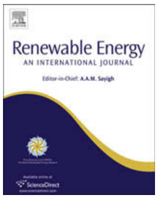
Renewable Energy xxx (2009) 1–4

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene



Detailed numerical simulation of the effect of defects created by electron irradiation on the performance degradation of a p^+–n–n^+ GaAs solar cell

A.F. Meftah [a,*], N. Sengouga [a], A.M. Meftah [a], A. Belghachi [b]

[a] Laboratory of Metallic and Semiconducting Materials, Faculty of Science and Engineering, Mohamed Kheider University, B.P. 145, 07000 Biskra, Algeria
[b] Laboratory of Semiconductor Devices Physics, Physics Department, University of Béchar, P.O. Box 417, Béchar 08000, Algeria

ARTICLE INFO

Article history:
Received 19 August 2008
Accepted 15 March 2009
Available online xxx

Keywords:
Solar cell
GaAs
Electron irradiation
Degradation

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 following 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. A strategy is adopted to check the truthfulness of this by simulating the effect of each single trap level separately on the output parameters of the cell. The simulation results show that only the shallowest deep electron trap is responsible for the degradation of J_{sc} while V_{oc} is mostly affected by other electron and hole traps especially the deepest one. This more detailed study is an extension of another work in which the effect of a group instead of individual levels is investigated.

1. Introduction

Solar cells used in space are exposed to energetic particles such as electrons, protons and neutrons. This results in the degradation of their performance on a long time scale. To understand the degradation of the solar cell quality, extensive experimental work was carried out by many groups [1–8]. Analytical modelling was used to relate this experimentally observed degradation to the irradiation induced defects [1,2]. The experimental characterisation is time consuming and can be very expensive. The analytical modelling has also to accept several simplifications, such as the dominance of deep defects (or recombination centres) in affecting the cell output parameters [1,2].

Numerical simulation is an alternative and a powerful tool. Many parameters can be varied to model the observed phenomenon. In this present study the variables are the defects and the phenomenon is the degradation of the solar cell output parameters. Numerical simulation can also offer a physical explanation of the observed phenomenon since internal parameters can be calculated such as the electrical field, the recombination rate and the free carrier densities. In addition to all these advantages, numerical simulation can be used as a tool to predict output parameters' degradation before any exposure to irradiation. It can also be used to estimate the projected lifetime of the solar cell. The lifetime is estimated by the degree of degradation, for example when the conversion efficiency of the output power of the solar cell reaches a certain minimal requirement. Numerical simulation predicts how much irradiation dose is able to degrade these parameters to the minimal requirement. The duration needed for the solar cell to receive this dose is its lifetime.

Usually several defects are created in the solar cell exposed to energetic particles in space [1–8]. So it is very difficult for an experimental work to relate the degradation to one particular defect in detail. In some recent work the degradation in the solar cell output parameters, in particular the short circuit current, is used in parallel with other techniques such as DLTS to evaluate some parameters of recombination centres such as the capture cross-sections [2,3]. This is done by considering that only recombination centres (levels near mid gap) are mainly responsible for the degradation of the short circuit current [2].

The advantage of numerical simulation is that the effect of the observed defects can be studied individually. This will certainly clarify which of the defects are responsible for the degradation of a particular parameter. In this respect either a group of similar or individual defects are included at once in the simulation. The first case was considered in another work [9]. The second case is considered in this work to show that not only the deep levels (recombination centres) but also traps (less deep levels) can

---

* Corresponding author. Tel./fax: +213 33 74 10 87.
E-mail address: af_mef@yahoo.fr (A.F. Meftah).

0960-1481/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.renene.2009.03.019

Please cite this article in press as: Meftah AF et al., Detailed numerical simulation of the effect of defects created by electron irradiation on..., Renewable Energy (2009), doi:10.1016/j.renene.2009.03.019

contribute to the degradation by electron irradiation. This indicates that neglecting the effect of the less deep levels may lead to errors in evaluating the recombination centre parameters.

2. Numerical model of the GaAs p^+–n–n^+ solar cell

A simulation program which 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, was developed. Namely, a stationary simultaneous solution of the following Poisson's equation and the hole and electron continuity equations, approximated using a finite difference scheme. These equations are:

$$\frac{1}{q}\frac{dJ_n}{dx} + G(x) - U(x) = 0 \tag{1a}$$

$$\frac{1}{q}\frac{dJ_p}{dx} - G(x) + U(x) = 0 \tag{1b}$$

$$\frac{d^2\psi}{dx^2} = -\frac{q}{\varepsilon\varepsilon_o}\rho(x) \tag{2}$$

where

$$J_n = -q\mu_n n\frac{d\psi}{dx} + k_B T\mu_n\frac{dn}{dx} \tag{3a}$$

and

$$J_p = -q\mu_p p\frac{d\psi}{dx} - k_B T\mu_p\frac{dp}{dx} \tag{3b}$$

are the electron and hole conduction current densities, G is the generation rate, μ_n and μ_p are the free electron and hole mobilities ($cm^2\,V^{-1}\,s^{-1}$), T is the absolute temperature, $\varepsilon_o = 8.85 \times 10^{-14}$ F cm^{-1} the permittivity of the free space and ε the dielectric constant, k_B is the Boltzmann constant, $\rho(x)$ is the space charge density and $U(x)$ is the recombination rate given by SRH (Shockley–Read–Hall) statistics:

$$U = \frac{(np - n_i^2)}{\tau_{pr}(n + n_1) + \tau_{nr}(p + p_1)} \tag{4}$$

where τ_{nr} and τ_{pr} are the minority carrier lifetime which are related to the defect level by $\tau_{nr} = 1/\sigma_n v_{th} N_r$, $\tau_{pr} = 1/\sigma_p v_{th} N_r$, where σ_n and σ_p are the capture cross-sections for electrons and holes, respectively, $v_{th} \sim 10^7$ cm s^{-1} is the thermal velocity, N_r is the defect density and n_1 and p_1 are the electron and hole densities when their quasi-Fermi levels coincide with the defect level.

In the initial state (before irradiation) a very low density for the native defects is supposed (about 10^{12} cm^{-3}) which is a typical requirement of good quality solar cells used for space applications. The native defects can be grouped in a single recombination centre with capture cross-sections of $\sigma_n = 10^{-13}$ cm^{-2} and $\sigma_p = 10^{-15}$ cm^{-2}. For the irradiated state the introduction rate (the number of defects per unit fluence), the energy position and the capture cross-section of each defect used in this work are summarized in Table 1 [2,3]. For the electron traps (E_1, E_2, E_3, E_4 and E_5) a high ratio of the capture cross-sections for electrons with respect to that of holes is assumed, that is $\sigma_n/\sigma_p = 100$. Oppositely, $\sigma_p/\sigma_n = 100$ for the hole traps (H_0, H_1, H_2 and H_3). It has to be pointed out that not much information whether electron traps and hole traps are both observed in n-type and p-type GaAs or that electron traps are only observed in n-type GaAs while hole traps are observed only in p-type GaAs. Therefore it is considered that both types of traps are present in both types of GaAs. This assumption is acceptable since the distinction between electron traps and hole traps is set by the σ_n/σ_p ratio. If for example a centre can act as a trap for electrons as well as for holes then it will have the capture cross-section for electrons of the electron trap and the capture cross-section for holes of the hole trap.

Table 1
Parameters of electron (E_i) and hole traps (H_i) induced in GaAs by electron irradiation; k is the introduction rate of defects, E_t the defect level position, σ_n and σ_p the capture cross-sections of electrons and holes, respectively [2,3].

Defects	k(cm^{-1})	$E_C - E_T$(eV)	σ_n(cm^2)
E_1	1.50	0.045	2.2×10^{-15}
E_2	1.50	0.140	1.2×10^{-13}
E_3	0.40	0.300	6.2×10^{-15}
E_4	0.08	0.760	3.1×10^{-14}
E_5	0.10	0.960	1.9×10^{-12}
Defects	k(cm^{-1})	$E_V + E_T$(eV)	σ_p(cm^2)
H_0	0.8	0.06	1.6×10^{-16}
H_1	0.1–0.7	0.29	5.0×10^{-15}
H_2	Not given	0.41	2.0×10^{-16}
H_3	0.2	0.71	1.2×10^{-14}

The solar cell used in this work has p^+ emitter and n^+ collector layers which are 0.02 and 0.04 μm thick, respectively, while the thickness of the n-type base region is 0.6 μm. The transparent layer used is glass/TCO (transparent conductive oxide). Its transmittance T and the back reflection coefficient R of the n/metal contact are taken into account. These are included in the generation rate G profile. When AM0 solar spectrum is used to simulate space conditions, G is given by the following expression:

$$G(x) = \sum_{\lambda} T\alpha(\lambda)\phi(\lambda)[\exp(-\alpha(\lambda)x) + R\exp(-\alpha(\lambda)(2d - x))] \tag{5}$$

where α is the absorption coefficient, φ is the photon flux and d is the thickness of the solar cell. Both α and φ depend on the wavelength λ. The parameters used in the numerical simulation are listed in Table 2.

The effect of irradiation induced defects is simulated by first calculating the J–V characteristic before irradiation then the effect of each single level on this characteristic. The output parameters of the cell: J_{sc}, V_{oc}, FF and η are then extracted. The aim of this is to show that the degradation cannot only be due to recombination centres as it is believed [2].

3. Results and discussion

The extracted J_{sc}, V_{oc}, FF and η in the initial state are 25.142 mA cm^{-2}, 0.904 V, 0.862, 19.596%, respectively (Table 3). These are fairly in agreement with standard values of GaAs solar

Table 2
The solar cell parameters used in the simulation.

Symbol	Parameter	Value
E_g	Energy gap (eV)	1.43
N_a	p^+-layer doping density (cm^{-3})	5×10^{17}
N_d	n-layer doping density (cm^{-3})	1×10^{15}
N_d	n^+-layer doping density (cm^{-3})	1×10^{17}
Φ	Irradiation dose (cm^{-2})	1×10^{17}
N_{nd}	Native defect density (cm^{-3})	1×10^{12}
σ_{no}	Electron capture cross-section for native defects	1×10^{-13} cm^2
σ_{po}	Hole capture cross-section for native defects	1×10^{-15} cm^2
T	Glass/TCO transmittance	0.8
R	n/metal contact reflectivity	0.8

Please cite this article in press as: Meftah AF et al., Detailed numerical simulation of the effect of defects created by electron irradiation on..., Renewable Energy (2009), doi:10.1016/j.renene.2009.03.019

Table 3
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	$\eta(\%)$
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

cells [10,11]. 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. For E_1 and H_0 it is found that these shallow levels have no significant influence on the initial *J–V* characteristic. The extracted J_{sc}, V_{oc}, FF and η are presented in Table 3 compared to the initial state.

It is clear that J_{sc} exhibits more sensitivity to less deep electron traps in particular 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 since they interact with free holes that have little contribution to the current density in comparison with free electrons. To explain the J_{sc} dependency on defect levels, the recombination rates corresponding to each defect level compared to the photo-generation rate are plotted in Fig. 2. According to free carrier continuity equations the current density is proportional to $\int(G(x) - U(x))\mathrm{d}x$, where $U(x)$ is given by Eq. (4). This expression of $U(x)$ is applicable to all defect types regardless of their energy positions in contrast to the simplified formula ($U_{n(p)} = \Delta n(p)/\tau_{n(p)}$) which takes into account only one defect (the most dominant). Then any reduction in the current density is due to the decrease in $G(x) - U(x)$. From Fig. 2(a), the electron trap E_2 has the highest recombination rate represented as U_{E2} 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.

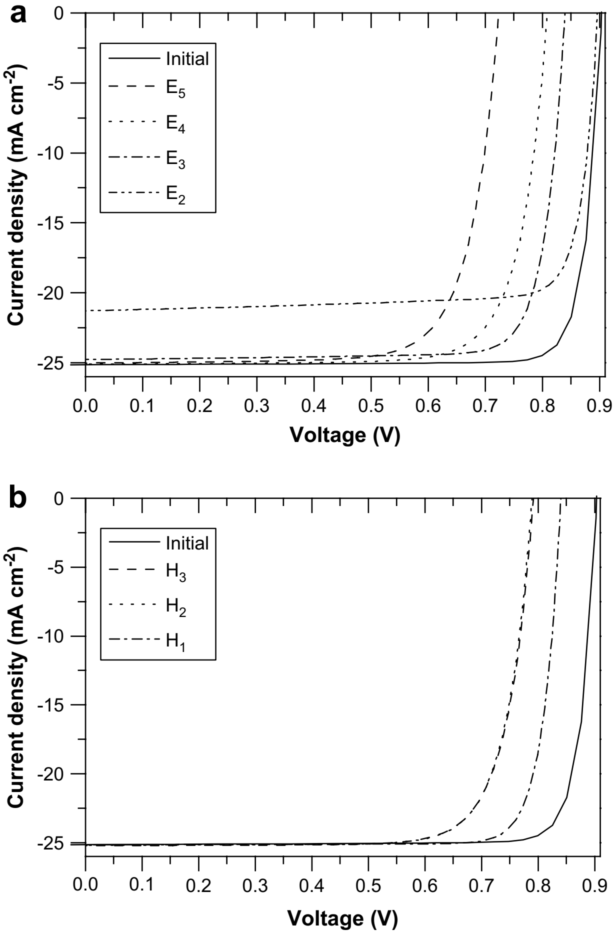


Fig. 1. The calculated *J–V* characteristic when (a) only single electron trap and (b) only single hole trap is considered, both compared to the non-irradiated case.

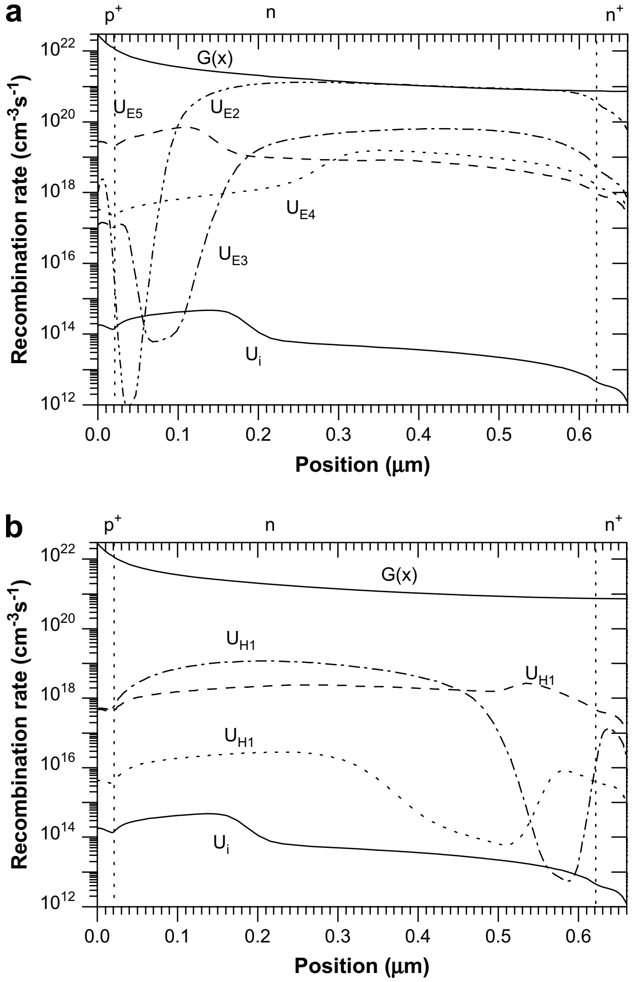


Fig. 2. The calculated recombination rates corresponding to each defect level: (a) electron traps and (b) hole traps.

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} [12];

$$V_{oc} = \frac{E_g}{q} - \frac{k_B T}{q} \ln\left[\frac{1}{J_{sc}} q N_c N_v \left(\frac{L_n}{n_n \tau_n} + \frac{L_p}{p_p \tau_p}\right)\right] \tag{6}$$

Where N_c, N_v are the effective densities of states in the conduction and valence band and L_n, L_p, n_n, p_p, τ_n, τ_p are the diffusion lengths,

Table 4
Comparison between V_{oc} obtained numerically and analytically.

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
$\frac{L_n}{n_n \tau_n} \times 10^{-11}$	1.0676	6.5545	33.0	393.0	465.36

Please cite this article in press as: Meftah AF et al., Detailed numerical simulation of the effect of defects created by electron irradiation on..., Renewable Energy (2009), doi:10.1016/j.renene.2009.03.019

Table 5
The extracted output parameters of the solar cell before and after irradiation, when deep levels and all levels are considered [9].

	J_{sc}(mA cm^{-2})	V_{oc}(V)	FF	η(%)
Before irradiation	25.142	0.904	0.862	19.596
Deep levels	25.11	0.595	0.7147	10.696
All levels	21.512	0.812	0.75957	13.272

the densities and the lifetimes of electrons and holes respectively. In Table 4, a comparison between the V_{oc} defect dependency obtained numerically and that calculated analytically using (2) in the case of electron traps for example, is presented. 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 4) 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 since E_2 is more ionized than E_5 (the deepest level) and its capture cross-section is smaller (Table 1).

In Table 5 a summary of another work [9] is reported. In this work it was found that J_{sc} is hardly affected by the deep levels only while V_{oc} and the other parameters are greatly reduced. The addition of less deep levels engenders further sensitivity of J_{sc} while the V_{oc}, FF and η deteriorations become reasonable. Hence the actual study is an enhancement of the previous findings.

4. Conclusion

The changes induced by electron irradiation in the output parameters of a GaAs p$^+$–n–n$^+$ solar cell are extracted from the photo-current voltage characteristics calculated by numerical simulation. The electron irradiation creates several defects which act as either recombination centres (deep levels) or traps (less deep levels). The effect of each defect level on the *J*–*V* characteristic is estimated in the aim to find out which of them are responsible for the degradation of a particular output parameter. It is found that electron trap levels affect all output parameters while hole trap levels hardly affect the short circuit current. For electron traps, the least deep level affects mainly the short circuit current. The deepest trap (for electrons and holes) affects mainly the open circuit voltage. This supports our previous work in which it was found that all defects contribute to the degradation and not only the deep one (recombination centres).

In the end an important point has to be clarified. The use of the simplified expression for the recombination rate, that is the recombination is dominated by one single recombination centre, may reproduce the degradation observed experimentally as reported by other groups. However, this can be a forced mathematical approach since using the full SRH, the degradation is reproduced if all defects are taken into account. Hence enormous errors are expected in evaluating the defect parameters based on the simplified approach.

References

[1] de Angelis N, Bourgoin JC, Takamoto T, Khan A, Yamaguchi M. Solar cell degradation by electron irradiation. Comparison between Si, GaAs and GaInP cells. Sol Energy Mater Sol Cells 2001;66:495–500.

[2] Bourgoin JC, Zazoui M. Irradiation-induced degradation in solar cell: characterisation of recombination centres. Semicond Sci Technol 2002;17:453–60.

[3] Pons D, Bourgoin JC. Irradiation-induced defects in GaAs. J Phys C Solid State Phys 1985;18:3839–71.

[4] Yamaguchi M. Radiation-resistant solar cells for space use. Sol Energy Mater Sol Cells 2001;68:31–53.

[5] Bourgoin JC, de Angelis N. Radiation-induced defects in solar cell materials. Sol Energy Mater Sol Cells 2001;66:467–77.

[6] Mbarki M, Sun GC, Bourgoin JC. Prediction of solar cell degradation in space from the electron–proton equivalence. Semicond Sci Technol 2004;19:1081–5.

[7] Hadrami M, Roubi L, Zazoui M, Bourgoin JC. Relation between solar cell parameters and space degradation. Sol Energy Mater Sol Cells 2006;90:1486–97.

[8] Warner JH, Messenger SR, Walters RJ, Summers GP, Lorentzen JR, Wilt DM, et al. Correlation of electron radiation induced-damage in GaAs solar cells. IEEE Trans Nucl Sci August 2006;53(No. 4):1988–94.

[9] Meftah AF, Sengouga N, Belghachi A, Meftah AM. Numerical simulation of the effect of recombination centres and traps created by electron irradiation on the performance degradation of GaAs solar cells. J Phys Condens Matter (IOP), submitted for publication.

[10] Green MA, Emery K, King DL, Igari S, Warta W. Solar cell efficiency tables (Version 21). Prog Photovolt Res Appl 2003;11:39–45.

[11] Chandrasekaran N, Soga T, Inuzuka Y, Imaizumi M, Taguchi H, Jimbo T. 1 MeV electron irradiation effects of GaAs/Si solar cells. Mater Res Soc Symp Proc 2005;836:L6.7.1–6.7.6.

[12] Sze SM. Physics of semiconductor devices. 2nd ed. New York: John Wiley and Sons; 1982.

Please cite this article in press as: Meftah AF et al., Detailed numerical simulation of the effect of defects created by electron irradiation on..., Renewable Energy (2009), doi:10.1016/j.renene.2009.03.019