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Effect of proton irradiation fluence on the performance of the $Al_xGa_{1-x}As/GaAs$ p^+nn^+ solar cell

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ABSTRACT/RESUME

Abstract: *The particles' radiation as protons induces severe degradation on the performance of solar cells used in the space application. This degradation is usually attributed to lattice damage in the active region of the solar cell. In this work numerical simulator SCAPS is used to model the effect of 1 MeV proton irradiation on the performance degradation of* p^+*-n-*n^+ *GaAs solar cell. The effect is predicted by the calculation of the current–voltage characteristics under AM0 illumination for a several doses of proton irradiation. Simulating the effect of electron and hole trap levels, deep and less deep helps to find out which of them is responsible for the degradation of particular output parameter. The simulation results have shown that the extracted output parameters of the cell* J_{SC}, V_{OC}, *FF,* η *before irradiation are: 24 mA/cm*^{2}*, 1.01 V, 0.88 and 15.65 %, respectively and a p+-n-n+GaAs solar cell is sensitive to* 10^{13} *cm*$^{-2}$ *proton irradiation fluence, the conversion efficiency* η *is the most sensitive parameter of the cell with a degradation ratio of 0.4. The deep electron traps, PR1 and PR2 are responsible for the degradation of the solar cell. The obtained results have shown that the resistivity of the solar cell to proton irradiation has improved by making the n+ GaAs collector thickness thinner, the conversion efficiency and the short circuit current density Jsc of the solar cell is increased to 6.7%, and 17.88 mA/cm*^{2} *of the initial value, respectively.*

I. Introduction

Space satellites and crafts working outside the atmosphere capture their energy from sunlight. In order to convert solar energy into electrical energy, photovoltaic panels are installed on the surface of satellites or space crafts. GaAs solar cells have been used for space applications since 1982. Due to their good properties such as high quantum efficiency and good irradiation tolerance, they are suitable for space applications [1]. The study of radiation induced defects in GaAs has received considerable attention due to the interest in using GaAs electronic devices for space systems. This subject is equally important for understanding damage in GaAs during ion implantation used in device processing. Although the energy range and type of radiation used in these two fields are different. The nature of the principal defects induced by radiation could have substantial similarities. It is well known that a long working of a semiconductor device in the space environment can result in varying degrees of permanent degradation of device performance due to radiation damage created in the semiconductor material. In space, these devices get irradiated with a range of light and heavy nuclear particles over a wide energy spectrum.

Many effort has been given to the effects of high energy radiation on solar cells' investigations. The principal use for photovoltaic cells is the main reason for such research, those cells thus far has been to provide power on space vehicles intended for long periods of operation in an environment which includes the high energy electrons and protons of the earth's radiation Il belts [2, 3].

The mostet employed technique to characterize defects created by irradiation is Deep-level Transient Spectroscopy (DLTS). For example, for electron irradiation: the introduction rate, the energy levels and the capture cross sections of defects in GaAs were determined by many authors [2,4,5,6]. Effects due to irradiation with protons have also received considerable attention. Many papers give the energy levels and capture cross sections of defects created by proton irradiation, using DLTS measurements [6, 7]. However, few information on the defect's introduction rates are given, specially the introduction rates of hole traps.The impact of the protons' radiation on solar cells and mention some of them [8, 9, 10] is continued by research.

In this paper, first we will consider a $Al_xGa_{l-x}As$/GaAs solar cell and will model the effect of 1 MeV proton irradiation using the parameters of the irradiation-induced defects on the performance degradation of the solar cell. Simulations are then carried out for 1 MeV proton irradiation with fluences ranging from 10^{11} to 10^{13} p/cm^2. The effect of type defect within the p^+nn^+ junction is quantified for different fluences. The type of defects which are the most responsible for the degradation of the GaAs solar cell photovoltaic parameters (short-circuit current, open-circuit voltage, fill factor and efficiency) are finally highlighted by parametric numerical simulations. Then we will study the effect of the n^+ GaAs collector thickness on the performance degradation of the solar cell. It will be shown that by choosing appropriate thickness for the n^+ GaAs collector layer, we can considerably reduce the long-term degradation of the solar cell.

II. Simulation

Numerical simulation is a powerful tool which helps in understanding experimental observation and to relate irradiation induced solar cell degradation to defects. Many parameters can be varied to model the observed phenomenon. It can also offer a physical explanation of the observed phenomenon since internal parameters such as the recombination rate and the free carrier densities can be calculated. In addition to all these advantages, numerical simulation can be used as a tool to predict output parameter degradation before any exposure to irradiation, and to estimate the lifetime of the solar cell as well.

In this work numerical simulator SCAPS is used to model the effect of 1 MeV proton irradiation on the performance degradation of p^+-n-n^+ GaAs solar cell. SCAPS is a Windows application program, developed at the University of Gent with LabWindows/CVI of National Instruments. It has been made available to university researchers in the photovoltaic community after the second PV World Conference in Wien, 1998 [11]. The program is organised in a number of panels (or windows or pages in other jargon), in which the user can set parameters or in which results are shown. The program opens with an `action panel', where the user can set an operating point (temperature,voltage, frequency, illumination), and an action list of calculations to carry out (I±V, C± V, C±f, Q(l)) [11].Which gives numerical solution of the carrier transport problem in a p+nn+ GaAs solar cell, a typical GaAs based solar cell configuration, recombination and generation profile, which is based on the electron and hole continuity equations together with Poisson equation. The Poisson's equation which relates the electrostatic potential to the space charge density is given by:

$$\varepsilon \frac{d^2\psi}{dx^2} = -\rho(x) \tag{1}$$

Where ε is the local permittivity, ψ is the electrostatic potential, and ρ is the local space charge density. The continuity equations in steady state for holes and electrons are expressed, respectively by:

$$\frac{1}{q}\frac{dJ_n}{dx} + G_n - R_n = 0 \tag{2}$$

$$-\frac{1}{q}\frac{dJ_p}{dx} + G_p - R_p = 0 \tag{3}$$

where p and n are hole and the electron concentration, G_p and G_n are the generation rates for holes and electrons, R_p and R_n are the recombination rates for holes and electrons, J_p and J_n are the hole and electron current densities and q is the electron charge.

To model irradiation induced defects, Shockley-Read-Hall recombination term is modified as follows [1]:

$$R_{SRH} = \sum_{j=1}^{m} \frac{n \cdot p - n_i^2}{\tau_p \cdot (n+n_t) + \tau_n \cdot (p+p_t)} \tag{4}$$

where

j (≈1 to m) is the number of defects created by irradiation; n_i, p, n, n_t and p_t are the intrinsic carrier concentration, the hole density, the electron density and the minority carrier densities respectively; $\tau_p$et τ_n are respectively lifetime of holes and electrons given by:

$$\frac{1}{\tau_{n/p}} = \frac{1}{\tau_{0_{n/p}}} + \frac{1}{\tau_{rad_{n/p}}} + N_t \sigma_{n/p} v_{th_{n/p}} \tag{5}$$

τ_0 is the native minority carrier lifetime; τ_{rad} is the radiative recombination rate; v_{th} is the carrier velocity; σ is the cross section for the capture of minority carrier by the non-radiative recombination center induced by the irradiation; N_t is the trap concentration, which is associated with the introduction rate of the recombination centers k and the fluence φ:

$$N_t = K \cdot \varphi \qquad \textbf{(6)}$$

The solar cell studied is a p^+nn^+ junction. It contains an AlGaAs (p^{++}) window with a variable Al/Ga molar fraction which confers the solar cell a gradual energy gap Eg, thus improving the short wavelengths photons absorption. The thicknesses and doping densities of each layer are given in Table 1. The p^+nn^+ /GaAs solar cell parameters used in the simulation are listed in Table 2.

Table 1. *Description of the p^+nn^+ GaAs solar cell structure modeled in this study.*

	Thickness (µm)	**Doping (cm^{-3})**
Window (p^+)	0.09	$1x10^{18}$
Emitter (p)	0.44	$4x10^{17}$
Base (n)	2.97	$1x10^{16}$
Collector (n^+)	0.5	$2x10^{17}$

Table 2. *The p^+nn+ /GaAs solar cell parameters used in the simulation.*

Symbol	**Parameter**	**Value**
E_g	Energy gap (eV)	1.43
N_{nd}	Native defect density (cm^3)	$1x10^{12}$
s_{no}	Electron capture cross-section for native defects (cm^2)	$1x10^{-13}$
s_{po}	Hole capture cross-section for native defects (cm^2)	$1x10^{-15}$

The electron traps we used in the simulation were have been characterized by S. R. Messenger et al. [12, 13]. And the hole traps were characterized by Warner et al .[13], and introduction rates are estimated by S. S. Li et al. [14]. These are differents because the traps also contain both deep and shallow electron and holes traps (Table 3).

Table 3. *Parameters of electron traps and hole traps in GaAs by proton irradiation.*

Defects	**$k(cm^{-1})$**[a] [14]	**E_c- E_t (eV)**[b] [12, 13]	**$\sigma_a(cm^2)$**[c]
$PR1$	42.6	0.791	2.03×10^{-12}
$PR2$	43.5	0.637	2.1×10^{-13}
$PR4'$	130.0	0.358	2.2×10^{-14}
$PR4''$	136.5	0.313	7.8×10^{-15}
$PR5$	181.9	0.110	4.0×10^{-15}
Defects		**E_v + $E_t(eV)$** [10]	**$\sigma_b(cm^2)$**
$PH2$	20	0.213	8.5×10^{-17}
$PH3$	40	0.355	1.7×10^{-15}
$PH4$	200	0.422	1.5×10^{-15}
$PH5$	240	0.544	5.8×10^{-18}

[a] *The introduction rate of defects.*
[b] *Activation energy of the defect level position.*
[c] *the capture cross sections of the defect.*

III. Results and discussion

Numerical simulation is first carried out considering no irradiation as a reference case. No electron and hole traps are generated, Figure 1 present comparison between our simulation results and the experimental measurements [15] of current-voltage characteristic of the AlGaAs/GaAs (p^+nn^+) solar cell.The extracted output parameters of the cell J_{SC}, V_{OC}, FF, η before irradiation are 24 mA/cm^2, 1.01 V, 0.88 and 15.65 %, respectively. These parameters are in good agreement with the experimental values of AlGaAs/GaAs solar cells reported from the literature [16, 17, 18] and Simulation a two dimensional (2D) [19, 20].

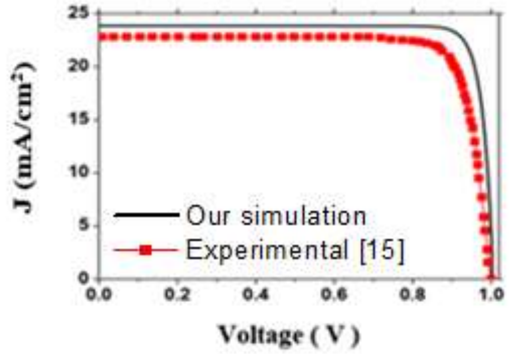

Figure 1. *Variation of the current density as a function of voltage.*

III.1. Effect of proton irradiation fluence

The characteristic J-V of the solar cell under AM0, submitted to different fluences (10^{11} - $10^{13}cm^{-2}$) of 1 MeV protons fluence is shown in Figure 2. By increasing the proton fluence, the electrical characteristics of the solar cell degrades. Figure 3 shows the normalized output parameters for different fluences. We note that the effect of the protons is very important in particular for the large dose of $10^{13} cm^{-2}$. J_{sc} has a degradation ratio of almost 0.7, V_{oc} a ratio of almost 0.65. The deterioration rate of these two parameters is in good similarity compared to the reference measures [21].

The FF always has less sensitivity with a degradation slightly higher than 0.8. The conversion efficiency η of the cell is the most sensitive parameter with a degradation ratio of 0.4, slightly than that measured. The difference between the rate of performance degradation compared with the Measurement reference is probably due to a difference between the simulated FF and the measured one, since the similarity of Jsc and Voc is quite appreciable.

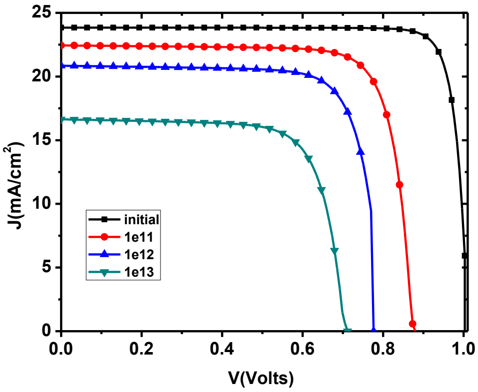

Figure 2. *Variation of the J(V) characteristics as a function of voltage for different fluences (10^{11}-10^{13} cm^{-2}) and 1 MeV proton irradiation.*

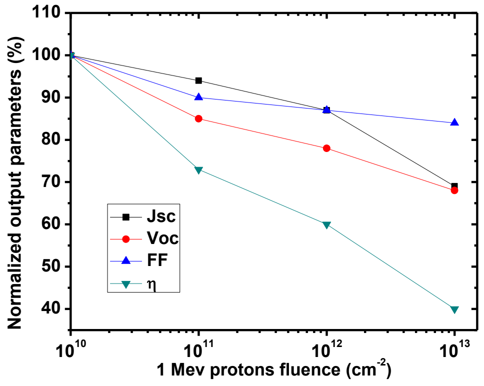

Figure 3. *Normalized output parameters as a function of fluence.*

To establish which trap induces the degradation on the performance of the AlGaAs/GaAs (p +nn^{+}) solar cell, a study of the effect of different fluences of 1 MeV proton (10^{11}, 10^{12}, 10^{13} cm^{-2}) irradiation was conducted. Two cases were considered, the first taking into account electron traps and the second hole traps.

III.2. Electron traps effect under 1 MeV proton irradiation

GaAs solar cell is the most sensitive to 10^{13} p/cm^{2} proton fluence, and the short-circuit current (Jsc) is the most influenced by the proton irradiation. For this proton irradiation fluence, five electron traps in the n-type GaAs and four hole traps in the p-type GaAs are created (Table 3). In this section, we have modelled the effect of all electron traps $PR1$, $PR2$, $PR4^{'}$, $PR4^{''}$and $PR5$ to study the effect of the irradiation-induced defects under 1 MeV proton irradiation for protons fluence ranging from 1x10^{11} to 1x10^{13} p/cm^{2}.Simulation results, show the normalized output parameters for different fluences considering electron traps. According to the results obtained electron traps degrade the short-circuit current by 68 % from their initial values when J_{sc} decreases from $24mA / cm^2$ to $16.67\ mA / cm^2$, a value slightly higher than $16.29\ mA / cm^2$ in the presence of all the traps. V_{oc} decreases from $1.01V$ to $0.60V$ which is however a little lower than 0.646 V in the presence of all traps. FF decreases from 0.88 to 0.722, a value that is very close to 0.723 obtained for the whole of traps. The conversion efficiency η is degraded by 15.65 % to 5.58%, a value which is however lower than that obtained in the case of presence of traps (5.60%). Thus the value 0.6 of Voc in the degraded state is the cause of the decrease of the conversion efficiency up to 5.58%. This may indicate that V_{oc} is more sensitive to degradation if only electron traps are present. Defects responsible for the performance degradation are the deep traps with activation energy of 0.791 eV for PR1 and 0.637 eV for PR2. They are the most responsible for the degradation of J_{sc}, because they are considered as recombination centers [22]. Their energy levels are closer to the intrinsic Fermi level, $E_f = 0.71$ eV. The defects PR1 and PR2 are more responsible for the reduction of the lifetime of minority carriers (see the mathematical relation 5).

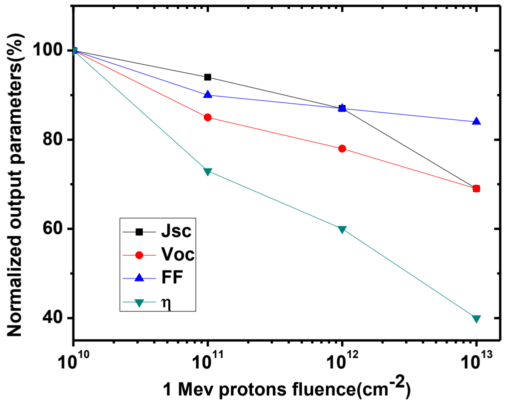

Figure 4. *Normalized output parameters as a function of fluence considering electron traps.*

III.3. Hole traps effect under 1 MeV proton irradiation

To study the effect of hole traps created under 1 MeV proton irradiation, we simulated the effect of hole traps, $PH2$, $PH3$, $PH4$ and $PH5$. Parameters of these defects are those cited in Tables 3. For GaAs solar cell, the physical data are the same as the ones in the previous section. The normalized of output parameters for different fluences considering hole traps are presented in Figure 5. The normalized value is the ratio of the parameter value after irradiation for a given fluence to that before irradiation. It can be seen that after irradiation, the conversion efficiency and the short circuit current density for the proton fluence of 1 x10^{13} p/cm^2 is degraded with about 28% and 11% of the initial values, respectively. This degradation can mainly be attributed to the presence of $PH5$, the deep hole trap.

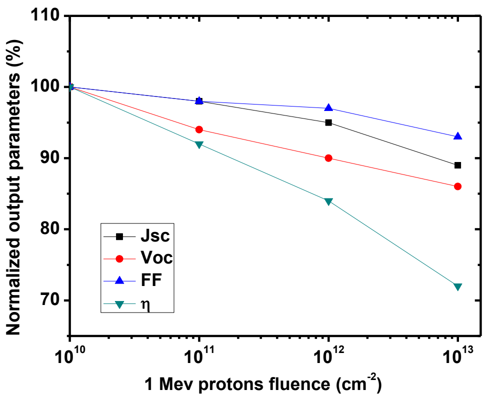

Figure5. *Normalized output parameters as a function of fluence considering hole traps.*

III.4. Deep traps effects:

According to Table 3, the defects induced by the irradiation of protons can also be classified into two types: deep and shallow traps. Separating the different defects according to their type and depth, the only deep trap levels (hole) is the PH5 which is positioned at 0.544 eV with respect to Ev with the smallest capture section of 5.8 × 10^{-18}cm^2 and an introduction rate of 240 cm^{-1}. When the deep electron traps are $PR1$ and $PR2$ with activation energy of 0.791 eV and 0.637 eV respectively. We aim to define which type of defects are responsible for the degradation of short-circuit current (Jsc).

In this section we simulated the effect of deep electron and hole traps (PR1, PR2 and PH5). The normalized output parameters for different fluences considering deep levels traps are presented in Figure 6. The results of output parameters obtained are the same which are obtained in the case of presence of the electron traps we distingue that defects responsible for the performance degradation are the deep electron traps PR1 and PR2. Especially the deepest PR1 which is the most responsible for the degradation of Jsc and η, because it is considered as recombination centers.

For high-proton energies, the loss mainly causes ionization. These energy losses may significantly influence the electrical characteristics of the devices, which must be the reason why degradation of AlGaAs/GaAs (p^+nn^+) solar cell performances has been observed in the presence of deep electron traps (Figure 4). In fact, the traps induce deep energy levels (E_t) in the semiconductor band gap and act as recombination centres. In the Shockley–Read–Hall (SRH) (see Equation (4) and (5)) process, an electron can be trapped at such a defect (or trap) and consequently recombines with a hole that is attracted by the trapped electron [23, 24]. This process is the dominant recombination-generation process in semiconductors at most operational conditions. It is typically non-radiative and the excess energy is dissipated into the lattice in the form of heat. The recombination centres reduce the free carrier lifetime [25].The lifetime is indirectly proportional to the trap density N_t (see mathematical relation (5)) [25, 26].

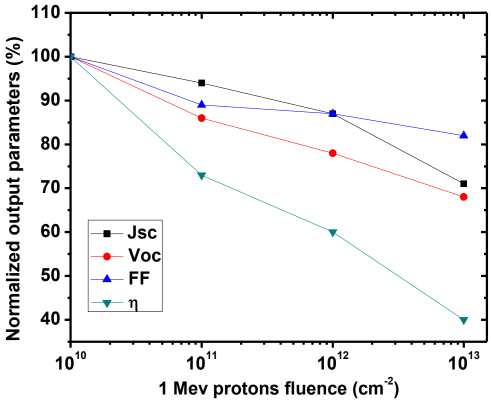

Figure 6. *Normalized output parameters for different fluences considering deep levels traps.*

III.5.The effect of the n+/GaAs layer thickness under 1 MeV proton irradiation and the proton fluence of 1x10^{13} p/cm^2

To study the effect of the collector thickness under 1 MeV proton irradiation and the proton fluence of 1 x10^{13} p/cm^2, the thickness of the collector layer is varied. Figure 7 presents J(V) characteristics of the collector thickness effect under 1 MeV proton irradiation and the proton fluence of 1x10^{13} p/cm^2. Simulation results show that by decreasing the thickness of the collector layer, the conversion efficiency of the solar cell is increased to 6.7% of its initial value. However, the Jsc increased to 17.88 mA/cm^2 of its initial value. When the thickness of the collector layer is reduced, more minority carriers can be collected by the p-n junction, and contribute to the photo-generated current. Therefore, the performance degradation of the solar cell will be reduced.

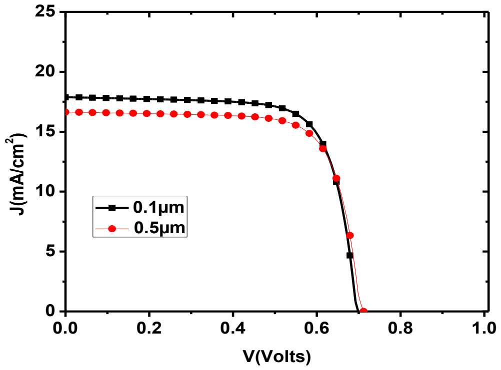

Figure 7. *J(V) characteristics of the collector thickness effect as a function of voltage, under 1 MeV proton irradiation and the proton fluence of 1x10^{13} p/cm^2.*

IV. Conclusion

Numerical simulation was carried out to study the effect of 1 MeV proton irradiation of a p+-n-n+ GaAs solar cell under AM0. Irradiation induces structural defects in the GaAs lattice. proton irradiation fluence created, five electron traps in the n-type GaAs and four hole traps in the p-type GaAs. We have modeled the effect of 1 MeV proton irradiation from 1 x10^{11} to 1 x l0^{13} proton fluences p/cm^2 on the performance degradation of a p$^+$-n-n$^+$ GaAs solar cell. We showed that by increasing the proton fluence from 1 x 10^{11} to 1 x 10^{13} p/cm^2 the electrical characteristics of the solar cell will be more degraded. we have modeled the effect of electron traps $PR1$, $PR2$, $PR4^{'}$, $PR4^{''}$and $PR5$ and hole traps, $PH2$, $PH3$, $PH4$ and $PH5$ created under 1 MeV proton irradiation for protons fluence ranging from 1x10^{11} to 1x10^{13} p/cm^2 in tow cases separately. Defects responsible for the performance degradation are the deep traps with activation energy of 0.791 eV and 0.637 eV for PR1 and PR2, respectively. They are the most responsible for the degradation of J_{sc}, because they are considered as recombination centers. Besides, when the thickness of the n$^+$ GaAs collector layer is reduced, more minority carriers can be collected by the p-n junction, and contribute to the photo-generated current. Therefore, the performance degradation of the solar cell will be reduced and improves the resistivity of the solar cell to proton irradiation.

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