Revue des Energies Renouvelables Vol. 11 N°4 (2008) 603 - 610
DOI: https://doi.org/10.54966/jreen.v11i4.110

Prediction of the performance degradation of GaAs solar cells by electron irradiation

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(reçu le 25 Octobre 2008 – accepté le 25 Décembre 2008)

Abstract - *Solar cells exposed to irradiation undergo severe degradation in their performance due to induced structural defects. To predict this effect, the current-voltage characteristics under AM0 illumination for a constant dose of electron irradiation are numerically calculated. From these characteristics the solar cell output parameters: the short circuit current density* J_{sc}, *the open circuit voltage* V_{oc}, *the fill factor FF and the conversion efficiency* η *are extracted. The irradiation induced defects introduce in the energy gap either recombination centres or traps. The irradiation induced degradation is widely attributed to the first type of defects. We have adopted a strategy to find out which defects are responsible for the degradation. This consists of simulating the effect of each defect separately on the output parameters. The simulation results show that traps are mainly responsible for the degradation of* J_{sc} *while recombination centres are responsible the degradation of* V_{oc}. *The other parameters (FF and* η*) are degraded by the combination of the traps and recombination centres.*

Résumé - *Les cellules solaires exposés à l'irradiation subissent une forte dégradation de leurs performances en raison de défauts structurels induits. Pour prévoir ce sens, les caractéristiques courant-tension sous un éclairement AM0, pour une dose constante d'irradiation d'électrons sont calculées numériquement. De ces caractéristiques, les paramètres de sortie des cellules solaires: la densité de courant de court-circuit* J_{sc}, *la tension de circuit ouvert* V_{oc}, *le facteur de remplissage FF et le rendement de conversion* η *sont extraits. L'irradiation induit des défauts dans le déficit énergétique, soit les centres de recombinaison ou de pièges. L'irradiation induit la dégradation, qui est largement attribuée au premier type de défauts. Nous avons adopté une stratégie visant à trouver des défauts qui sont responsables de la dégradation. Il s'agit de simuler l'effet de chaque défaut séparément sur les paramètres de sortie. Les résultats de la simulation montrent que les pièges sont principalement responsables de la dégradation de* J_{sc} *et que tous les centres de recombinaison sont responsables de la dégradation de* V_{oc}. *Les autres paramètres (FF* et η*) sont dégradés par la combinaison de pièges et des centres de recombinaison.*

Keywords: Paramètres de sortie – Cellule solaire – Dégradation – Pièges – Centres de recombinaison.

1. INTRODUCTION

Among compound semiconductor materials, GaAs is commonly preferred for spatial applications because of its advanced technology [1]. When exposed to particle irradiations such as electrons and protons, GaAs solar cells undergo significant deterioration in their performance.

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This is a serious problem for satellite power supplies. The mechanism of irradiation-induced degradation has been widely studied [2-8]. Electron irradiation for example introduces simple intrinsic defects that give rise to energy levels (recombination centers and traps) in the energy gap [4, 5].

It is believed that only deep levels (recombination centers) are responsible of the solar cell degradation since they decrease the free carrier lifetime [5].

In this work we show by numerical simulation using the full Shockley-Read-Hall, 'SRH' statistics that recombination centres induce a strong deterioration of V_{oc}, FF and η, while they hardly affect J_{sc}. To achieve this we have simulated the effect of each defect separately for an electron irradiation dose of 1×10^{17} cm^{-2}. This allowed us to quantify the degradation induced by each level on a particular solar cell parameter.

2. NUMERICAL MODELING

The simulation program developed provides a one dimensional numerical solution of the carrier transport problem in a GaAs p^+-n-n^+ solar cell subject to surface recombination velocity boundary conditions. A stationary simultaneous solution of Poisson's, hole and electron continuity equations, approximated by a finite difference, is obtained.

The effect of irradiation-induced defects is simulated by introducing each single level separately. The aim of this is to distinguish the effect of each defect level on the output parameters of the cell.

The solar cell used in this work has p^+ emitter and n^+ collector layers which are 0.02 and 0.04 µm thick and doped with 5×10^{17} and 1×10^{17} cm^{-3}, respectively, while the thickness of the n-type base region is 0.6 µm, doped with 1×10^{15} cm^{-3}. The transparent layer used is glass/TCO (transparent conductive oxide). Its transmittance ($T=0$) and the back reflection ($R=0.8$) of the n/metal contact are taken into account in the generation rate distribution, given by the following expression:

$$G(x) = \sum_{\lambda} T\alpha(\lambda).\phi(\lambda).\left[\exp(-\alpha(\lambda).x) + R\exp(-\alpha(\lambda).(2d-x))\right] \quad (1)$$

where α is the absorption coefficient, ϕ is the photon flux and d the thickness of the solar cell. Both α and ϕ depend on the wavelength λ.

The defects used in the simulation are electron traps: E_1, E_2, E_3, E_4 and E_5, and hole traps: H_0, H_1, H_2 and H_3 [5].

3. RESULTS AND DISCUSSION

We suppose that before irradiation native defects have a very low density (about 10^{12} cm^{-3}). This is a typical requirement of good quality solar cells used for space applications. Their capture cross sections are $\sigma_n = 10^{-13}\,cm^{-2}$ and $\sigma_p = 10^{-15}\,cm^{-2}$. The extracted J_{sc}, V_{oc}, FF and η in this case are 25.142 mA.cm^{-2}, 0.904 V, 0.862, 19.596 %, respectively. These are fairly in agreement with standard values of GaAs solar cells [9, 10]. The influence of each defect level on the $J-V$ characteristic for electron traps (E_2, E_3, E_4 and E_5) and for hole traps (H_1, H_2 and H_3) is shown in Fig. 1.

We found that the shallow levels E_1 and H_0 have no significant influence on the initial $J-V$ characteristic.

The deduced J_{sc}, V_{oc}, FF and η are presented in **Table 1** compared to the initial, before irradiation, state. It is clear that J_{sc} exhibits more sensitivity to less deep electron traps E_3 and E_2. However it is hardly influenced by deep electron trap levels (E_4, E_5) or hole trap levels (H_3, H_2, H_1). The non influence of hole traps can be understood sine they interact with free holes that have little contribution to the current density in comparison with free electrons.

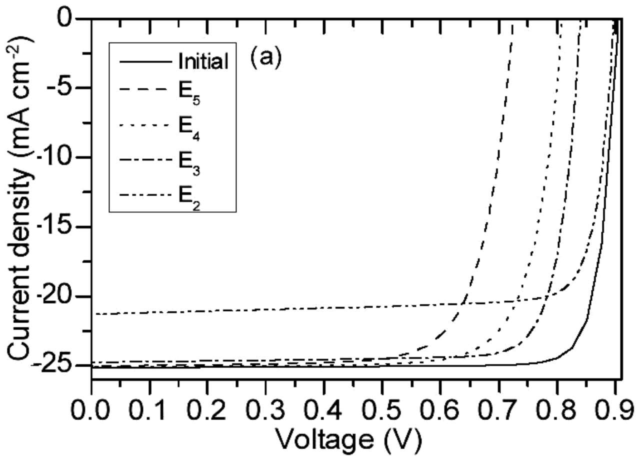
Contrarily, V_{oc} decreases as the defect level depth increases. This behaviour is indeed confirmed by applying the analytical relationship between V_{oc} and J_{sc} [11]:

$$V_{oc} = \frac{E_g}{q} - \frac{k_B T}{q} \ln\left[\frac{1}{J_{sc}} q . N_c . N_v \left(\frac{L_n}{n_n \tau_n} + \frac{L_p}{p_p \tau_p} \right) \right] \quad (2)$$

where N_c, N_v are the effective densities of states in the valence and conduction band, E_g is the band gap and L_n, L_p, n_n, p_p, τ_n, τ_p are the diffusion lengths, the densities and the lifetimes of electrons and holes respectively.

Table 1: The effect of each defect level on the initial output parameters of the cell

Defect level	J_{sc} ($mA.cm^{-2}$)	V_{oc} (V)	FF	η (%)
Initial	25.142	0.904	0.862	19.596
E_5	25.022	0.724	0.75505	13.678
E_4	25.113	0.808	0.78062	15.840
E_3	24.768	0.839	0.82873	17.221
E_2	21.286	0.896	0.82832	15.798
H_3	25.22	0.792	0.78121	15.604
H_2	25.183	0.790	0.78525	15.622
H_1	25.151	0.840	0.84827	17.921



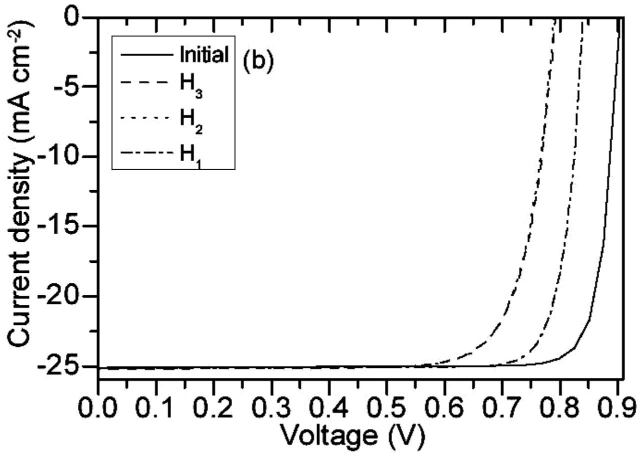


Fig. 1: The calculated $J-V$ characteristic when (a) only electron traps and (b) only hole traps are considered, both compared to the non irradiate case

In **Table 2**, we present a comparison between the V_{oc} defect dependency obtained numerically and that calculated analytically using Eq. (2) in the case of electron traps for example.

The V_{oc} defect dependency is related mainly to the $L_n / n_n . \tau_n$ ratio which has a maximum value for E_5 (see **Table 2**) where the corresponding n_n and τ_n values are 1.389×10^{15} cm^{-3} and 5.2632×10^{-12} s.

For E_2, however, n_n and τ_n reach 2.2626×10^{16} cm^{-3} and 10^{-10} s, respectively. This is expected sine E_2 is more ionized than E_5 (the deepest level) and its capture cross section is smaller [5].

Table 2: Comparison between V_{oc} obtained numerically and analytically, and $L_n / n_n . \tau_n$

V_{oc} (V)	Initial	E_2	E_3	E_4	E_5
Simulated	0.904	0.896	0.839	0.808	0.724
Analytical	0.9324	0.8803	0.8433	0.7795	0.7751
$\frac{L_n}{n_n . \tau_n} .10^{-11}$	1.0676	6.5545	33.0	393.0	465.36

To explain the J_{sc} dependency on defect levels, we plotted in Fig. 2 the recombination rates corresponding to each defect level compared to the photo generation rate. It is well known that the current density is proportional to $\int (G(x) - U(x)) dx$, where $U(x)$ is the recombination rate.

Then any reduction in $G(x) - U(x)$ will decrease the current density. The electron trap E_2 has the highest recombination rate represented as U_{E_2} in Fig. 2(a) which leads to the highest reduction in J_{sc} observed in Fig. 1(a). The other electron traps (E_3, E_4 and E_5) have comparable overall recombination rates therefore comparable reduction of the current density.

To explain the recombination rate profile set by the different defect levels, we plot those of n, p, and $n.p / n_i^2$ in Fig. 3(a), 3(b), 3(c), 3(d), 3(e), 3(f), where n_i is the intrinsic density. This is done since the recombination rate at a defect level according to Shockley-Read-Hall statistics is given by [12, 13].

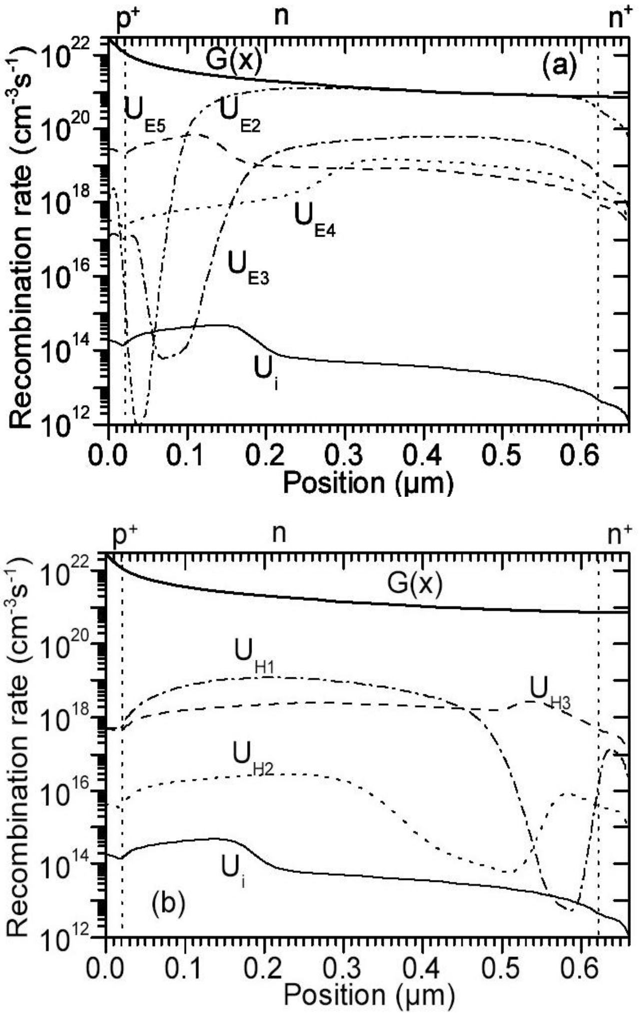


Fig. 2: The calculated recombination rates corresponding to each defect level

$$U = \frac{(n.p - n_i^2)}{\tau_{pr}(n + n_1) + \tau_{nr}(p + p_1)} \tag{3}$$

where τ_{nr} and τ_{pr} are the minority carrier lifetime which are related to the defect level by $\tau_{nr} = 1/C_n N_r$, $\tau_{pr} = 1/C_p N_r$, where C_n and C_p are the capture coefficients for electrons and holes, respectively, N_r is the defect density, n_1 and p_1 are the electron and hole densities when theirs quasi-Fermi levels coincide with the defect level.

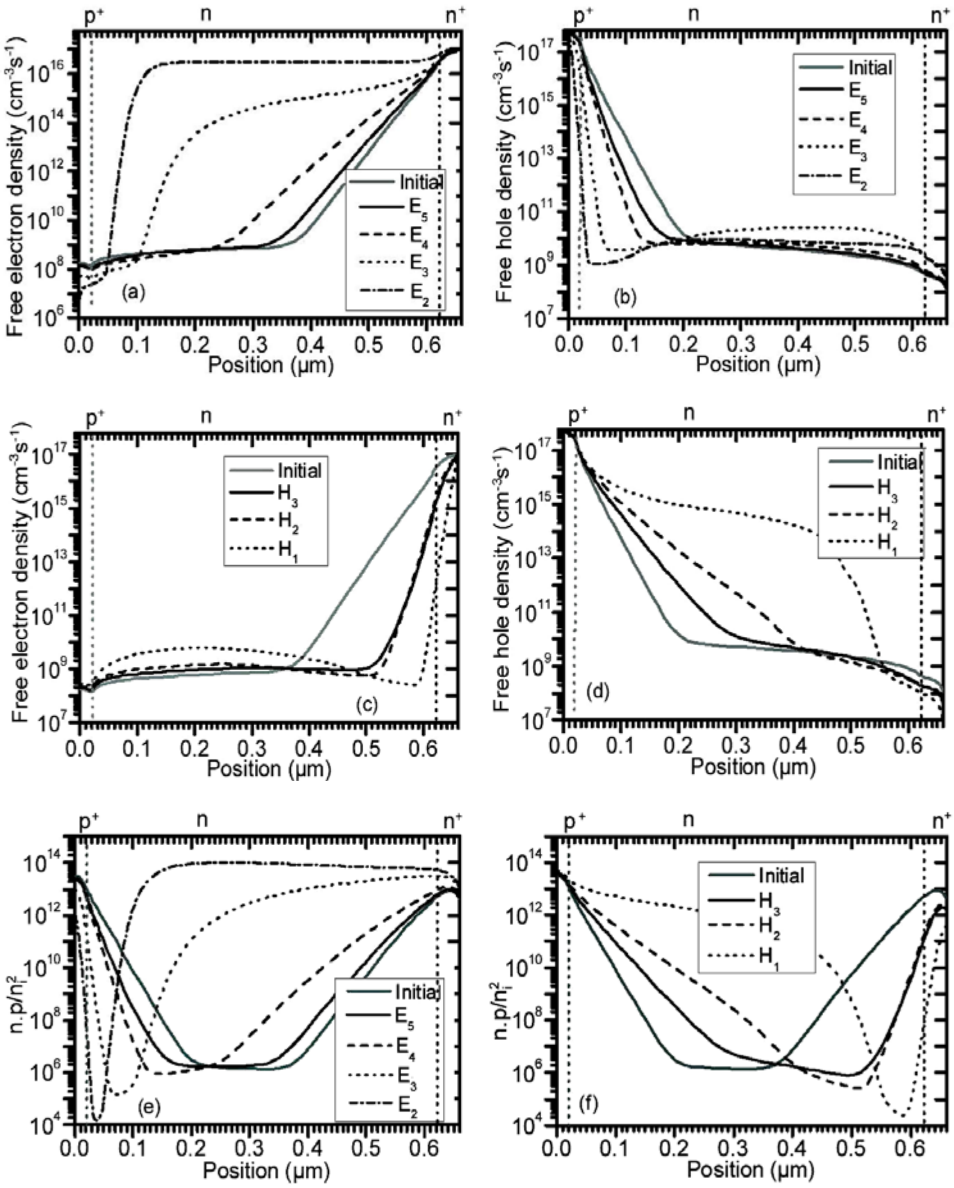


Fig. 3: n , p , and $n.p / n_i^2$ profiles for the different defect levels

From Fig. 3(a), there is a considerable increase of n in the base region as the electron trap is less deep, while p decreases less significantly in the left side of the device (Fig. 3(b)).

This is reproduced on the n.p profile (Fig. 3(e)) that appears as the predominant term in U_{E_2} profile. Almost the same observation holds in case of hole traps, where the largest increase of p in the base region for the least deep hole tap H_1 (Fig. 3(d)) while a decrease of n (Fig. 3(c)) in the right side of the device occur.

This also leads to the fact that the n.p product (Fig. 3(f)) dominate the highest recombination rate shape, U_{H_1}.

4. CONCLUSION

We have numerically simulated the effect of electron irradiation on the performance of GaAs p^+-n-n^+ solar cells. Damage-induced by electron irradiation give rise to several defect levels. These introduce recombination centers and traps in the energy gap of the semiconductor. First the current-voltage characteristic is calculated. Then the effect of each defect level on this characteristic is estimated.

The cell output parameters are then extracted from these characteristics for each case stated above. The aim of simulating the effect of each defect level separately is to find out which of them are responsible for the degradation of a particular output parameter. Two distinguished effects were observed. First, donor levels affect all output parameters. Second, acceptor levels hardly affect the short circuit current.

For the first case, the less deep donor levels affect mainly the short circuit current, while the deeper ones affect mainly the open circuit voltage. The deeper is the donor level, the smaller is the effect on the short circuit current while the bigger is the effect on the open voltage circuit.

For the second case the deeper is the acceptor level, the bigger is the effect on the open circuit voltage.

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