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The $Al_xGa_{1-x}As$ window composition effect on the hardness improvement of a p^+–n–n^+GaAs solar cell exposed to the electron irradiation

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ABSTRACT

Numerical simulation was used to study the $Al_xGa_{1-x}As$ window composition effect on the current–voltage characteristics of a p^+–n–n^+GaAs solar cell under AM0 illumination and exposed to 1 MeV electron irradiation. Such solar cells are used in satellites and undergo severe degradation in their performance due to induced structural defects. The irradiation induced defects are modeled as energy levels in the energy gap of GaAs. To predict this effect, the current voltage characteristic and the spectral response are evaluated for different electron irradiation fluences for two types of cells. In the first we use a narrow $Al_{0.31}Ga_{0.69}As$ window as a small part of the p^+ layer while in the second type we use an $Al_xGa_{1-x}As$ window with a gradual Al mole fraction. The obtained results show that the $Al_xGa_{1-x}As$ window with a gradual Al mole fraction reduces the degradation of the output parameters of the solar cell and its spectral response by irradiation in particular for the short wavelengths.

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1. Introduction

When exposed to cosmic particle irradiations, solar cells undergo significant deterioration in their performance. This constitutes a serious problem for the power supplies of satellites operating in orbits [1–7]. Photovoltaic based power sources for satellites require radiation resistant and high efficiency solar cells. Among compound semiconductor materials, GaAs is commonly preferred for space applications because of its more advanced and cheaper technology, higher conversion efficiency and radiation resistance [8]. Unfortunately an all-GaAs solar cells suffer from carrier loss due to a high surface recombination velocity [9–11]. In order to reduce such loss a wide band gap surface layer of $Al_xGa_{1-x}As$ is placed on the top of a GaAs emitter to create an heterojunction solar cell [9,11–12].

In this work numerical simulation is used to predict the degradation of the *J–V* characteristic of a p^+–$Al_xGa_{1-x}As/p^+$–n–n^+-GaAs solar cells by 1 MeV electron irradiation, and the effect of the $Al_xGa_{1-x}As$ layer thickness and composition on the cell's sensitivity to the electron irradiation. We have used two cells with different window structures. Both cells have ($Al_xGa_{1-x}As$/GaAs)-p^+ type window/emitter, and n^+-type collector layers which are 0.53 and 0.5 μm thick, respectively, while the thickness of the n-type base region is 2.97 μm (Fig. 1). For the first cell (Cell 1), the window is $Al_{0.31}Ga_{0.69}As$ with a thickness of 0.03 μm while for the second cell (Cell 2), the window is $Al_{0.31}Ga_{0.69}As/Al_{0.19}Ga_{0.81}As/Al_{0.1}Ga_{0.9}As$ with a total thickness of 0.09 μm. The doping densities of the different regions are: $2 \times 10^{18}\ cm^{-3}$ for the Al_xGa_{1-x} As-p^+ type window, $4 \times 10^{17}\ cm^{-3}$ for the GaAs-p^+ type emitter, $1 \times 10^{16}\ cm^{-3}$ for the n type GaAs base and $2 \times 10^{17}\ cm^{-3}$ for the n^+ type GaAs collector.

We note that we have studied in a previous work [11] the effect of the $Al_xGa_{1-x}As$ layer on the degradation of the spectral response of these solar cells and the obtained results are also presented in this work.

2. Numerical details

The simulation program that we developed is based on the Kurata method [13] which gives a one-dimensional numerical solution of the carrier transport problem in a p^+–n–n^+ solar cell. A stationary simultaneous solution of Poisson's equation and hole and electron continuity equations, approximated by a finite difference, is obtained. The numerical method of resolution is detailed elsewhere [7,11]. The cell's top surface is subjected to AM0 illumination with a power density of 135.6 mW/cm^2. The absorbed light produces electron–hole pairs. The generation rate distribution at a position *x* from the illuminated front is given by the following expression [14]:

$$G(x) = \sum_{\lambda=0.2}^{0.9\mu m} T(\lambda)\alpha(\lambda)\phi(\lambda)[\exp(-\alpha(\lambda)x) + R\exp(-\alpha(\lambda)(2d - x))] \quad (1)$$

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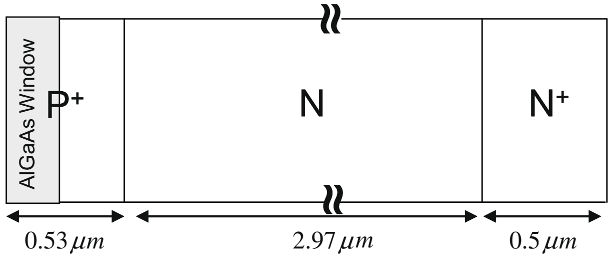

Fig. 1. A schematic diagram of the solar cell used in this work.

where λ is the wavelength of the illumination, T is the transmittance of the cell's top surface (AlGaAs window) at normal incidence, α is the absorption coefficient, φ is the photon flux, R is the back reflection and d is the thickness of the solar cell. α and φ depend also on the layer's composition.

The total recombination rate of the free carriers includes the Shockley–Read–Hall (SRH) recombination rate, the radiative direct recombination rate and the Auger recombination rate. The SRH recombination rate of an ith defect is given by [15]:

$$U_i = \frac{n \cdot p - n_i^2}{\tau_{ni}n + n_{1i} + \tau_{pi}p + p_{1i}} \tag{2.a}$$

where n and p are, respectively, the free electron and hole densities. τ_{ni} and τ_{pi} are the minority carrier lifetime, which are related to the defect's density N_i and capture cross sections for electrons and holes σ_n and σ_p by $\tau_{ni} = 1/\sigma_n v_{th} N_i$ and $\tau_{pi} = 1/\sigma_p v_{th} N_i$, v_{th} is the thermal velocity supposed to be the same for electrons and holes for simplicity, n_i is the semiconductor intrinsic density and n_{1i} and p_{1i} are the electron and hole densities when their quasi-Fermi levels coincide with the defect level. Before irradiation we consider $\tau_{ni} = \tau_{no} = 4.9 \times 10^{-9}$ s and $\tau_{pi} = \tau_{po} = 2 \times 10^{-8}$ s [11,16].

The radiative direct recombination and the Auger recombination rates are, respectively, given by [17]:

$$U_{rd} = B(np - n_i^2) \tag{2.b}$$

$$U_{Aug} = (C_{nAu}n + C_{pAu}p)(np - n_i^2) \tag{2.c}$$

where B and $C_{nAu(pAu)}$ are constants that reflects the direct and Auger transitions, respectively. $B = 7 \times 10^{-10}$ cm^3 s^{-1} and $C_{n,pAu} = 10^{-30}$ cm^6 s^{-1} [11,18].

Defects due to irradiation are presented in Table 1 [11]. $E_1, \ldots, E_5$ are the electron traps, $H_0, \ldots, H_3$ are the hole traps, E_C and E_V are, respectively, the conduction band energy and the valence band energy, and E_T is the trap energy. The density of each defect is obtained by multiplying the introduction rate of the defect k (cm^{-1}) by the electron fluence (Φ (cm^{-2})).

Table 1
Defect levels due to 1 MeV electron irradiation.

Defects [5,7]	k	$E_C - E_T$ (eV)	σ_n (cm^2)
E_1	1.50	0.045	2.2×10^{-15}
E_2	1.50	0.140	5×10^{-13}
E_3	0.40	0.300	5×10^{-14}
E_4	0.08	0.760	3.1×10^{-13}
E_5	0.10	0.960	3×10^{-11}
Defects [5,7]	k	$E_T + E_V$ (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^{-14}
H_2	Not given	0.41	1.0×10^{-15}
H_3	0.2	0.71	1.0×10^{-13}

3. Results and discussions

The spectral response and the current–voltage characteristics of the illuminated cells (Cell 1 and Cell 2) before and after irradiation are calculated. These are presented in Figs. 2 and 3 [11] respectively.

From Fig. 2 the spectral response of Cell 2 is inferior to that of Cell 1 between 0.5 and 0.85 µm before irradiation. This is expected since the absorption occurs mainly in the AlGaAs window for Cell 2 and in the GaAs emitter for Cell 1 and the absorption coefficient of AlGaAs is smaller than that of GaAs in the most efficient region of the AM0 spectrum as shown in Fig. 4 [11].

Now the irradiation effect will be discussed. For the $\Phi = 10^{14}$cm^{-2} electron fluence, the degradation is more pronounced between 0.75 and 0.9 µm while for $\Phi = 10^{15}$ cm^{-2} and $\Phi = 10^{16}$ cm^{-2} the irradiation effect is over the whole wave length range (Fig. 2) [11]. These observations are fairly in agreement with measurement and simulation in [16,19] although the used cell's structure and defect levels are different.

The extracted photocurrent, photovoltage, fill factor and efficiency before and after irradiation (from Fig. 3) are presented in Table 2. The values for the non-irradiated cell are fairly in agreement with standard values for such cells [6,19–20]. It is also clear that the output parameters of the Cell 1 are more degraded than those of Cell 2.

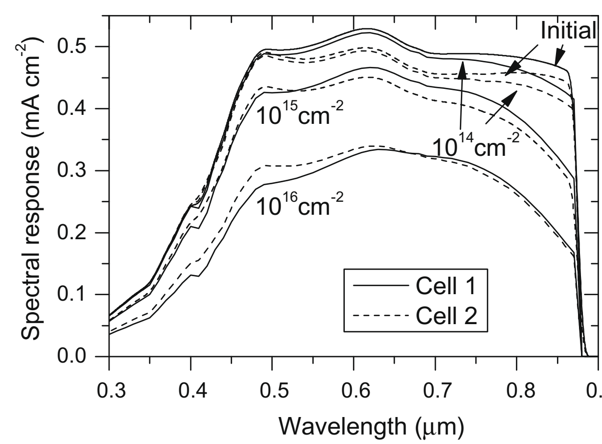

Fig. 2. Degradation of the spectral response by the different electron fluences.

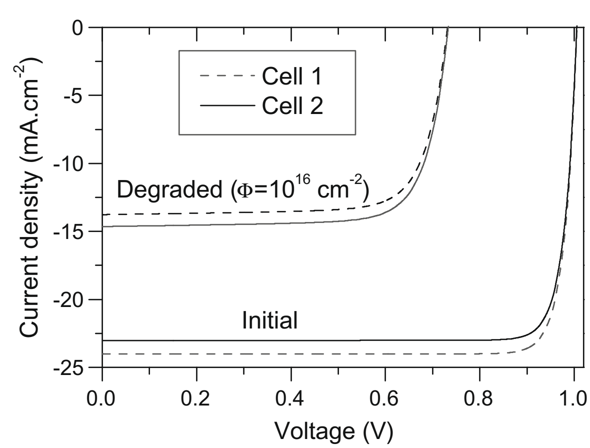

Fig. 3. The calculated J–V characteristics of the illuminated solar cells before and after irradiation by 1×10^{16} cm^{-2} electron fluence.

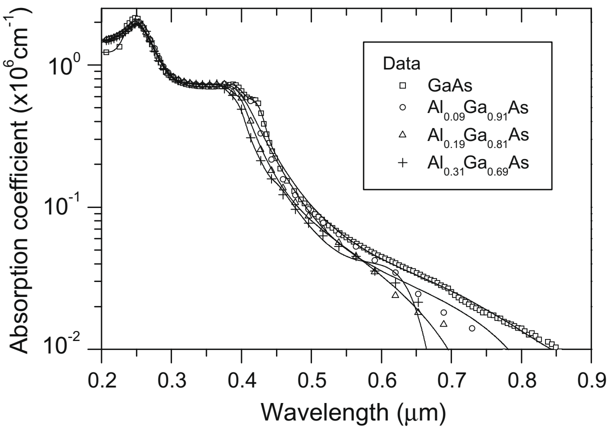

Fig. 4. The fitted and tabulated [21] absorption coefficient for the different $Al_xGa_{1-x}As$ layers.

Table 2
The calculated cell's output parameters before and after irradiation by 10^{16} e cm^{-2} dose.

	J_{sc} (A cm^{-2})	V_{oc} (V)	FF	η (%)
Before irradiation				
Cell 1	24.0×10^{-3}	1.01	0.88	15.65
Cell 2	23.0×10^{-3}	1.01	0.88	15.00
After irradiation				
Cell 1	13.76×10^{-3}	0.73	0.76	5.65
Cell 2	14.64×10^{-3}	0.74	0.76	6.03

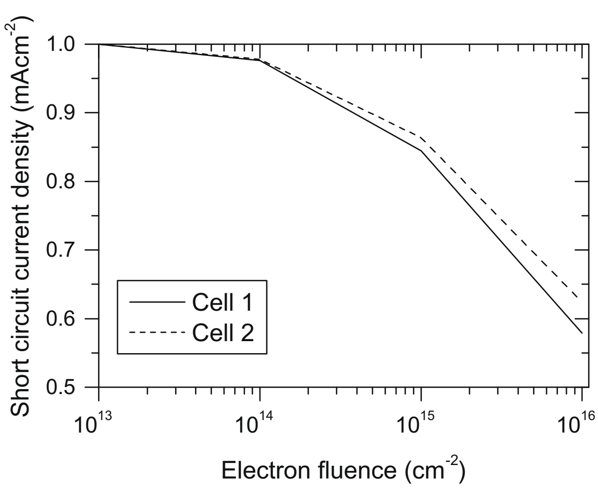

Fig. 5. The normalized short circuit current density degradation.

Finally by comparing the irradiation effect on Cell 1 and Cell 2, we find that the gradual AlGaAs window improves the resistance of the spectral response for the short wavelength although the initial one (before irradiation) is poorer [11]. This is more clarified in Fig. 5 which shows the degradation of the normalised short current densities for the two cells. For both cells the degradation magnitudes are in the experimental range [6,16,22]. Cell 2 shows better resistance to electron irradiation due to the fact that deep levels are more effective in GaAs which has smaller energy gap than AlGaAs [11].

4. Conclusion

A one-dimensional modeling of an AlGaAs-p$^+$/GaAs-(p$^+$–n–n$^+$) solar cell, operating under AM0 solar spectrum and exposed to 1 MeV electron irradiation is presented. This is to study the effect of the AlGaAs window on the cell sensitivity to the electron irradiation defects. It was found that the use of a gradual energy gaps $Al_xGa_{1-x}As$ window reduces the degradation of the output parameters of the solar cell and its spectral response by irradiation in particular for the short wavelengths due to the fact that deep levels are more effective in GaAs which has smaller energy gap than AlGaAs.

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