

# **Study of the effect of the annihilation lifetime on the dependence of some kinematic and intrinsic parameters of a silicon heterojunction solar cell (HIT), illuminated by a monochromatic light.**

## **Abstract**

In this paper, a coexistence of annihilation, diffusion and relaxation processes of excitons is observed under high or low excitation. These physical phenomena are described in an annihilation process between two excitons which, by a transfer of energy, allows the electrons of the quasiparticles to keep part of their energy.

In order to better understand these physical phenomena, we proceeded to a numerical method of solving the transport equations of the charge carriers and a calculation of some appendices which allowed us to obtain results.

These results then allowed us to study the influence of the annihilation lifetime on: the diffusion length, the density, the photocurrent density and the internal quantum efficiency of the charge carriers.

**Keywords:** Photovoltaic system, Electricity grid, Self-consumption, Self-generation, Expense, profitability.

## **1. Introduction**

The effect of excitons in a solar cell has long been considered unimportant for the production of photovoltaic energy by some researchers. Until recently, the effect of excitons on current transport has not been studied because excitons are neutral and their number in semiconductors at a temperature greater than or equal ambient temperature has been considered insignificant [1]. This view was modified by Hangleiter [2], who highlighted the role of excitons in recombination via deep impurities [3] and improved Auger-band recombination by electron-hole correlation [4]. This theory has been confirmed experimentally by many authors [2,5,6].

But despite all these advances, excitonic theories are complex and often difficult to solve analytically. This led some authors like [7] to use a numerical resolution method. Others like [8,9,10], based on quantum phenomena, studied the annihilation of excitons in a semiconductor.

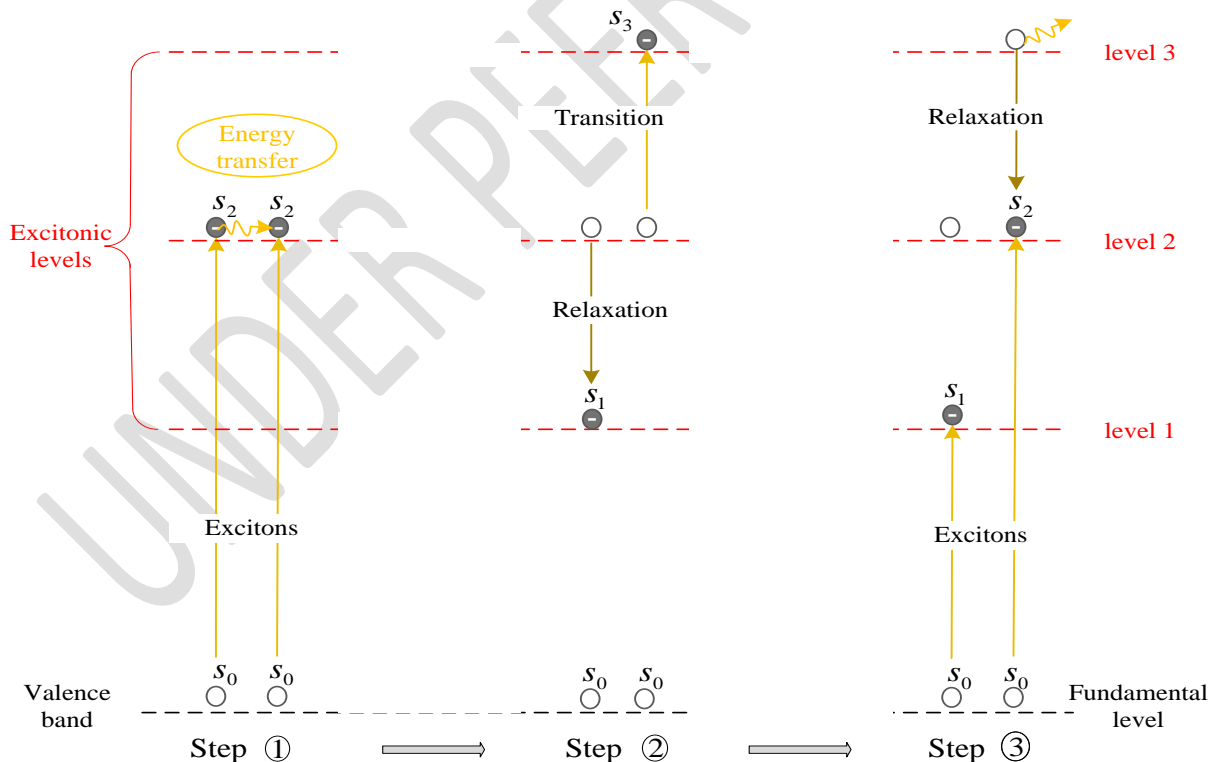
As a continuation of all this work, we used the annihilation life of excitons in a silicon heterojunction cell (HIT) to understand its influence on the kinematic and intrinsic parameters of the HIT cell.

## **2. Exciton-exciton annihilation:**

Annihilation can be defined as a transition of two excited states by an energy transfer. The energy transfer occurs not only between a donor (in an excited state) and an acceptor (in the fundamental state). But it can also occur transitions between two excited states (an excited donor and an excited acceptor) that give a donor with higher energy levels and an acceptor with a lower excited state or an acceptor in

the fundamental state. This process of energy transfer between two excitons is known as exciton annihilation. Exciton annihilation becomes more and more important when the excitation density is high. The annihilation destroys a particle in the Wannier state. Since the excitons in inorganic semiconductors (silicon) are of Wannier type, then it is more correct to study the time at which excitons annihilate than to study their lifetime, because annihilation is not worth the direct recombination of excitons, but it destroys their excited states which allows them to transit into higher states or relax into lower energy excitonic states. In this case, the scattering length of the exciton corresponds to the distance traveled in the matter before its annihilation. This length is limited by the finite lifetime of the exciton (the exciton lifetime) in a defect-free material.

The phenomenon of annihilation by energy transfer between two excitons can lead to the emission of one, two or more photons or simply to a release of heat. When two excitons annihilate, one of the excitons (donor) gives up part of its energy to the other exciton (acceptor) by relaxing to a lower energy level and allowing the acceptor to transit to a higher energy exciton level before relaxing and losing its energy in the form of heat. Contrary to direct recombination where the two excitons recombine while losing their energies or to the intra-band relaxation which leads to two excitons which are at a lower excitonic level, the exciton-exciton annihilation delays the recombination of the excitons and allows them to diffuse as long as possible in the photovoltaic cell (see figure 1 and 2).

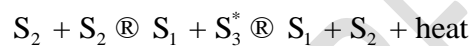


**Figure 1:** Internal conversion of the excitation energy of an electron of the second excitonic level by an exciton-exciton annihilation process

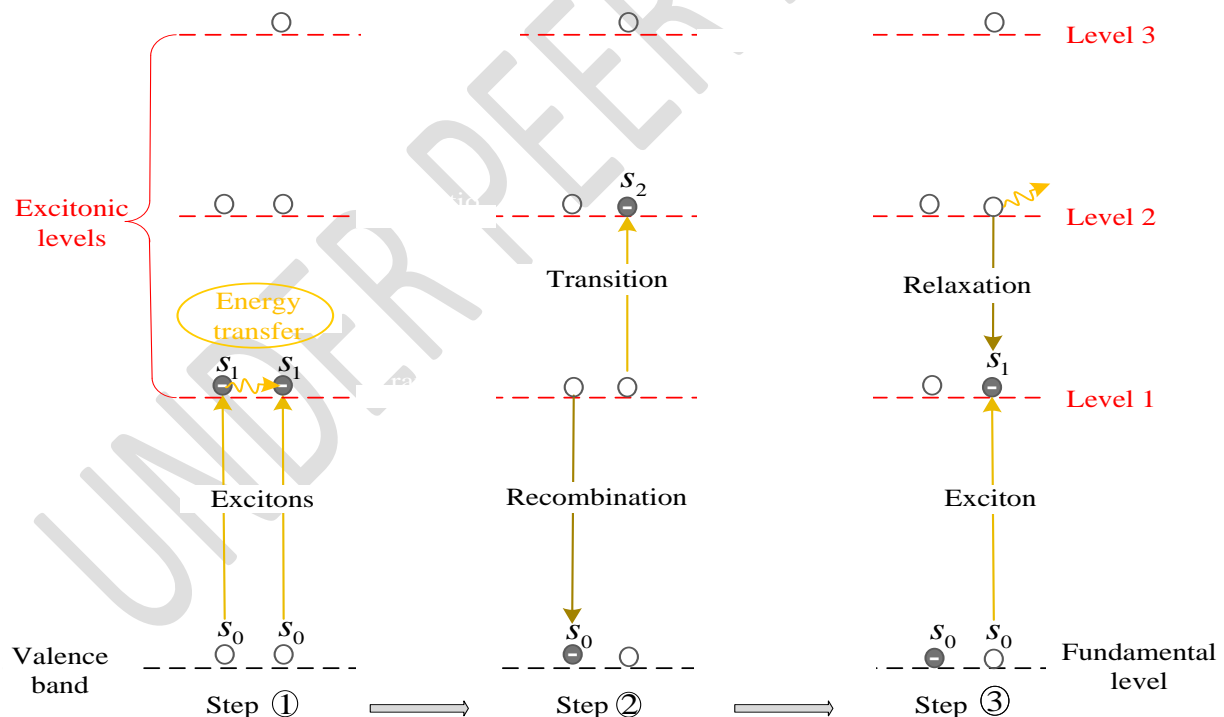
The annihilation process of two excitons which are at the second excitonic level is described by 3 steps defined as follows :

- the energy transfer between the donor singlet exciton and the acceptor singlet exciton at the second excitonic level ;
- the transition of the singlet acceptor exciton to the third excitonic level and the relaxation of the singlet donor exciton to the first excitonic level ;
- a relaxation of the singlet acceptor exciton from the third excitonic level to the second excitonic level by losing part of its energy in the form of heat.

We have noticed that two excitons of the level 2 by annihilating each other change excitonic state, but do not recombine. Since in our study the excitons are in the Wannier state, then the annihilation changes the Wannier state of the excitons. This results in an unstable singlet exciton of the first excitonic level and an unstable singlet exciton of the second excitonic level. Thus, this physical phenomenon can be described as a change of physical state:



S denotes the type of exciton (Singlet exciton), the subscripts 1,2,3 represent the 1,2,3 excitonic energy levels, respectively, and the star (\*) defines a highly unstable excitonic state.



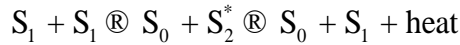
**Figure 2:** Internal conversion of the excitation energy of an electron of the first exciton level by an exciton-exciton annihilation process

In the case of the annihilation of two singlet excitons of level 1, we observe the same steps and processes of annihilation of two singlet excitons of level 2, but with different results.

- First an energy transfer between the donor singlet exciton and the acceptor singlet exciton at level 1.

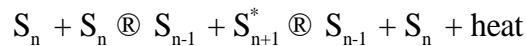
- Then a transition of the singlet acceptor exciton to level 2 and a relaxation of the singlet donor exciton to the fundamental level.
- Finally a relaxation of the singlet exciton acceptor from level 2 to level 1 by losing part of its energy in the form of heat.

The result is a stable electron in the fundamental state and an unstable singlet exciton in level 1. Thus, this physical phenomenon can be described by the following change of physical state:



$S_0$  is a stable singlet state while  $S_1$  and  $S_2$  are unstable excited singlet states or simply singlet excitons.

This reaction can be generalized with excitons in any excitonic energy level.

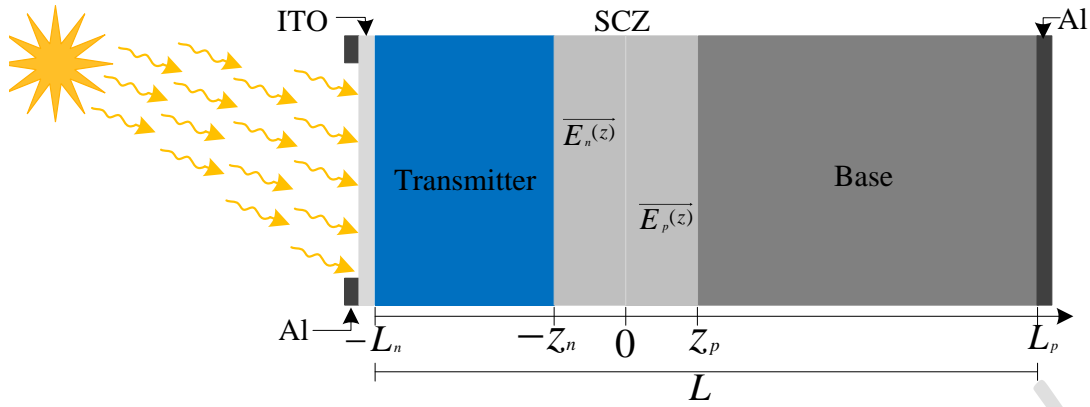


With  $n$  representing the  $n$ th excitonic energy level. The process can stop at the second step of annihilation and the acceptor exciton which is in a very unstable state can be collected before relaxing. Let us recall that this is only one possibility among others. We cannot study all the physical phenomena that govern the annihilation between two or more excitons of the same type (singlet-singlet) or of different types (singlet-triplet). And knowing that one can have several excited levels ( $n$ ) where excitons can annihilate, one can only note the unpredictable character of excitons. Moreover, the relaxation phenomena described in [11], combined with the annihilation of excitons and the short lifetime of excitons, make the study of excitonic phenomena in semiconductors complex. The fact that excitons are very much in the minority compared to free charge carriers causes most researchers to neglect them in their papers [12,13,14]. While authors like M. Faye [15], S. Zh. Karazhanov [16], R. Corkish [17] and so many other researchers concerned with the importance of excitons in photovoltaic cells, have proved in one way or another their contribution to photovoltaic energy production.

At present, it would not be possible to theoretically describe excitonic phenomena in the most reliable or explicit way, without resorting to quantum mechanics. More precisely, exciton annihilation is often described by quantum mechanics with the annihilation operator which defines the Wannier state change of the exciton or "destroys the exciton". This operator is always accompanied by the creation operator which describes the ability of excitons to move in the crystal lattice from one to the other and the interactions between the two operators which define the excitonic nature of the particles see [10,18,19]. Moreover, when the electrons of a crystal are pushed into interstitial positions, we say that the excitons annihilate, in a delocalized state.

### 3. Modeling:

We consider a silicon heterojunction cell of type ( $n^+p$ ), length  $L$ , illuminated by monochromatic light in the presence of excitons.



**Figure 3:** Structure of a silicon heterojunction solar cell (a-Si:H/c-Si), type (n<sup>+</sup>p)

The cell is composed of three parts:

- The emitter: area heavily doped with donor atoms  $10^{19} \text{ cm}^{-3}$  ;
- The space charge zone (SCZ): located between the emitter and the base where an electric field prevails. This field allows the separation of electron-hole pairs that arrive at the junction ;
- The base: quasi-neutral zone, doped with acceptor atoms  $1.14 \times 10^{17} \text{ cm}^{-3}$ .

The mechanisms of generation, recombination and diffusion govern the continuity equations.

### 3.1 Transport of charge carriers in the base

In the doped base of type (p), the minority carriers which are electrons of charge (-q), come from the free electron-hole pairs and excitons. The density of holes obeys the law of conservation of charges represented by the system of equations (1).

$$\begin{cases} D_e \frac{d^2 n_e}{dz^2} + m_e \frac{d[n_e E_p(z)]}{dz} = \frac{n_e - n_{e0}}{\tau_e} + b N_A (n_e - n_{e0}) - \frac{n_x - n_{x0}}{\tau_d} - G_e \\ D_x \frac{d^2 n_x}{dz^2} + m_x \frac{d[n_x E_p(z)]}{dz} = \frac{n_x - n_{x0}}{\tau_a} - b N_A (n_e - n_{e0}) + \frac{n_x - n_{x0}}{\tau_d} - G_x \end{cases} \quad (1)$$

Where ( $D_e$ ) and ( $D_x$ ) are the scattering coefficients of electrons from free electron-hole pairs and excitons,  $b$  is the volume coupling coefficient of bound electron and hole, ( $n_{e0}$ ) and ( $n_{x0}$ ) their equilibrium concentrations, ( $N_A$ ) is the concentration of acceptors in the base, and  $\tau$  is the lifetime of charge carriers.

The two equations in system (1) are closed by the following boundary conditions:

- **Initial conditions:**

$$\begin{cases} D_e \frac{dn_e}{dz} = S_e (n_e - n_{e0}) \Big|_{z=0} \\ D_x \frac{dn_x}{dz} = S_x (n_x - n_{x0}) \Big|_{z=0} \end{cases} \quad (2)$$

- **Final conditions:**

$$\begin{aligned} D_e \frac{dn_e}{dz} &= -S_e(n_e - n_{e0}) \\ D_x \frac{dn_x}{dz} &= -S_x(n_x - n_{x0}) \end{aligned} \quad (3)$$

Where  $S_e$  and  $S_x$  represent the electron and exciton recombination velocities, respectively.

### 3.2. Electron transport equations and adimensional boundary conditions:

To facilitate the numerical solution of these equations, it is often necessary to dimensionalize them in order to have homogeneous solutions.

By positing  $z = z^*L$ ,  $w = w^*L$ ,  $n_e = n_e^*N_r$ , and  $n_x = n_x^*N_r$  and replacing  $z$ ,  $w$ ,  $n_e$  and  $n_x$  with their values in the systems of equations (1), one obtains the following dimensionless diffusion equations.

$$\begin{aligned} F_{0e} \frac{d^2 n_e^*}{dz^{*2}} + K_e \frac{dn_e^*(w_p^* - z^*)}{dz^*} &= -A_e(n_x^* - n_{x0}^*) + B_e(n_e^* - n_{e0}^*) + (n_e^* - n_{e0}^*) - G_e^* \\ F_{0x} \frac{d^2 n_x^*}{dz^{*2}} + K_x \frac{dn_x^*(w_p^* - z^*)}{dz^*} &= A_x(n_x^* - n_{x0}^*) - B_x(n_e^* - n_{e0}^*) + (n_x^* - n_{x0}^*) - G_x^* \end{aligned} \quad (4)$$

With:

$$\begin{aligned} F_{0e} &= \frac{D_e \tau_e}{L^2} & K_e &= \mu_e \tau_e \frac{E_0}{w} & A_e &= \frac{\tau_e}{\tau_d} & B_e &= b \tau_e N_A & G_e^* &= \frac{8 \tau_e}{9 N_r} G \\ F_{0x} &= \frac{D_x \tau_a}{L^2} & K_x &= \mu_x \tau_a \frac{E_0}{w} & A_x &= \frac{\tau_a}{\tau_d} & B_x &= b \tau_a N_A & G_x^* &= \frac{1 \tau_a}{9 N_r} G \end{aligned}$$

By proceeding in the same way, we obtain the dimensionless boundary conditions.

#### ➤ Initial conditions:

$$\begin{aligned} A_{de} \frac{dn_e^*}{dz^*} &= (n_e^* - n_{e0}^*) \\ A_{dx} \frac{dn_x^*}{dz^*} &= (n_x^* - n_{x0}^*) \end{aligned} \quad (5)$$

#### ➤ Final conditions:

$$\begin{aligned} A_{Le} \frac{dn_e^*}{dz^*} &= -(n_e^* - n_{e0}^*) \\ A_{Lx} \frac{dn_x^*}{dz^*} &= -(n_x^* - n_{x0}^*) \end{aligned} \quad (6)$$

With:

$$A_{de} = A_{Le} = \frac{D_e}{S_e L} \quad A_{dx} = A_{Lx} = \frac{D_x}{S_x L}$$

Some parameters such as the scattering coefficients of holes, electrons and excitons of these equations depend on the temperature. The equations being non-linear, the calculation does not have an analytical solution and must be self-consistent. Therefore a numerical solution of these equations is necessary.

### 3.3 Numerical (algebraic) model of the continuity equations in the base:

To obtain a numerical solution of our problem, we must transform the differential equations of the mathematical model into a system of algebraic equations obtained after discretization. We have chosen the power law as a discretization method. This method consists in integrating the equations on a discrete set called control volume. This results in the system of algebraic equations (7).

$$\begin{cases} b_{1,k} \cdot n_{k,I_0} - c_{1,k} \cdot n_{k,I_0+1} = d_{1,k} & i = I_0 \\ -a_{w,k} \cdot n_{k,i-1} + a_{M,k} \cdot n_{k,i} - a_{r,k} \cdot n_{k,i+1} = S_{m,k} & I_0 + 1 \leq i \leq I_m - 1 \\ -a_{m,k} \cdot n_{k,I_m-1} + b_{m,k} \cdot n_{k,I_m} = d_{m,k} & i = I_m \end{cases} \quad (7)$$

With here:

$$\begin{aligned} b_{1,k} &= a_{M1,k} - 2 \cdot C_{dk} \cdot a_{w1,k} & ; & \quad c_{1,k} = a_{r1,k} - a_{w1,k} & ; & \quad d_{1,k} = s_{1,k} - 2 \cdot C_{dk} \cdot a_{w1,k} \cdot n_{k0} \\ C_{Lk} &= \frac{\delta z_{I_m}}{A_{Lk}} & ; & \quad a_{m,k} = 1 & ; & \quad b_{m,k} = 1 + C_{Lk} & ; & \quad d_{m,k} = C_{Lk} n_{k0} \end{aligned}$$

The coefficients  $a_{w,k}$ ,  $a_{M,k}$  and  $a_{r,k}$  are evaluated at the interfaces of the control volume using the power law scheme. They represent the combined conduction and diffusion fluxes. The expressions for these coefficients are given in [20].

With the coefficients of the discrete equations represented in the following table.

**Table1:** Expressions of the coefficients of linear systems

Coefficients	Expressions
$a_{w,k}$	$D_{w,k} \cdot A(P_{w,k}) + \text{Max}[F_{w,k}; 0]$
$a_{M,k}$	$a_{r,k} + a_{w,k} + S_{M,k}$
$a_{r,k}$	$D_{r,k} \cdot A(P_{r,k}) + \text{Max}[-F_{r,k}; 0]$

The obtained strongly non-linear, iterative method is being the use of an necessary.

### 3.4. Ancillary calculations of the numerical program:

#### 3.4.1. Carrier photo-current density:

The photocurrent density is composed of the scattering current due to carrier scattering via photons and the conduction current due to the effect of the electric field of the space charge region.

#### 3.4.2. Conduction current:

In a material, charged electrons collide with atoms in the crystal lattice. Each shock corresponds to a loss of energy. Between two shocks, the electrons are accelerated uniformly in the opposite direction of the electric field  $E(z)$  of the ECZ with a velocity  $\vartheta(z) = \mp \mu \cdot E(z)$ . The photocurrent density is then written:

➤ **For electrons:**

$$J_{c,e} = q \cdot n_e \cdot m_e \cdot E(z) \quad (8)$$

➤ **For excitons:**

$$J_{c,x} = q \cdot n_x \cdot m_x \cdot E(z) \quad (9)$$

The velocities  $\vartheta_e(z)$  and  $\vartheta_x(z)$  are proportional to the electric field. The sign of the carrier mobility coefficients  $\mu_e(z)$  and  $\mu_x(z)$  depends on their charges (-q).

### 3.4.3. Diffusion current:

Fick's law, which is an experimental law established in by Adolphe Fick, states that: the number of particles per unit time and volume ( $\Phi$ ) is defined by the equation ( $\Phi$ ) =  $-D \frac{dn}{dz}$  [21].

From this expression, we can deduce, the photocurrent densities of electrons and excitons.

➤ **For electrons:**

$$J_{d,e} = q \cdot D_e \cdot \frac{dn_e}{dz} \quad (10)$$

➤ **For excitons:**

$$J_{d,x} = q \cdot D_x \cdot \frac{dn_x}{dz} \quad (11)$$

### 3.4.4. Photocurrent densities of charge carriers:

The photocurrent densities of electrons and excitons are the sums of the two contributions: the diffusion and the conduction currents.

➤ **For electrons:**

$$J_e = q \cdot n_e \cdot m_e \cdot E(z) + q \cdot D_e \cdot \frac{dn_e}{dz} \quad (12)$$

➤ **For excitons:**

$$J_x = q \cdot n_x \cdot m_x \cdot E(z) + q \cdot D_x \cdot \frac{dn_x}{dz} \quad (13)$$

The resultant of the photocurrent densities of the electrons and excitons is the total photocurrent density of the carriers in the  $J = J_e + J_x$  basis.

### 3.4.5. Spectral response and quantum efficiency:

The spectral response (SR) is, analogously, the ratio of the intensity  $I(\lambda)$  generated by the cell to the incident power  $P_0(\lambda)$ , for each wavelength. It is thus to illuminate the cell and measure the current it delivers.

$$SR(l) = \frac{I(l)}{P_0(l)} = \frac{I(l)/S}{j_0(l)} = \frac{J(l)}{j_0(l)} \quad (14)$$

Where  $\varphi_0(\lambda)$  is the incident photon flux and S is the area of the cell. To calculate the absorbed photon flux, we make the difference between the photon flux at the entrance of the material (the illuminated face) and the photon flux transmitted at a depth z in the base. It then comes:

$$j_a(l) = j_0(l) [1 - R(l)] [1 - e^{-\alpha(l) \cdot z}] \quad (15)$$

It is generally this quantity which is measured and which makes it possible to calculate the quantum efficiency.

We distinguish the external quantum efficiency (EQE) of internal quantum efficiency (IQE) in which we take into account the flow of photons absorbed by the active layer of the cell.

$$EQE(l) = \frac{J(l)}{qI_0(l)} \quad (16)$$

The expression presented here takes into account optical losses such as reflection or transmission through the cell: it is the external quantum efficiency.

It can be corrected for optical losses to give the IQE which takes into account the characteristics of the cell (scattering, surface and volume recombinations and / or absorption of the material considered).

By definition, the IQE is the ratio between the number of photons transmitted and photogenerated on the number of photons absorbed. It can also be defined as the ratio between the EQE and the absorption coefficient of the layer of thickness  $z$ .

$$IQE(l) = \frac{EQE(l)}{A(l)} \quad (17)$$

With here:  $A(\lambda) = [1 - R(\lambda)][1 - e^{-\alpha(\lambda)z}]$  being the absorption coefficient of the layer of thickness  $z$ . The results from this program or calculation code are discussed and interpreted.

#### 4. Results and discussion

Since the dependence of the kinematic and intrinsic parameters and especially the charge carrier behavior in the silicon heterojunction photovoltaic cell is still under discussion, we are interested in the effect of the exciton annihilation lifetime with respect to some kinematic and intrinsic parameters, with emphasis on their dependencies. Thus, exciton annihilation is a function of temperature and doping rate in the base ( $N_A$ ). The cell is overdoped in donor atom on one hand (emitter) and doped in acceptor atom on the other hand (base), so we can consider that the doping rate is constant and remains fixed once the majority carrier balance between emitter and base is established and the space charge region is created.

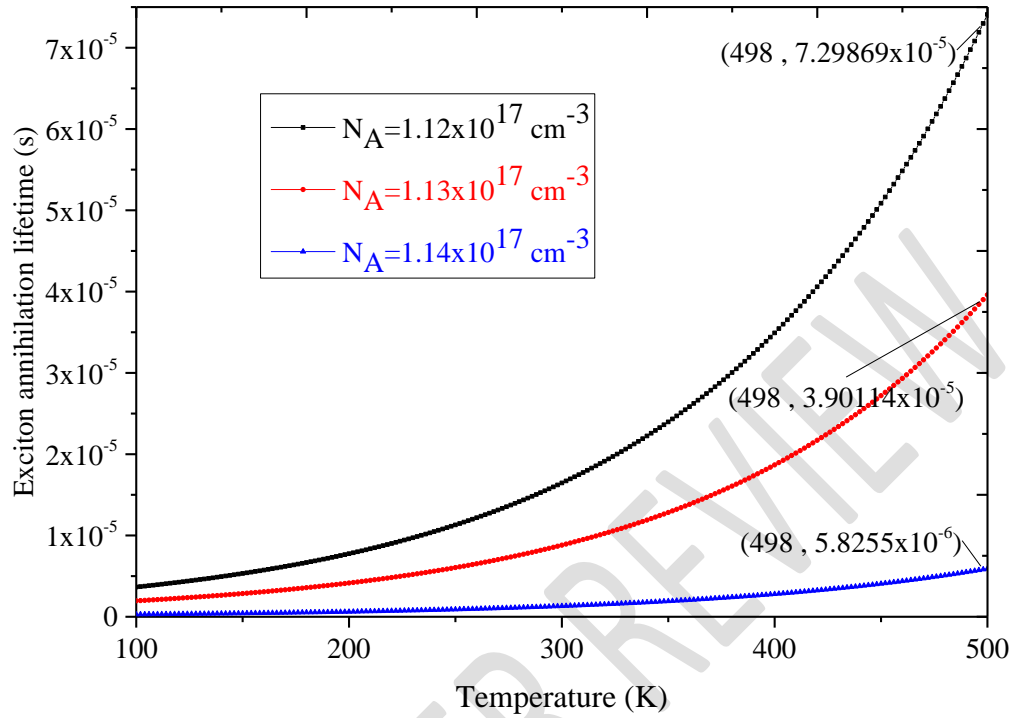
Therefore, the effect of temperature on the exciton annihilation lifetime is studied by varying the doping rate in the base to have the most suitable value so that excitons cannot harm the cell energy production (HIT).

##### 4.1 Choice of doping rate:

In Figure 4 is plotted the annihilation lifetime as a function of temperature with different values of the doping rate ( $N_A$ ).

At low temperatures (below 273 K), regardless of the doping rate, used here, the exciton annihilation lifetimes remain low in the vicinity of  $1 \times 10^{-5}$  s. Above 273 K, we observe an increase in the exciton annihilation lifetime that reaches  $7.298 \times 10^{-5}$  s for a doping rate of  $1.12 \times 10^{17} \text{ cm}^{-3}$ ,  $3.901 \times 10^{-5}$  s for a spiking rate of  $1.13 \times 10^{17} \text{ cm}^{-3}$  and  $5.825 \times 10^{-6}$  s for a spiking rate of  $1.14 \times 10^{17} \text{ cm}^{-3}$ .

We can see that increasing the temperature is favorable for the time at which excitons annihilate. On the other hand, an increase in doping significantly decreases the time taken by the exciton in the semiconductor before annihilating.



**Figure 4:** Exciton annihilation lifetime as a function of temperature with different values of the doping rate

The excitatory effect of the temperature defined in [22] allows the excitons to last before annihilating. On the other hand, increasing the doping rate creates recombination sites or defects which decrease the time taken by the excitons before annihilating.

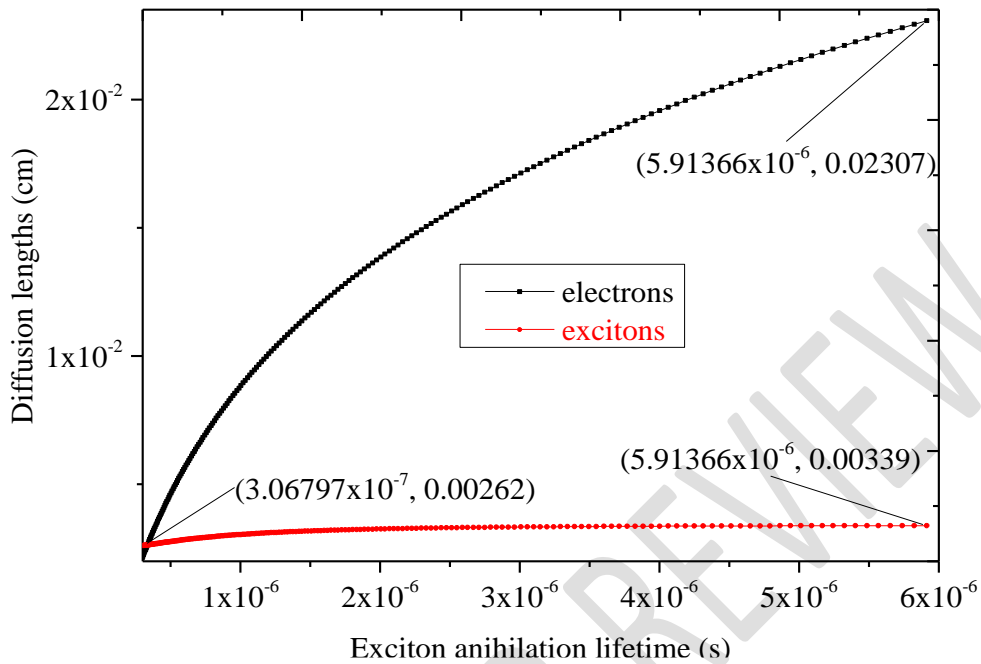
For consistency and physical reality, we decided to set the doping rate ( $N_A = 1.14 \times 10^{17} \text{ cm}^{-3}$ ). With this value, we obtain annihilation lifetimes close to and less than or equal to the electron lifetimes. This is logical, because excitons do not often last in the cell.

After having chosen the doping rate to have adequate annihilation lifetimes and to have evaluated the effect of an external parameter (temperature) on the annihilation lifetime to better understand the physical phenomena, we will study the diffusion lengths of electrons and excitons as a function of the annihilation lifetime of excitons.

#### 4.2 Scattering length of charge carriers

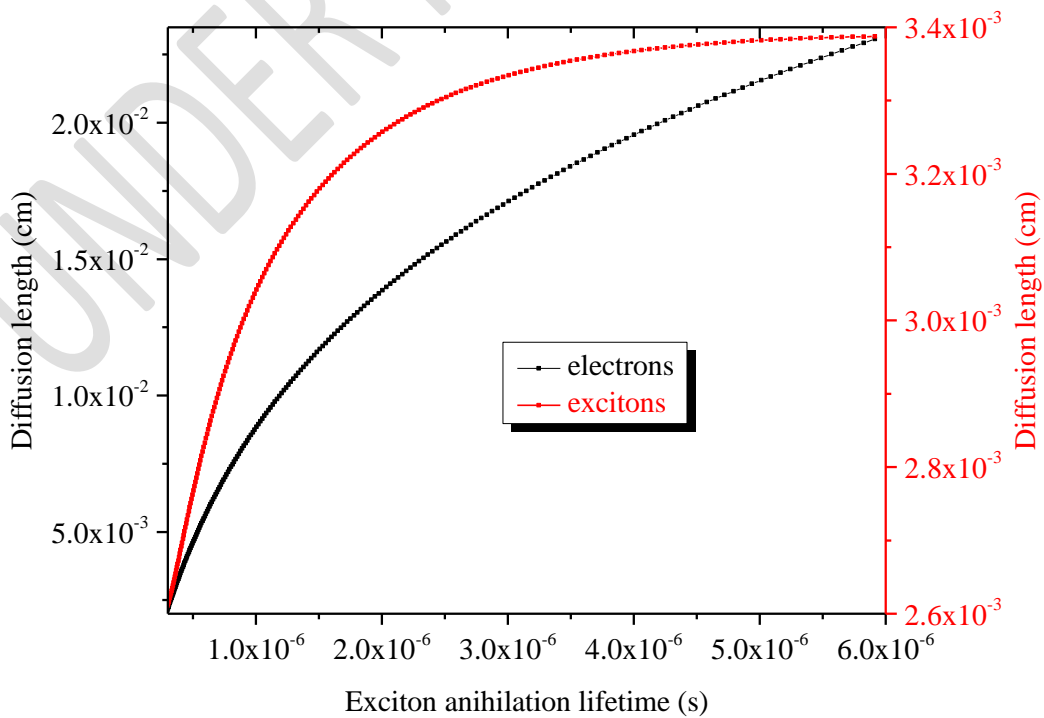
Figures 5 and 6 represent respectively the scattering lengths of electrons and excitons at the same scale and at different scales as a function of the annihilation lifetime of excitons.

We can see from Figure 5 that electrons scatter the farthest than excitons and the scattering length of excitons increases from a value of 0.00262 cm to a value of 0.00339 cm, when the exciton annihilation lifetime is increased from a value of  $3.06797 \times 10^{-7}$  s to a value of  $5.91366 \times 10^{-6}$  s.



**Figure 5:** Scattering lengths of electrons and excitons as a function of the exciton annihilation lifetime

Since the excitonic physical quantities are small when compared to the physical quantities of the free electron-hole pairs, we have in figure 6 a growth of the scattering lengths of free electrons and excitons from a value of 0.00262 cm to a value of 0.00339 cm, for exciton annihilation lifetimes ranging from  $3.06797 \times 10^{-7}$  s to  $5.91366 \times 10^{-6}$  s.



**Figure 6:** Scattering lengths of electrons and excitons at different scales as a function of the annihilation lifetime of excitons

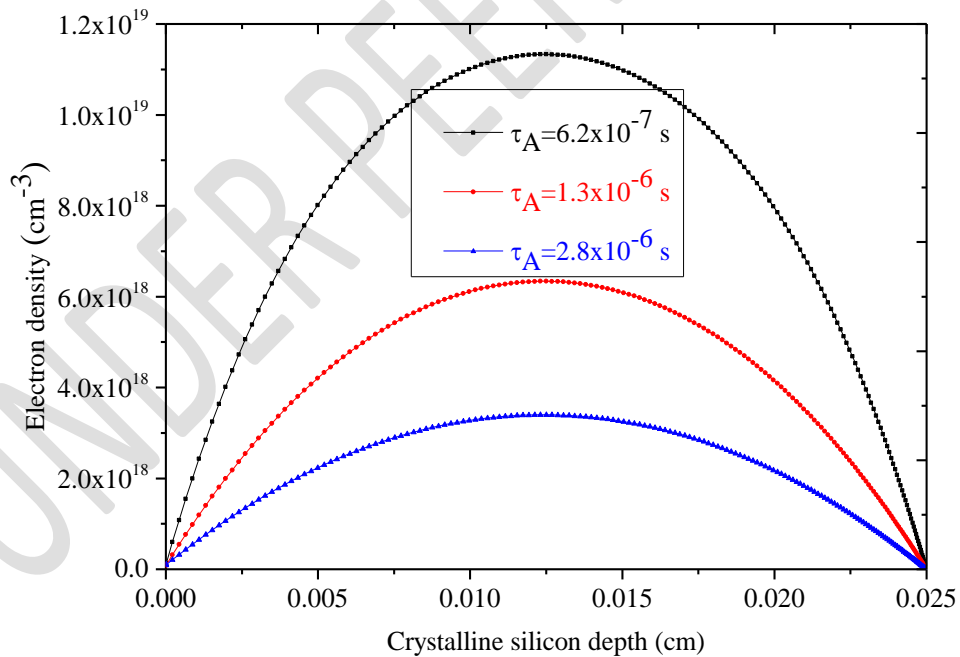
The excitons spending more time in the photovoltaic cell before being annihilated diffuse as far as possible thanks to the excitation energy which, in the form of kinetic energy, diffuses them until they annihilate.

In the case of free electron scattering, the annihilation lifetime of the excitons is affected by the temperature effect. By delaying the annihilation of excitons we bring a stability of the free charge carriers for a certain time, which allows the electrons to diffuse as far as possible. In addition, the annihilation of excitons in a delocalized state creates defects or recombining centers, which can prevent the free electrons from diffusing as far as possible. So everything that delays the annihilation process is favorable to the diffusion of charge carriers.

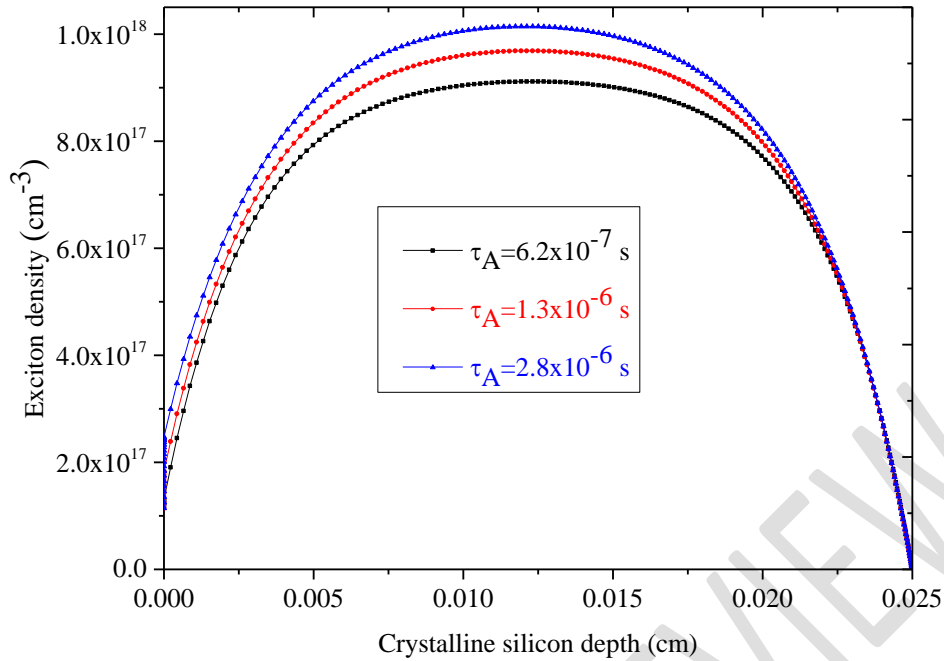
#### 4.3. Density of charge carriers

Figures 7 and 8 represent respectively the electron and exciton densities as a function of the depth of crystalline silicon with different values of the exciton annihilation lifetime.

An increase in the exciton annihilation lifetime leads to a decrease in the electron density and an increase in the exciton density.



**Figure 7:** Electron density as a function of depth in crystalline silicon with different values of exciton annihilation lifetime.



**Figure 8:** Density of excitons as a function of the depth of the crystalline silicon with different values of the annihilation lifetime of excitons

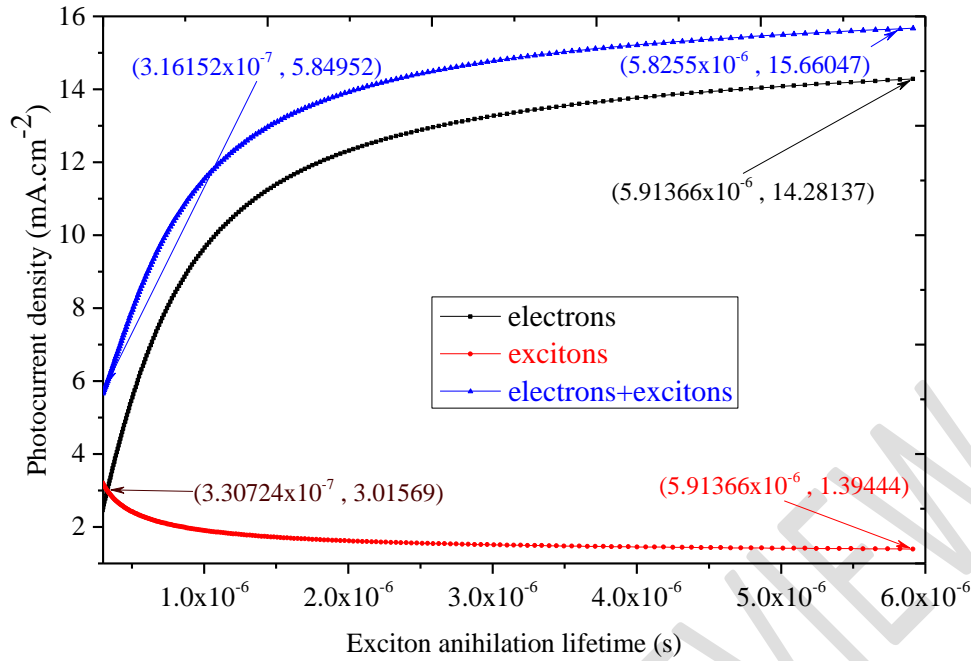
As the annihilation lifetime of the excitons increases, their numbers in the cell increase due to the loss of energy of the free electrons which relax to occupy excited levels. These relaxation phenomena combined with direct recombinations decrease the density of free electrons. Hence the antagonistic effect on the mobility of charge carriers described in [11], which is manifested with the annihilation lifetime of excitons. Furthermore, we can say that the fact that excitons do not last in the photovoltaic cell is favorable to the density of free electrons.

To produce electricity from photovoltaic origin, it is important to have a large amount of charge carriers in the cell, but it is more useful to direct and diffuse them to the collectors, so that they can be collected and participate in the electrical charges.

However, the ordered movement of the charge carriers towards the receiving electrodes is the photocurrent density of the charge carriers. These will be studied as a function of the annihilation lifetime, to better understand the excitonic phenomena in the cell.

#### 4.4. Photocurrent density of load carriers

Figure 9 shows the photocurrent densities of electrons, excitons and total as a function of the annihilation life of excitons. The photocurrent densities of electrons and total increase with the annihilation life, while the photocurrent density of excitons decreases.



**Figure 9:** Photocurrent density of charge carriers as a function of exciton annihilation lifetime.

Delayed annihilation of excitons when they are generated in the cell often leads to energy losses that can decrease the photocurrent density of excitons that are in a stable state. In addition, given their short lifetimes, a very long annihilation lifetime is unfavorable to them. Therefore, the faster they are annihilated the better for the photocurrent density of the excitons.

On the other hand, by increasing the life time of the exciton before its annihilation, one decreases the phenomena of relaxation and radiative recombination which decreases the generation of free charge carriers. The annihilation of excitons in a delocalized state creates recombination sites that trap free charge carriers. Thus, it is more cost effective to have higher annihilation lifetimes to have the maximum number of photons generated by free carriers, than to use low annihilation lifetimes to have a minimal contribution of bound electrons, as free charge carriers are in the majority in the cell and generate the largest number of photons.

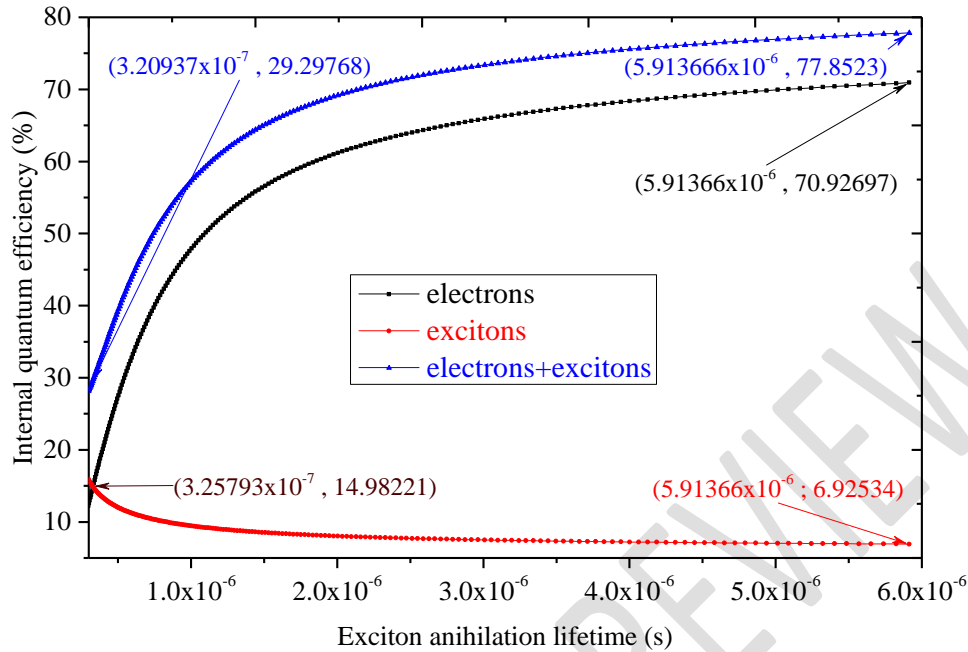
To better understand the participation of charge carriers when the exciton annihilation lifetime is varied, we will make a study of the internal quantum efficiency of electrons, excitons and total.

#### 4.5. The internal quantum efficiency of charge carriers

In terms of efficiency, we get a clear picture of the participation of each of the two types of charge carriers shown in Figure 10.

Specifically, we observe internal quantum efficiency ranging from 14.98221%, for an exciton annihilation lifetime of  $3.25793 \times 10^{-7}$  s to respective values of internal quantum efficiency of free electrons and excitons of 70.92697% and 6.92534%, for an exciton annihilation lifetime of  $5.91366 \times 10^{-6}$  s.

This, for the same exciton annihilation lifetimes, leads to internal quantum efficiency of the HIT cell between 29.29768% and 77.8525%.



**Figure 10:** Internal quantum efficiency of charge carriers as a function of the annihilation lifetime of excitons

The excitons, when they are not annihilated, remain bound, which does not facilitate their dissociation. However, for them to participate in the quantum efficiency, they must be dissociated. Hence a decrease of the internal quantum efficiency of the excitons as a function of the annihilation lifetime of the excitons.

On the other hand, by annihilating the excitons create disorder in the cell, leading to traps that can recombine the free charge carriers. Thus the longer the excitons remain in the cell without being annihilated, the less free electrons recombine and the more they participate in the HIT cell efficiency.

## 5. Conclusion

After having described the physical phenomena that governs the annihilation between two excitons, we have established a mathematical model of a system of two nonlinear continuity equations. The equations are solved numerically by the finite volume method, after being scaled.

The results of this numerical resolution, allowed us to note that the excitons last as long as possible in the cell, when the doping is weak. This allowed us to fix an adequate value of the doping rate, corresponding to adequate annihilation lifetimes for the excitons. Then, we showed that the longer the excitons last in the cell, the more the charge carriers diffuse, because the annihilation of excitons is synonymous with disorder in the cell. Moreover, this disorder is unfavorable to the density of free

electrons and favorable to that of excitons. Hence the antagonistic effect of the annihilation lifetime on the charge carriers.

Finally, we have opted for a higher annihilation lifetime of excitons, to have the maximum of photons generated by the carriers than to have the maximum of photons generated by the excitons. The profitability of the generated photons is well evaluated by internal quantum efficiency of the cell going from 29.29768 % to 77.8525 %.

### Références :

- [1]. R. Corkish, D. S. P. Chan and M. A. Green ; Excitons in silicon diodes and solar cells: A three-particle theory ; Institute of Physics, 1996, 79(1), pp 195-203.
- [2]. A. Hangleiter ; Nonradiative recombination via deep impurity levels in silicon: Experience ; Physical Review B, 1987, 35(17), pp 9149-9161.
- [3]. A. Hangleiter ; Nonradiative recombination via deep impurity levels in semiconductors: The Auger Excitonic Mechanism ; Physical Review B, 1988, 37(5), pp 2594-2604.
- [4]. A. Hangleiter and R. Hacker ; Enhancement of band-to-band Auger recombination by electron-hole correlations ; Phys. Rev. Lett, 1990, 65(2), pp 215-218.
- [5]. J. P. Wolfe and A. Mysyrowicz ; Excitonic matter ; Scientific American, 1984, 250(3), pp 70-79.
- [6]. J. Dziewior and W. Schmidt ; Auger coefficients for highly doped and highly excited silicon ; Applied Physics Letters, 1977, 31(5), pp 346-348.
- [7]. M. Faye, M. Mbow et M. Ba ; Numerical modeling of the effects of excitons in solar cell junction  $n^+p$  of the model by extended the space charge layer ; International Review of Physics ; 2014, 8(4), pp.102-109
- [8]. M. Balkanski, État actuel du problème de l'exciton, J. Phys. Radium, 1958, 19 (2), pp.170-182.
- [9]. G. Soavi, S. D. Conte, C. Manzoni, D. Viola, A. Narita, Y. Hu, X. Feng, U. Hohenester, E. Molinari, D. Prezzi, K. Müllen and G. Cerullo ; Exciton–exciton annihilation and biexciton stimulated emission in graphene nanoribbons ; Nature Communications, 2016, 7(11010) ; pp 1-7.
- [10]. J. Fiuràšek, Engineering quantum operations on traveling light beams by multiple photon addition and subtraction, Phys. Rev. A 80 [quant-ph], 2009, 80(5), pp 1-7.
- [11]. O. Ngom, M. Faye, S. Ndiaye, C. Mbow, B. Ba ; Behavior of free electrons and excitons, due to their mobility under the effects of optoelectric parameters in a silicon heterojunction cell (HIT): Interdependence of physical phenomena acting on free and bound load carriers ; Journal of Scientific and Engineering Research, 2020, 7(5) ; pp 1-15.
- [12]. G. Sahin, M. Dieng, M. A. Ould El Moujtaba, M. I. Ngom, A. Thiam, G. Sissoko ; Capacitance of Vertical Parallel Junction Silicon Solar Cell under Monochromatic Modulated Illumination ; Journal of Applied Mathematics and Physics, 2015, 3(11) ; pp 1536-1543.

- [13]. S. Mbodji, M. Zoungrana, I. Zerbo, B. Dieng, G. Sissoko ; Modelling Study of Magnetic Field's Effects on Solar Cell's Transient Decay ; World Journal of Condensed Matter Physics, 2015, 5 ; pp 284-293.
- [14]. B.H. Rose and H.T. Weaver, Determination of Effective Surface Recombination Velocity and Minority Carrier Lifetime in High-Efficiency Si Solar Cells, Journal of Applied Physics, 1983, 54(1), pp 238-247.
- [15]. M. Faye, M. Mbow, M. Ba ; Numerical Modeling of the Effects of Excitons in a Solar Cell Junction  $n^+p$  of the Model by Extending the Space Charge Layer ; International Review of Physics (I.RE.PHY) ; 8(4), ISSN 1971-680X (August 2014).
- [16]. S. Zh. Karazhanov, Temperature and doping level dependence solar cell performance Including excitons, Solar Energy Materials & Solar Cells 63 (2000), pp 149-163.
- [17]. R. Corkish, D. S. P. Chan, and M. A. Green ; Excitons in silicon diodes and solar cells: A three-particle theory, Institute of Physics. [(S0021-8979(1996) 0070-9)].
- [18]. J. Aberg, Catalytic Coherence, Phys. Rev. Lett. 113 [quant-ph], Vol. 3, 2014, pp 1-39.
- [19]. J. Vogel, W. Li, A. Mokhberi, I. Lesanovsky, and F. Schmidt-Kaler ; Shuttling of Rydberg ions for fast entangling operations ; Phys. Rev. Lett. 123 [physics.atom-ph] ; Vol. 2, 2019 ; pp 1-8.
- [20]. A. Hangleiter and R. Hacker ; Enhancement of band-to-band Auger recombination by electron-hole correlations ; Phys. Rev. Lett, 1990, 65(2), pp 215-218.
- [21]. C. Truesdell ; Mechanical Basis of Diffusion ; The Journal of Chemical Physics, 1962, 37(10), pp 2336–2344.
- [22]. O. Ngom, M. Faye, M. Mbaye, C. Mbow and B. Ba ; Numerical Study of the Effect of Temperature on the Performance of a Silicon Heterojunction Solar Cell (HIT) in the Presence of Excitons ; International Journal of Materials Science and Applications, Special Issue: Advanced Materials for Energy Storage and Conversion Applications, 8(4), pp 56-67.