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Research Article

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Impact of Excitons on the Performance of the Silicon Solar Cell

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Abstract We studied the influence of excitons on short-circuit and saturation currents and on the spectral response of a monocrystalline silicon solar cell. The short-circuit current generated by the electrons decreases with the force of electron-hole coupling. To better quantify the impact of excitons, we plot the ratio between the short-circuit current generated by the electron-exciton system and the short-circuit current generated by electrons only (excitons neglected) by considering the non-cohabitation condition of electrons and excitons at the junction ($\Delta n_{ex0} = 0$). The result obtained shows a negative effect of the excitons on the short circuit-current. The excitons have also a negative effect on the saturation current. Indeed, when the electron and the hole forming the exciton are strongly bonded, their mobility decreases in the material causing a reduction of the electrons and excitons diffusion lengths. This reduces the short circuit-current and saturation current. We conclude our work by a quantitative study of the influence of excitons on the spectral response. The generation of excitons has a negative effect in the long wavelength range with a 6% decrease in the spectral response at a wavelength of 900 nm.

Keywords Exciton, coupling coefficient, short-circuit current, saturation current, spectral response

1. Introduction

The formation of excitons depends on the bond between the electron and the hole. This bond is modeled by a coefficient b called the exciton bond coefficient or coupling coefficient. When b is weak (10^{-12} cm^3.s^{-1} < b ≤ 10^{-9} cm^3.s^{-1}), the electron and hole of the exciton are weakly bound: these two particles do not form an exciton. However, if the electron and the hole of the exciton are strongly bound (10^{-9} cm^3.s^{-1} < b ≤ 10^{-7} cm^3.s^{-1}), an exciton is obtained [1-3]. In this case, the mobility of the particles decreases, thus causing a reduction in the effective diffusion lengths of the electrons. The study of the excitons on the performance of the solar cell, which our study revealed to be negative, consists of studying the influence of the coupling coefficient on the short-circuit and saturation currents and on the spectral response generated by the electron-exciton system. Indeed, in order to make this effect more visible, we have plotted the ratio between the short-circuit current generated by the electron-exciton system and that generated by the electrons only (without excitons). We consider a model of solar cell silicon n^+p simplified. The contribution of the emitter is neglected and the excitation energy is low.

2. Theoretical model

We consider the basic model of Green and Zhang, only minority carriers in the p- region are considered. The problem is to determine electrons and excitons densities between the positions x = 0 (the junction) and x = H (the back side). The distribution of carriers is governed by two coupled differential equations found in articles by Zhang and Corkish [1,2,4].

$$D_e d^2 \frac{\Delta n_e}{dx^2} = \frac{\Delta n_e}{\tau_e} + b(\Delta n_e N_A - \Delta n_{ex} n^*) - G_{e0} \exp[-\alpha x] \quad (1)$$

$$D_{ex} \frac{d^2 \Delta n_{ex}}{dx^2} = \frac{\Delta n_{ex}}{\tau_{ex}} - b(\Delta n_e N_A - \Delta n_{ex} n^*) - G_{ex0} \exp[-\alpha x] \quad (2)$$

Solving this equation system involves the following boundary conditions [4]:

At the junction:

$\Delta n_e (0) = 0$ (3)

$\Delta n_{ex} (0) = 0$ (4)

At the rear face

$$D_e \frac{d\Delta n_e}{dx}(H) = -S_e \Delta n_e(H) + b_s \Delta n_{ex}(H) \quad (5)$$

$$D_{ex} \frac{d\Delta n_{ex}}{dx}(H) = -S_{ex} \Delta n_{ex}(H) - b_s \Delta n_{ex}(H) \quad (6)$$

S_e and $S_{ex}$are respectively the recombination velocity of electrons and excitons in the rear surface.

b_s is the surface conversion velocity of excitons into free pairs electron-hole [4].

Indeed $S_e \rightarrow \infty$corresponds to an ohmic contact and $S_e = 0$ to a perfect surface .

Equations (3) and (4) respectively reflect the non- accumulation of electrons and perfect dissociation of excitons into free electrons and holes at the junction while the equations (5) and (6) are the phenomena of electrons and excitons recombination and excitonic conversions to the back surface.

The resolution of this system of equations leads to the following equations

$$\Delta n_e(x) = -M_{12}\left[A\exp\left(-\varepsilon_1^{1/2} x\right) + \chi_e \exp(-\alpha x) + B\exp(-\varepsilon_2^{1/2} x) + \chi_{ex} \exp(-\alpha x)\right]$$

$$\Delta n_{ex}(x) = (M_{11} - \varepsilon_1)\left[A\exp\left(-\varepsilon_1^{1/2} x\right) + \chi_e \exp(-\alpha x)\right] + (M_{11} - \varepsilon_2)\left[B\exp(-\varepsilon_2^{1/2} x) + \chi_{ex}\exp(-\alpha x)\right]$$

$$A = -\frac{\begin{bmatrix} D_e M_{12}\sqrt{\varepsilon_1}(\chi_e + \chi_{ex}) - S_e M_{12}(\chi_e + \chi_{ex}) \\ -b_s(\chi_e + \chi_{ex})(M_{11} - \varepsilon_1) \end{bmatrix} \exp\left(-\sqrt{\varepsilon_1} H\right) + \begin{bmatrix} -D_e M_{12}\alpha(\chi_e + \chi_{ex}) + S_e M_{12}(\chi_e + \chi_{ex}) + b_s \chi_e (M_{11} - \varepsilon_1) \\ + b_s \chi_{ex}(M_{11} - \varepsilon_2) \end{bmatrix} \exp(-\alpha H)}{\left\{ \begin{matrix} \left[-D_e M_{12}\sqrt{\varepsilon_1} + S_e M_{12} + b_s (M_{11} - \varepsilon_1)\right] \exp\left(-\sqrt{\varepsilon_1} H\right) \\ + \\ \left[D_e M_{12}\sqrt{\varepsilon_2} - S_e M_{12} - b_s (M_{11} - \varepsilon_2)\right] \exp\left(-\sqrt{\varepsilon_2} H\right) \end{matrix} \right\}} - (\chi_e + \chi_{ex})$$

$$B = \frac{\begin{matrix} \left[D_e M_{12}\sqrt{\varepsilon_1}(\chi_e + \chi_{ex}) - S_e M_{12}(\chi_e + \chi_{ex}) - b_s(\chi_e + \chi_{ex})(M_{11} - \varepsilon_1)\right] \exp\left(-\sqrt{\varepsilon_1} H\right) \\ + \\ \left[-D_e M_{12}\alpha(\chi_e + \chi_{ex}) + S_e M_{12}(\chi_e + \chi_{ex}) + b_s \chi_e (M_{11} - \varepsilon_1) + b_s \chi_{ex}(M_{11} - \varepsilon_2)\right] \exp(-\alpha H) \end{matrix}}{\left\{ \begin{matrix} \left[-D_e M_{12}\sqrt{\varepsilon_1} + S_e M_{12} + b_s (M_{11} - \varepsilon_1)\right] \exp\left(-\sqrt{\varepsilon_1} H\right) \\ + \\ \left[D_e M_{12}\sqrt{\varepsilon_2} - S_e M_{12} - b_s (M_{11} - \varepsilon_2)\right] \exp\left(-\sqrt{\varepsilon_2} H\right) \end{matrix} \right\}}$$

$$\chi_e = \frac{1}{M_{12}\delta^{1/2}(\alpha^2 - \varepsilon_1)}\left[(M_{11} - \varepsilon_2)\frac{G_{e0}}{D_e} + M_{12}\frac{G_{ex0}}{D_{ex}}\right]$$

$$\chi_{ex} = \frac{1}{M_{12}\delta^{1/2}(\alpha^2 - \varepsilon_2)}\left[(\varepsilon_1 - M_{11})\frac{G_{e0}}{D_e} - M_{12}\frac{G_{ex0}}{D_{ex}}\right]$$

The expressions of the quantities involved in these relations are available in the articles of Corkish and Zhang [1-2]. The short-circuit current generated by the electrons and the excitons in the base is given by:

$$J_e = qD_e \frac{d\Delta n_e}{dx}\Big|_{x=0} \quad \text{et} \quad J_{ex} = qD_{ex}\frac{d\Delta n_{ex}}{dx}\Big|_{x=0}$$

$$J_e = -qM_{12}\left[A\varepsilon_1^{1/2}\exp\left(-\varepsilon_1^{1/2} x\right) + \alpha\chi_e \exp(-\alpha x) + B\varepsilon_2^{1/2}\exp(-\varepsilon_2^{1/2} x) + \alpha\chi_{ex}\exp(-\alpha x)\right]$$

$$J_{ex} = -qD_{ex}\left\{ \begin{matrix} (M_{11} - \varepsilon_1)\left(A\varepsilon_1^{1/2}\exp\left(-\varepsilon_1^{1/2} x\right) + \alpha\chi_e \exp(-\alpha x)\right) \\ + \\ (M_{11} - \varepsilon_2)\left(B\varepsilon_2^{1/2}\exp(-\varepsilon_2^{1/2} x) + \alpha\chi_{ex}\exp(-\alpha x)\right]) \end{matrix} \right\}$$

The short circuit current density by neglecting the excitons, obtained by HOVEL is [5]:

$$J_H = \frac{qF\alpha L_e}{\alpha^2 L_e^2 - 1} \times \left[\alpha L_e - \frac{\frac{S_e L_e}{D_e}\left(\cosh\frac{H}{L_e} - \exp(-\alpha H) + \sinh\frac{H}{L_e} + \alpha L_e \exp(-\alpha H)\right)}{\frac{S_e L_e}{D_e}\sinh\frac{H}{L_e} + \cosh\frac{H}{L_e}} \right]$$

3. Results and Discussions

3.1. Short-circuit current as a function of the coupling coefficient

In this figure, we have represented the short-circuit current generated by each of the charge carriers in the base as a function of the binding coefficient of the excitons

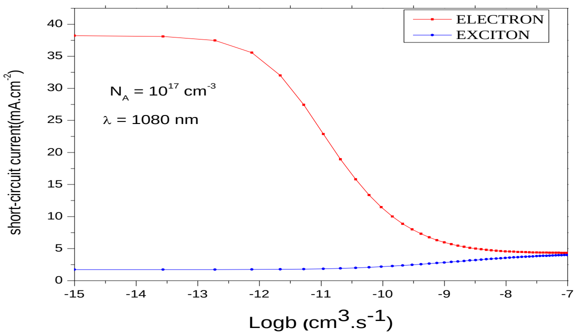

Figure 1: Densities of the short - circuit current as a function of the exciton binding coefficient (λ=1080 nm, H=1000µm, N_A=10^{17} cm^{-3})

The short-circuit current generated by the electrons decreases with the force of the electron-hole coupling while that generated by the excitons increases.

For the low values of the exciton bond coefficient ($10^{-15}cm^3.s^{-1} \leq b \leq 10^{-12}$ $cm^3.s^{-1}$), there is a negligible change in short-circuit currents. This same observation is noted for the very high values of this coefficient (10^{-9} $cm^3.s^{-1}$ $< b \leq 10^{-7}$ $cm^3.s^{-1}$). On the other hand, for 10^{-12} $cm^3.s^{-1} < b \leq 10^{-9}$ $cm^3.s^{-1}$, a very short drop of the short-circuit current generated by the electrons is obtained and a jump in the short-circuit current generated by the excitons. The interpretation of these curves involves the variations of the effective diffusion lengths as a function of b. Indeed, if b has a very low value, the electrons and the excitons diffuse respectively with diffusion lengths $L_1 \approx L_e$ and $L_2 \approx L_{ex}$ invariables. The values of the coefficient b between 10^{-12} and 10^{-9} $cm^3.s^{-1}$ indicate the transition phase between the weak coupling and the strong coupling. In this phase, the effective diffusion length of the electrons L_1 decreases abruptly, which explains the fall in the short-circuit current observed. For the large values of b, the diffusion of the excitons influences that of the electrons. The electron and the exciton diffuse with a constant effective diffusion length L_1 greater than L_{ex}, which explains the equality of the two short-circuit currents and the growth of the current generated by the excitons.

Influence of the doping rate

The following figure shows the influence of the doping rate on the profile of the short-circuit current as a function of b. A lowering of the short - circuit current profiles is obtained as a function of the increasing values of the doping rate in acceptor atoms. The increase of impurities in the material accelerates the phenomena of capture of excitons leading to the formation of exciton-impurity complexes, thus promoting the phenomena of recombination.

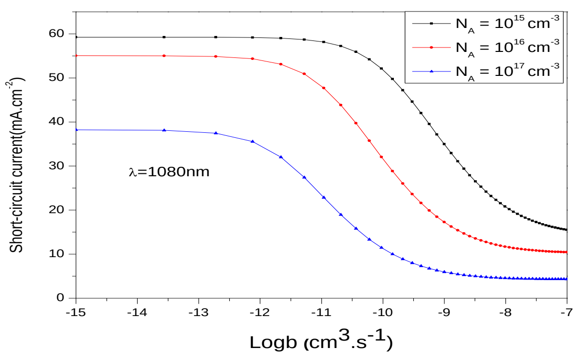

Figure 2: Densities of the short - circuit current as a function of the exciton binding coefficient for three values of the doping rate: N_A = 10^{15} cm^{-3}, N_A = 10^{16} cm^{-3} et N_A = 10^{17} cm^{-3}

3.2. Quantification of the effect of excitons on the short-circuit current

In order to quantify the effect of the excitons on the short-circuit current, we have plotted in Fig. 3 the ratio between the short-circuit current generated taking into account the excitons and that generated by neglecting them, found in the work of Hovel. This figure shows that the excitons reduce the short-circuit current when their binding coefficient is high. However, for low values of b, the excitons have no quantifiable effects. There is therefore a negative effect of the excitons, in the strong coupling and a negligible effect in the weak coupling.

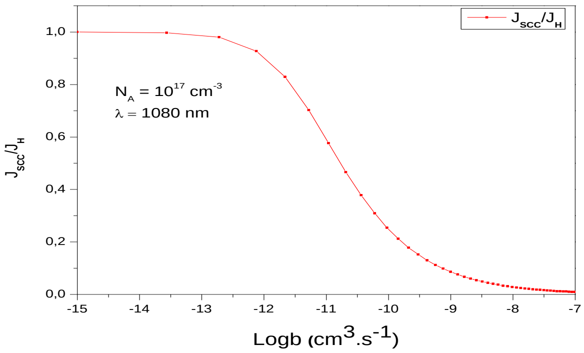

Figure 3: Ratio of the short-circuit current density taking into account the excitons with that obtained by neglecting the excitons. (λ=1080 nm, H=1000µm, $N_A=10^{17}cm^{-3}$)

3. 3. Saturation current as a function of b

We study the influence of excitons on the saturation current. The polarization voltage is fixed at -0.5V and we consider the condition of non-cohabitation of the excitons with the electrons at the junction (Δn_{ex0} = 0). To quantify this influence of the excitons, we calculated the ratio between the saturation current obtained taking into account the excitons and that obtained by neglecting them. The variations of such a ratio as a function of the coupling coefficient are recorded in Fig. 4. A decrease in the saturation current as a function of b is noted. Moreover, the excitons lower the saturation current in the strong couplings but are without observable effects in the weak coupling.

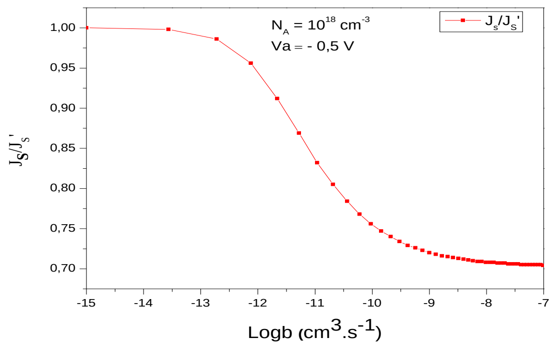

Figure 4: Rapport de la densité du courant de saturation tenant compte des excitons J_S avec celle obtenue en les négligeant J_S'. (Va = - 0,5 V, H =1000µm, $N_A=10^{17}cm^{-3}$)

Influence of doping rate

Fig. 5 shows the influence of the doping rate on the saturation current. We consider three values of the doping rate $N_A=10^{16}cm^{-3}$, $N_A=10^{17}cm^{-3}$ and $N_A=10^{18}cm^{-3}$.In the weak electron - hole coupling, the doping rate has no effect on the saturation current. However, for the other couplings, its increase leads to a considerable decrease in the saturation current which could be explained by the formation of an exciton-impurity complex, favoring the phenomena of recombination.

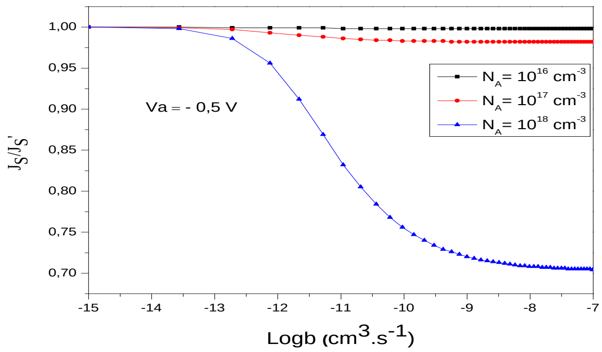

Figure 5 : Ratio of the dark saturation current density taking into account the excitons with that obtained by neglecting the excitons, for three values of the doping rate : $N_A=10^{16}$ cm^{-3}, $N_A=10^{17}$cm^{-3} and $N_A=10^{18}$cm^{-3} (Va = - 0,5 V, H=1000µm)

3.4. Spectral response

We have plotted in the following figures the spectral responses with or without excitons for each type of coupling.

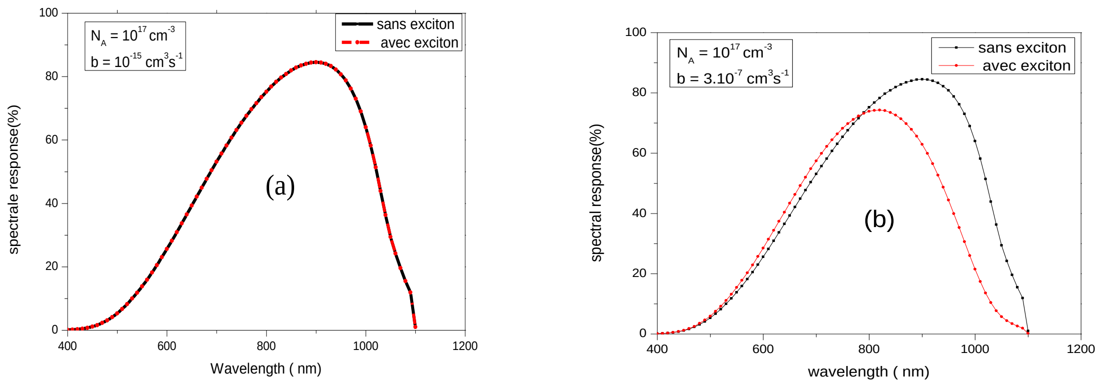

Figure 6: Spectral response as a function of the incident wavelength for weak coupling (a) and for strong coupling (b)

When the electron and the hole are weakly bonded, a negligible effect of the excitons is obtained. The spectral response reaches a maximum value of 84% at a wavelength equal to 900 nm.

Contrary to the previous case, the excitons have a clearly visible effect in Fig.6.b, when the coupling is strong. In the long wavelength range, the effect of the excitons is negative. A spectral response equal to 78% at a wavelength equal to 900 nm is also obtained. Moreover, the maximum of the spectral response is obtained at a lower wavelength. Indeed, the generation of excitons takes place in the long wavelengths. The strong generation of coupled excitons leads to a large loss of free electrons.

4. Conclusion

We investigated in this paper the influence of excitons on the performance of the solar cell. This study revealed that excitons reduced the performance of the solar cell. The excitons having a lower diffusion length than the electrons and the holes, carry the electrons in their movement, which results in a decrease in the diffusion length of the latter. To increase the yield of the photopile, one can reflect on the method of conversion of all the excitons into free electron-hole pairs.

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