ISSN: 2277-9655
Scientific Journal Impact Factor: 3.449
(ISRA), Impact Factor: 2.114

IJESRT

INTERNATIONAL JOURNAL OF ENGINEERING SCIENCES & RESEARCH TECHNOLOGY

EFFECT OF EXCITONS ON THE EXTERNAL QUANTUM EFFICIENCY OF THE INORGANIC SOLAR CELLS BASED ON SILICON

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ABSTRACT

Exciton dissociation in solar cells, based on inorganic materials, is easily done under the effect of the electric field and the average temperature. Our study is oriented inorganic solar cells because of their high photovoltaic properties, in particular the charge carriers generating the quantum efficiency. The electron continuity equations and exciton coupled, governing generation-recombination mechanisms and diffusion after a monochromatic illumination from the front face and a thermal insulation from the back face 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 external quantum efficiency, calculated for different values of the absorption coefficient.

The effects of the heating factor, the volume coupling coefficient and the surface conversion velocity on the external quantum efficiency were analyzed.

KEYWORDS: Average temperature, heating factor, coupling, quantum efficiency, excitons.

INTRODUCTION

Time Technology rang. She needs energy to form a complete circle, very useful for example to the researcher. This example is one of many showing that the energy requirements increase from day to day. To fill this gap, we think of solar energy. Its conversion into electrical energy is an important potential. Indeed, the amount of energy from the sun is immense. It can deal with any imbalances between supply and strong demand. The efficiency of solar cells, based on inorganic materials have been greatly improved and researchers still continue their improvement to meet this need.

In order to increase efficiency and reduce the cost of manufacturing solar cells, researchers are still oriented inorganic solar cells based on silicon. The absorption of photons by such solar cells, generates free charge carriers which form a current under the effect of an applied electric field in the space charge layer. It also generates excitons which dissociate into electron-hole pairs.

Some of these researchers like Mr. Burgelman and B. Minnaer [2] developed a numerical model applicable to organic solar cells in the presence of excitons. Further, [7] developed an analytical model to optimize performance heterojunction solar cells.

The aim of our study is to develop a numerical model applicable to inorganic solar cells in the presence of excitons for different values of the absorption coefficient. Our contribution will make the most active research in the field of photovoltaic solar energy, lead to lower prices and higher yields. We conducted our study by considering a solar cell subjected monochromatic illumination through the front side and a thermal insulation from the back face by taking into account inclusion of the space charge layer and the non-uniformity of the dissociation and recombination excitons in this area. The continuity equations for electrons and excitons coupled and the heat, which govern the generation-recombination and diffusion mechanisms have been solved by a numerical approach based on the finite volume method. 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.

POSITION OF THE PROBLEM AND MATHEMATICAL FORMULATION

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

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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

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

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 f_x is that the excitons. We consider for an inorganic solar cell $f_e=1$ and f_x [2].

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

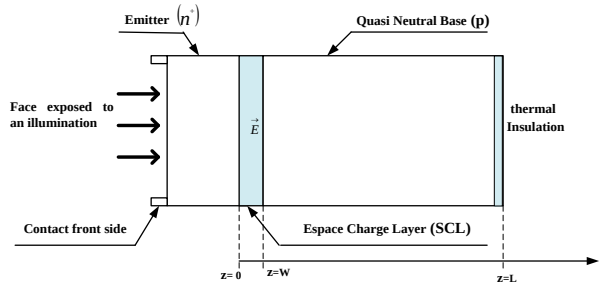

Figure 1: n+p solar cell silicon under monochromatic illumination

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 [9].

Mathematical formulation

Considering the modeling assumptions above and the following reference physical quantities (concentration for carriers), (for the temperature difference), and (for the spatial variables), (generation rate of carriers and that of excitons), the non-dimensional equations for the coupled system and the heat become:

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

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

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

Along With

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

$$n_x^*=\frac{n_x}{C_r},\ n_{in}^*=\frac{n_{in}}{C_r},$$

$$G^*=\frac{G_{eh}}{G_r},\quad G^*=\frac{G_x}{G_r},\quad t^*=\frac{a}{L^2}t,$$

$$T^*=\frac{T-T_a}{\Delta T_r}$$

The amount is the electron diffusion coefficient calculated from the ambient temperature considered constant. The "diffusion coefficient" dimensionless expressed as:

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

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

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

For the excitons

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

For the temperature

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

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 [JK^{-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 [$cm\ s^{-1}$]

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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

NUMERICAL PROCEDURE

The three differential equations with the partial derivative are solved by the finite volume method.
It is to discretize the computational domain into a number of finite volumes called volume controls in which the transport equations are integrated [5].
As different parts of our area (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.
The diagonal sorting system obtained after discretization equations and initial and boundary conditions, is solved by an iterative method of relaxation line by line type Gauss Siedel [5].

RESULTS AND DISCUSSION

To validate our code, we compared our results with those of Mr. Burgelman and B. Minnaer [2].
The results from the mathematical and numerical modeling of various phenomena are summarized by considering the representation below.
We present essentially influences the coupling coefficients and the heating factor on the external quantum efficiency of electrons and excitons in the junction.
The tests we conducted showed that the time step, the index that tracks the position of the load area space interface / base, the number of nodes, the permitted relative error and the relaxation parameter $\delta t^* = 10^{-3}$; $i_w = 81$; $i_m = 201$; $\varepsilon = 10^{-3}$ and $r_e = 0.15$ are a good compromise between an acceptable calculation volume and a reasonable calculation time. The volumetric coefficient of coupling which depends on the electric field exciton dissociation and the average temperature is given by

$$bv\{E(z)\} = bv\_low \times \exp\left[\left(1 - \frac{z}{w}\right) \times \ln\left(\frac{bv\_\max}{bv\_low}\right)\right]$$

[2]. Along With $bv\_low = 10^{-16}\, cm^3\, s^{-1}$, $10^{-16}\, cm^3\, s^{-1} \le bv\_\max \le 10^{-7}\, cm^3\, s^{-1}$

DENSITY OF PHOTOCURRENT OF CHARGE CARRIERS

Assuming a negligible electric field in the database is to say a quasi-neutral basis, the density of photocurrent generated by the wavelength of radiation is given by the equation:
The density of photocurrent of the electrons to the junction is defined by:

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

Along With

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

And the excitons at the junction is defined in the presence of a concentration gradient:

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

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

The total density of photocurrent of the solar cell is equal to the sum of those electrons and excitons to a monochromatic illumination through the front side:

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

We represent in Figure 4 the photocurrent as a function of absorption coefficient for a range of wavelengths between 0.7μm and 1.05μm; corresponding to the main absorption depths allowing exploration of the entire volume of the cell.

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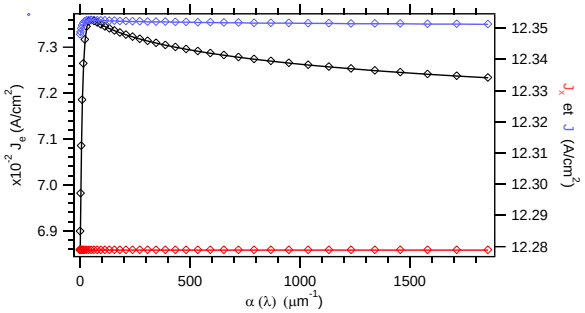

Figure 3: Density of photocurrent of electrons and excitons for a silicon-based solar cell depending on the absorption coefficient
Z_e=30 nm ; N_A=10^{16} cm^{-3} ; N_D=10^{19} cm^{-3} ; n_i=1.45 10^{10} cm^{-3} ; n_mott=1.0310^{18} cm^{-3} ; Se= Sx =10 cm s^{-1} ; F_0=10. ; α(λ) ≠0 ; Fact_ch=2.10^{-2} ; f_x=1 ; f_e=0 ; L_e≠L_x=f (average temperature) ; bv_inf=10^{-16} cm^3 s^{-1} ; bs_max=10^{+1} cm s^{-1}

These wavelengths correspond to the energy incident photons close the gap of the semiconductor material silicon (11.1 eV).
These results show the effect of excitons on the density total photocurrent, more precisely on the quantum efficiency. So that the density total photourant and quantum efficiency are due to the effect of the exciton.

QUANTUM EFFICIENCY OF THE SOLAR CELL ACCORDING TO THE ABSORPTION COEFFICIENT

The quantum efficiency of a solar cell according to the wavelength of the incident light is measured by the spectral response. To determine the spectral response, the solar cell is subjected to a monochromatic light which can be varied in the absorption range of the material used. It is defined by the following relationship:

$$RS(\lambda) = \frac{J(\lambda)}{P(\lambda)} \qquad (8)$$

For the external quantum efficiency, multiply by a factor RS:

$$RQE = RS(\lambda) \times h \times \alpha(\lambda) \qquad (9)$$

With: $\alpha(\lambda = \frac{1}{\lambda}$ the absorption coefficient (μm^{-1})

RQE : The External Quantum Efficiency (%)

$RS(\lambda)$: Spectral Response (A.W^{-1})

It allows us to obtain the percentage of electrons and excitons in the photocurrent participant relative to the number of incident photons.
For a researcher in the field of design of electronic devices, it became for him to predict the behavior of these systems with rigorous models. The simulation is widely used in the field of solar cells to determine the most important physical parameters for the operation thereof. It has also been widely used in this field to minimize the loss of the cell in order to obtain maximum efficiency.
The results below in Figure 4, Figure 5 and Figure 6 show the values noted the external quantum efficiency increases when those of the absorption coefficient increases. The large values of the absorption coefficient corresponding to small values of the wavelength. These findings are due to the fact that there is less photo carriers generated when the wavelength is large. To the great values of the absorption coefficient losses to surface recombination is low, the quantum efficiency characterizes the quality of the material.
Furthermore, we study the influence of some parameters on the external quantum efficiency.

Influence of volume coupling coefficient on the external quantum efficiency

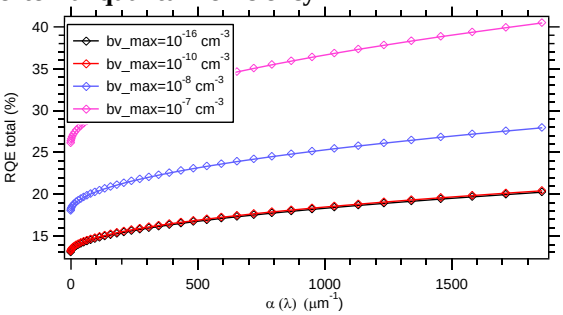

Figure 4: Influence of the volume of coupling coefficient on the change of the quantum efficiency for a silicon-based solar cell depending on the absorption coefficient
Z_e=30 nm ; N_A=10^{16} cm^{-3} ; N_D=10^{19} cm^{-3} ; n_i=1.45 10^{10} cm^{-3} ; n_mott=1.0310^{18} cm^{-3} ; Se= Sx =10 cm s^{-1} ; F_0=10. ; α(λ) ≠0 ; Fact_ch=2.10^{-2} ; f_x=1 ; f_e=0 ; L_e≠L_x=f (average temperature) ; bv_inf=10^{-16} cm^3 s^{-1} ; bs_max=10^{+1} cm s^{-1}

Influence of the surface conversion of the external quantum efficiency

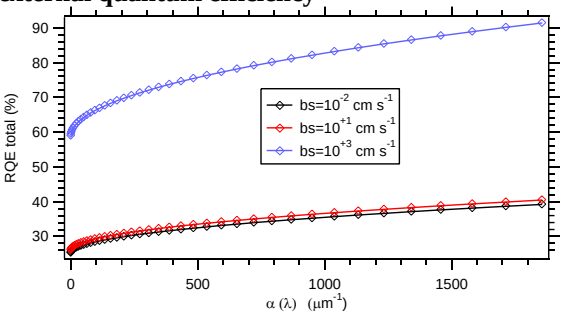

Figure 5: Influence of the surface conversion velocity of the variation of the quantum efficiency for a silicon-based solar cell depending on the absorption coefficient
Z_e=30 nm ; N_A=10^{16} cm^{-3} ; N_D=10^{19} cm^{-3} ; n_i=1.45 10^{10} cm^{-3} ; n_mott=1.0310^{18} cm^{-3} ; Se= Sx =10 cm s^{-1} ; F_0=10. ; α(λ) ≠0 ; Fact_ch=2.10^{-2} ; f_x=1 ; f_e=0 ; L_e≠L_x=f (average temperature) ; bv_inf=10^{-16} cm^3 s^{-1} ; bv_max=10^{-7} cm^3 s^{-1}

Influence of the heating factor on the external quantum efficiency

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Scientific Journal Impact Factor: 3.449
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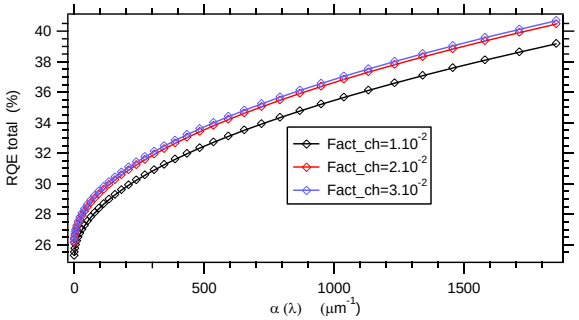

Figure 6: Influence of the heating factor in the variation of the quantum efficiency for a silicon-based solar cell depending on the absorption coefficient Z_e=30 nm ; N_A=10^{16} cm^{-3} ; N_D=10^{19} cm^{-3} ; n_i=1.45 10^{10} cm^{-3} ; n_mott=1.0310^{18} cm^{-3} ; Se= Sx =10 cm s^{-1} ; F_0=10. ; α(λ) ≠0 ; f_x=1 ; f_e=0 ; L_e≠L_x=f (average temperature) ; bv_inf=10^{-16} cm^3 s^{-1} ; bv_max=10^{-7} cm^3 s^{-1} ; bs_max=10^{+1} cm s^{-1}

In the case of volume coupling (Figure 4), the external quantum efficiency of the solar cell is important for the cell made with strong volume couplings. The increase in quantum efficiency starts from $bv\_\max = 10^{-8}\, cm^3\, s^{-1}$. This threshold corresponds to the strong field exciton dissociation. The exciton dissociation field also depends on the width of the space charge layer which is a function of the average temperature. Therefore the increase in average temperature also involves that of the exciton dissociation field.

The values of conversion velocity, used to simulate the variation of the cell's external quantum efficiency are: bs = 10^{-2} cm s^{-1}, bs = 10^{+1} cm s^{-1} and bs = 10^{+3} cm s^{-1}. The quantum efficiency is not significant for low and average values of the surface conversion velocity. Furthermore a surface conersion velocity of the order of 10^{+3} cm s-1 increases the external quantum efficiency. This value is also an excitation threshold of the solar cell. The surface conersion velocity allows the surface exciton dissociation into free electrons.

To study the variation of the external quantum efficiency as a function of the heating factor (Figure 6), we calculated the look of this performance against the absorption coefficients for different values of the heating factor. Values taken into consideration heating factor are: Fact_ch = 1.10^{-2}, 2.10^{-2} and Fact_ch= = 3.10^{-2}. The influence of the heating factor in the external quantum efficiency only confirms its action on the charge carriers generated and the total photocurrent. So that it causes an increase in the number of charge carriers generated.

CONCLUSION

We made a numerical study of the effect of excitons in the external quantum efficiency of the cell. This study, we began with a comparison of the total photocurrent electrons and the excitons of the total photocurrent of these charge carriers. This study showed that the total photocurrent approached that of the excitons.

We also analyzed the influence of volume coefficients, of the surface conversion velocity and that of the heating factor on the external quantum efficiency of the cell. The numerical study was a company in order to identify these appropriate parameters for design of a numerical model applicable to the inorganic cells.

It is clear from our study that the influence of coupling coefficients on the external quantum efficiency requires a threshold value. The increase in these factors leads that of external quantum efficiency. And with the influence of surface conversion velocity we obtain the quantum efficiency of the highest cell. The results also show that the heating factor has a positive effect on the quantum efficiency, but the quantum efficiency can vary with increasing heat.

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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ISSN: 2277-9655
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