ J_r = \frac{D_o \times C_r}{L} \quad et \quad J_e^* = D_T^* \frac{\partial n_e^*}{\partial z^*}\bigg|_{z=1}$$

The photocurrent density of excitons at the junction is defined in the presence of a gradient of concentration:

$$J_x = q \times R_\mu \times J_r \times J_x^* \qquad (6)$$

With $J_x^* = D_T^* \frac{\partial n_x^*}{\partial z^*}\bigg|_{z=1}$

The total photocurrent density of the solar cell is equal to the sum between the electron photocurrent density and the excitons to a monochromatic light from the front:

$$J = J_e + J_x \qquad (7)$$

A) Total photocurrent density as a function of the average temperature at the junction: with bv high in the base

Figure 3 shows the evolution of the total photocurrent density function of the average temperature to a high coupling coefficient in the space charge layer and the base.

1) Influence of the heating factor

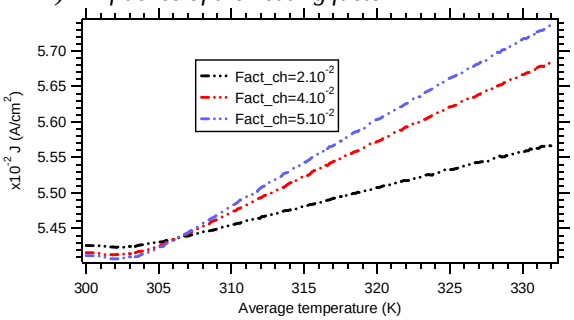

Figure 3a: Influence of the heating factor on the variation of the total photocurrent density of the charge carriers in function of the average temperature
$N_A=10^{16}$ cm^{-3} ; $N_D=10^{19}$ cm^{-3} ; $n_i=1.45\ 10^{10}$ cm^{-3} ; n_mott=1.0310^{18} cm^{-3} ; bs=10^{-2} cm s^{-1} ; **λ**=400 nm ; Se= Sx =10 cm s^{-1} ; Fo=10.

2) Influence of the number of Fourier

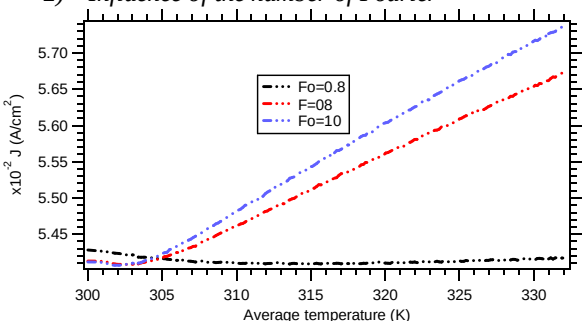

Figure 3b: Influence of the number of Fourier on the variation of the total photocurrent density of charge carriers as a function of the average temperature
bs=10^{-2} cm s^{-1} ; Fact_ch=5.10^{-2}. The other parameters are as in figure 3a

3) Influence of the surface conversion veloccity

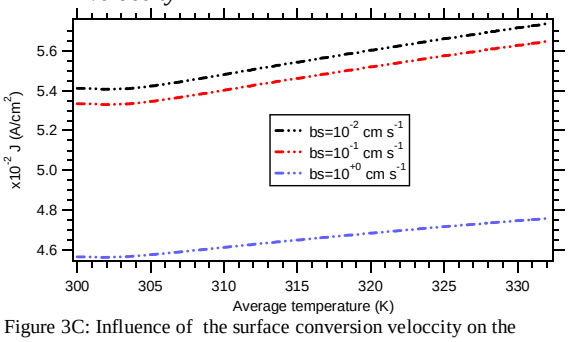

Figure 3C: Influence of the surface conversion veloccity on the variation of the total photocurrent density of charged carriers as a function of the average temperature
Fact_ch=5.10^{-2} ; Fo=10. The other parameters are as in figure 3a

The curves in Figure 3 show that the effects of the heating factor and the number of Fourier on the variation of the total photocurrent density are synonymous. These effects are respectively on the

positive variation of the total photocurrent density. However, we note some of those special heater factor and Fourier number to a lower average temperature of at least 305K and even see the other settings. In this interval total photocurrent density decreases with the increase of these various parameters. This last remark is primarily due to a lower charge accumulation rate and then at a low field exciton dissociation. As soon as the excitement level is reached the photocouant density increases. The heating factor increases the number of carriers and the number photocrés Fourier decreases recombination thereof where the positive effects on the photocurrent density. While in the face under illumination, low and medium of the surface conversion veloccity reduces total photocurrent density due to a low conversion of the exciton into free electrons.

B) Total photocurrent density as a function of the average temperature at the junction: with bv low in the database

Figure 4 shows the evolution of total photocurrent density function of the average temperature for a strong coupling coefficient in the space charge region and weak in the database.

1) Influence of the heating factor

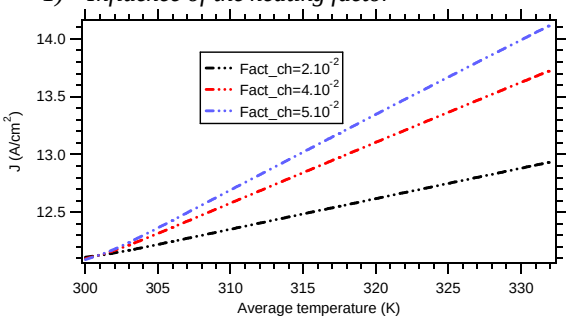

Figure 4a: Influence of the heating factor on the variation of the total photocurrent density of the charge carriers in function of the average temperature
bs=10^{-2} cm s^{-1} ; Fo=10. The other parameters are as in figure 3a

2) Influence of the number of Fourier

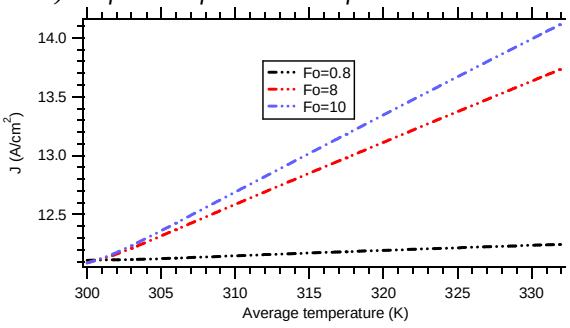

Figure 4b: Influence of the number of Fourier varying the total photocurrent density of the charge carriers in function of the average temperature
bs=10^{-2} cm s^{-1} ; Fact_ch=5.10^{-2}. The other parameters are as in figure 3a

3) Influence of the surface conversion velocity

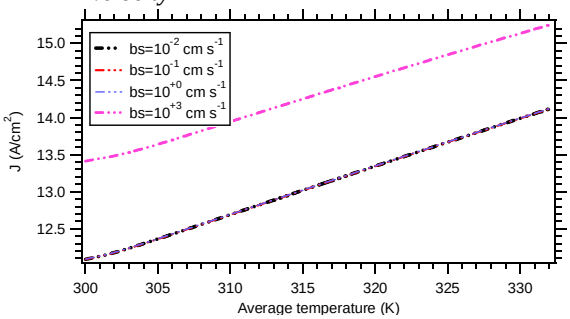

Figure 4c: Influence of the rate of conversion on the variation of the total photocurrent density of charge carriers as a function of the average temperature
Fact_ch=5.10^{-2} ; Fo=10. The other parameters are as in figure 3a

The low volume coupling in the base, the values recorded in the total photocurrent density are higher than those obtained in the strong coupling. In this case the low volume coupling coefficient in the database, we note an absence of stimulation threshold compared to the average temperature. At 300K, we already have a high rate charge accumulation and the average temperature we have a sufficient number of dissociated excitons. In addition, all parameters have positive effects on the variation of photocouant including excitons of the surface conversion veloccity. The low volume coupling of electrons and excitons in the basic foster participation of the charge carriers to the photocurrent density.

V NOMENCLATURE

Latin Letters:

a	thermal diffusivity [$cm^2 s^{-1}$]
C	Density equivalent status [m^{-3} or cm^{-3}]
D	diffusion coefficient [$cm^2 s^{-1}$]
E	Electric field [V m^{-1}]
Fact_ch	Factor heated
Fo	Relationship between time diffusion and convection
G	generation rate [N cm^{-3} s^{-1}]
K	Boltzmann constant [J K^{-1}]
L	The diffusion length [cm]
n	Concentration of carriers, [m^{-3} or cm^{-3}]
q	Electric charge [C]
R	Rate of exciton recombination of electrons [$cm^{-3}s^{-1}$]
S	Speed of recombination [cm s^{-1}]
t	time [s]
T	Temperature dimensional [K]
U	recombination rate [cm^{-3} s^{-1}]
W	width of the depletion zone [cm]

Greek symbols:

α	absorption coefficient μm^{-1}]
λ	wavelength of the light source [μm]
μ	mobility of electrons and excitons [cm^2 v^{-1} s^{-1}]

ρ	Average density of the semiconductor, [kg m^{-3}]
τ	lifetime of electrons and excitons [s]

Indices Exhibitor:

A	acceptor
D	donor
e	on the electron
x	relative to the exciton
h	relative to the hole
in	intrinsic
m	average
o	at equilibrium
i	th component
(*)	Related to the dimensionless variables
(°)	Relative to a constant

Dimensionless numbers characteristics:

$F_0 = \frac{\tau \times D^0}{L^2}$ Relationship between the broadcasting time and life

$Fact\_ch = \frac{\Delta T_r}{T_a}$ Relationship between heat flux imposed and conduction

$R_\mu = \frac{\mu_x}{\mu_e}$ relationship between the mobility of excitons and electrons

VI CONCLUSION

The numerical study of the average temperature effect on the total photocurrent density short circuit was made with two types of volume coupling coefficients fixed in the base. The finite volume method was used to discretize the equations of transport of the charge carriers in permanant regime and that of the heat and Thomas algorithm for resolution.

The computer code that we developed was validated by the results of work in the literature.

It is clear from our study that the heating factor and the number of Fourier have positive effects on the total photocurrent density of the charge carriers. While the surface conversion veloccity has a negative effect on the latter in the case of strong coupling in the base.

It also appears from our work a very interesting comparative study between the total photocurrent densities obtained with two forms of volume coupling coefficient in the base. Finally, to have a high density of total photocurrent our numerical model can be achieved with a form of the strong coupling coefficient that depends on the average temperature in the space charge layer and another form of weak coupling coefficient fixed in the base.

APPENDIX

$$A = \frac{\mu_e \tau_e E_m}{w} \; ; \; A_{eL} = \frac{D^0}{LS_e} \; ; \; A_{xL} = \frac{D^0}{LS_x} \; ; \; A_{0x} = \frac{D^0}{LS_{0x}}$$

$$B_{eL} = \frac{b_s}{S_e} \; ; \; B_{xL} = \frac{b_s}{S_x} \; ; \; B_{0x} = \frac{b_s}{S_{0x}}$$

$$B_e = \tau_e b C_r \; ; \; B_x = \tau_x b C_r$$

$$C_e = \frac{\tau_e G_r}{C_r} \; ; \; C_x = \frac{\tau_x G_r}{C_r}$$

$$G_{eh} = G_{eho} \exp(-\alpha z) \; ; \; G_x = G_{xo} \exp(-\alpha z)$$

$$G_{eho} = f_e \alpha(\lambda) N(\lambda) \; ; \; G_{xo} = f_x \alpha(\lambda) N(\lambda)$$

$$N(\lambda) = 5.03110^{+18} \lambda P(\lambda)$$

$$\alpha(\lambda) = 0.526367 - 1.14425/\lambda + 0.585368/\lambda^2 + 0.039958/\lambda^3$$

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