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Irradiation effect on the electrical characteristics of an AlGaAs/GaAs based solar cell: Comparison between electron and proton irradiation by numerical simulation

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ABSTRACT

In this work we use numerical simulation to make a comparison between the effect of electron and proton irradiation on the current voltage (J–V) characteristics of a GaAs based solar cell. This is an extension of a previous work in which we have demonstrated that the use of a gradual gap $Al_xGa_{1-x}As$ window improves the resistivity of the cell to electron irradiation. In this paper we use the gradual gap Al_xGa_{1-x} layer as window material on the top of the GaAs cell and we study the effect of its thickness on the output parameters of the cell exposed to 1 MeV electron and proton irradiation. The external cell parameters are: the short circuit current (J_{sc}), the open circuit voltage (V_{oc}), the fill factor (FF) and the conversion efficiency (η). Our results show that J_{sc} is more sensitive to electron irradiation while V_{oc} is a little bit more sensitive to proton irradiation. This gives nearly the same effect of the two types of irradiation on the conversion efficiency of the cell. We found also that the increase of the gradual $Al_xGa_{1-x}As$ window thickness from 0.09 to 0.3 μm improves the resistivity of the solar cell to irradiation.

1. Introduction

The study of the radiation effect on semiconductor devices has been an important field of research for many years now. The space environment consists of many different types of energetic particles.

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Electrons and protons with a wide range of energies dominate the space-radiation environment [1]. These particles can induce a serious degradation in the electrical performance of the solar cells used as power sources for satellites [1–6]. The requirement of radiation resistant and high efficiency solar cells has pushed the III–V technology to totally replace the silicon technology in space applications since they have higher conversion efficiency and radiation resistance [2–4,7–10]. Gallium Arsenide is the most advanced amongst III–V semiconductors, which has excellent conversion efficiency and good radiation tolerance [2–4,7–10].

Predicting the effect of particle irradiation in devices is a way to estimate the lifetime of a device exposed to these particles. The mechanism of irradiation-induced degradation has been widely studied. High-energy electron and proton irradiation produce atomic displacements in semiconductor materials and, as a result, lattice defects such as vacancies, interstitials, complex defects are generated. Lattice defects that act as recombination centers or majority- and minority-carrier trapping centers cause a decrease in the output power of solar cells [4].

Deep-level Transient Spectroscopy (DLTS) is the most employed technique to characterize defects created by irradiation. For example, for electron irradiation: the introduction rate, the energy levels and the capture cross sections of defects in GaAs were determined by many research groups [4,7,11–13]. 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 [13–18]. However, little information on the defect's introduction rates are given, in particular the introduction rates of hole traps.

In a previous study, numerical simulations were performed to investigate how the radiation sensitivity of a p^+n solar cell after exposure to 1 MeV electron irradiation was influenced by the layer thickness and Al mole fraction of the $Al_xGa_{1-x}As$ window layer [19,20]. This work is an extension of the previous work which has now been extended to consider the effects of proton irradiation. The degradation of the photovoltaic response is simulated using a defect-based physics model. The defect parameters, i.e. defect activation energy, capture cross section and introduction rates, are required as inputs to the model and these data were found in the literature [12–18]. The degradation of the photovoltaic response is compared for electron and proton irradiation.

2. Numerical simulation

The simulation program used is the same developed in our previous works [19–21], based on the Kurata method [22] which gives a one-dimensional numerical solution of the carrier transport problem in a p^+n GaAs solar cell, a typical GaAs based solar cell configuration. A stationary simultaneous solution of Poisson's equation and hole and electron continuity equations, approximated by a finite difference, is obtained. Further details can be found in [19,21]. The p^+ $Al_xGa_{1-x}As$ window is formed by $Al_{0.31}Ga_{0.69}As/Al_{0.19}Ga_{0.81}As/Al_{0.1}Ga_{0.9}As$ layers with gradual energy gaps. We found in our previous studies that incorporating an AlGaAs window layer structure with a gradual change in energy gap enhances the spectral response at shorter wavelengths [19,20]. The thicknesses and doping densities of each layer are given in Table 1. Fig. 1a shows the equilibrium energy band diagram of the p^+n GaAs solar cell. In Fig. 1b, the band diagram of a standard p^+n GaAs solar cell, similar to that of Ref. [16] is shown for comparison. The advantage of our design is the internal electric field, due to the gradual band profile, helps in reducing recombination. The cell's top surface is subjected to AM0 illumination with a power density of 135.6 W/cm^2 [23].

Table 1
Description of the p^+n GaAs solar cell structure modeled in this study. The layer thicknesses and doping concentrations are given.

	Window (p^+)			Emitter (p^+)	Base (n)	Collector (n^+)
	$Al_{0.31}Ga_{0.69}As$	$Al_{0.19}Ga_{0.81}As$	$Al_{0.1}Ga_{0.9}As$			
Thickness (μm)	0.03	0.03	0.03	0.44	2.97	0.5
Doping (cm^{-3})	1×10^{18}	1×10^{18}	1×10^{18}	4×10^{17}	10^{16}	2×10^{17}

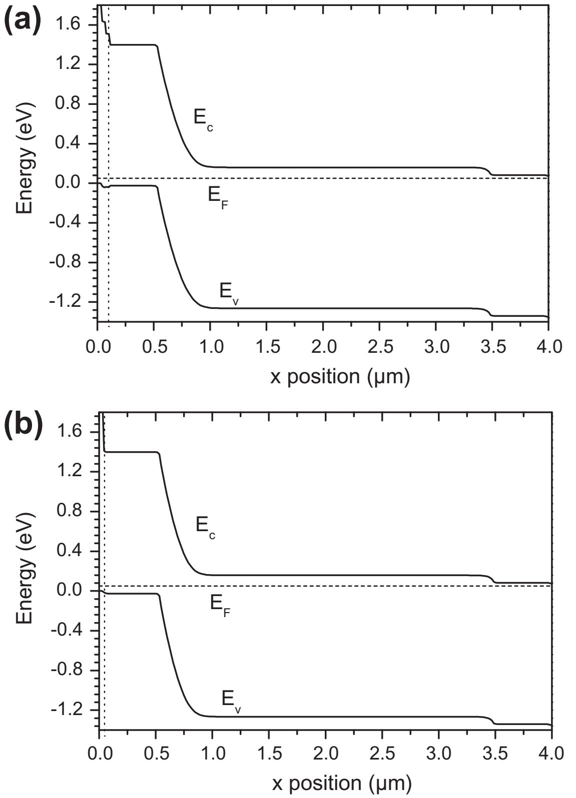

Fig. 1. (a) The band diagram of the p+n GaAs solar cell, with a graded AlGaAs band gap, simulated in this work in equilibrium (no illumination and no bias) showing the band discontinuities at the AlGaAs/GaAs interface. (b) The band diagram of a standard p+n GaAs solar cell, similar to that in Ref. [12], in equilibrium for comparison with the solar cell structure used in this work (a).

Irradiation-induced defects are defined by their defect concentrations (introduction rate × irradiation fluence), their ionization energies E_t and the electron and hole capture cross sections σ_n and σ_p. 1 MeV electron irradiation of GaAs solar cells generally produces three to four electron traps and one to four hole traps, depending on the electron fluence and flux, and the defect density and the number increases with increasing electron fluence and flux [11]. The electron and the hole traps parameters used in this work are those in [8,12], and are summarized in Table 2.

For 1 MeV proton irradiation, the electron traps parameters used are those in [13,14], and summarized in Table 3. Unfortunately, for the hole traps (minority carrier's traps in n-type GaAs), it was very difficult to find values in the literature. For example, [16] gives only the energy levels and capture cross section for 53 MeV proton irradiation while their introduction rates were not evaluated since they seem to disappear as the fluence increases. In [13], it was reported that the introduction rate decreases with proton energy for electron traps (majority carrier's traps). The same energy dependence was observed for minority carrier lifetime measurements on GaAs bulk light-emitting diodes [24]. In the same context, a prediction gives 300–500 cm^{-1} for the introduction rate value of recombination centers induced by 1 MeV proton irradiation [25,26]. In [11] comparable energies with those of [13,16] were found. Therefore we have used commonly observed defects in these references. Their introduction rates were roughly deduced taking into account their observed dependence on energy and fluence from the discussion above. Table 4 summarize the parameters of the hole traps used in this work.

Table 2
Summary of introduction rates, activation energies, and capture cross sections for majority electron traps and minority hole traps in n-type GaAs after 1 MeV electron irradiation [12,13].

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}
	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 (assumed 0.4 in this work)	0.29	5.0×10^{-15}
H_2	Not given (assumed 0.1) in this work)	0.41	2.0×10^{-16}
H_3	0.2	0.71	1.2×10^{-14}

Table 3
Summary of introduction rates, activation energies, and capture cross sections for majority electron traps in n-type GaAs after 1 MeV proton irradiation [14,15].

Defects	k (cm^{-1})	$E_C - E_T$ (eV)	σ_n (cm^2)
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	4×10^{-15}

Table 4
Summary of minority hole traps in n-type GaAs subjected to 1 MeV proton irradiation: energy levels and capture cross sections are from [14] while the introduction rates are roughly estimated from [11].

Defects	k (cm^{-1})	$E_V + E_T$ (eV)	σ_p (cm^2)
PH2	20 (assumed)	0.213	8.5×10^{-17}
PH3	40 (assumed)	0.355	1.7×10^{-15}
PH4	200 (assumed)	0.422	1.5×10^{-15}
PH5	240 (assumed)	0.544	5.8×10^{-18}

Usually, the irradiation fluence of protons is less than that of electrons [1–16]. Hence, a fluence range of 10^{11}–10^{13} cm^{-2} for protons [11,13–16] and 10^{14}–10^{16} cm^{-2} for electrons [1–12] are used.

3. Results and discussion

3.1. Electron irradiation

The J–V characteristics of the solar cell simulated at 300 K under AM0 before and after electron irradiation are shown in Fig. 2. The photovoltaic outputs of the cell: the short circuit current density (J_{sc}), the open circuit voltage (V_{oc}), the fill factor (FF) and the conversion efficiency (η) as a function of fluence are extracted from Fig. 2 and provided in Table 5. The initial values are: 23.86 mA/cm^2, 1.01 V, 0.88 and 15.6%, respectively. These values are in the measured range [27–30].

At the highest fluence (10^{16} cm^{-2}) the remaining value of J_{sc} is 0.6 which is in the range of experimental measurements from Refs. [25,26]. However, this value in Ref. [30] is 0.75 which is a bit higher than our simulated results. The remaining value of V_{oc} is 0.67 which is roughly in agreement with the V_{oc} degradation measurement from Refs. [2,25,26]. However, this value is about 0.75 and 0.87 in Refs. [29,30], respectively. The parameter that shows the least sensitivity to electron irradiation is FF. Its

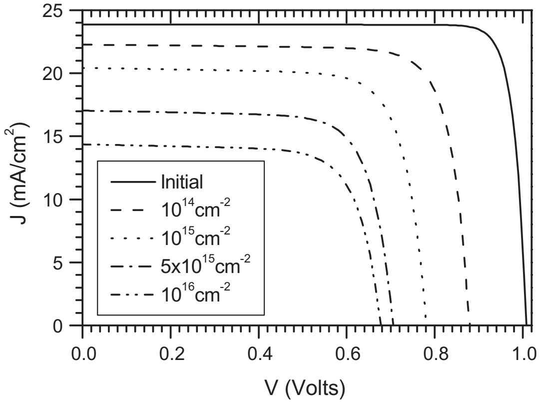

Fig. 2. The illuminated J–V characteristic of the p$^+$n GaAs solar cell: solid line; before electron irradiation and dotted lines; 10^{14}, 10^{15}, 5×10^{15} and 10^{16} cm^{-2} fluences.

Table 5
The output parameters, extracted from Fig. 2, of the p$^+$n GaAs solar cell before (initial) and after 1 MeV electron irradiation for different fluences.

Fluence (cm^{-2})	J_{sc} (mA/cm^2)	V_{oc} (V)	FF	η%
Initial (10^{10})	23.86	1.01	0.88	15.60
10^{14}	22.27	0.88	0.796	11.5
10^{15}	20.416	0.781	0.765	8.70
5×10^{15}	17.04	0.706	0.751	6.60
1×10^{16}	14.362	0.678	0.730	5.23

remaining value is 0.83 which is similar to measurements in Refs. [29,30]. Finally our results give a remaining value of 0.33 for η which is in agreement with Ref. [1]. However this value is a bit less than 0.5 reported by Refs. [4,29,30]. The differences between our simulation results with some measurements may be due to the difference of the structures used in these references.

Now the effect of the p$^+$ AlGaAs window and the p$^+$ GaAs emitter thicknesses is studied. However, it is well known that the increase of the total thickness of the p$^+$ layer is not desirable because it encourages further direct recombination. Thus, two cases are considered. First, the whole p$^+$ (AlGaAs/GaAs) layer thickness is kept constant at 0.53 μm while that of the p$^+$ AlGaAs window is increased from 0.09 to 0.3 and to 0.4 μm. Second, the p$^+$ AlGaAs window thickness is kept constant at 0.09 μm while that of the p$^+$ GaAs emitter is decreased from 0.44 to 0.2 and to 0.1 μm. The output parameters at initial and degraded states (10^{16} cm^{-2}) are summarized in Table 6. For the first case, we notice an improvement in J_{sc} at the degraded state, from 14.36 to 15.72 mA/cm^2 for the 0.3 μm thick AlGaAs window. V_{oc} and FF exhibit very small increase and thus are less affected. The corresponding increase in efficiency is from 5.23% to 5.80%. In the second case J_{sc} reaches 17.56 mA/cm^2 at the degraded state when the p$^+$ GaAs emitter thickness is decreased from 0.44 to 0.1 μm. This gives an improvement of the efficiency at the degraded state from 5.80% to 6.41%. V_{oc} shows a very small increase at 0.1 μm while FF decreases a little bit. Thus, the optimum thicknesses of the p$^+$ AlGaAs window and the p$^+$ GaAs emitter layers are: 0.09 and 0.1 μm respectively.

3.2. Proton irradiation

In this section we present the effect of the proton irradiation on the photovoltaic outputs parameters of the solar cell. The J–V characteristics simulated before and after proton irradiation are shown in Fig. 3. Table 7 gives the value of J_{sc}, V_{oc}, FF and η before and after irradiation extracted from Fig. 3.

Table 6
The output parameters of the p⁺n GaAs solar cell before (initial) and after 1 MeV electron irradiation (degraded with a fluence of 10^{16} cm^{-2}) for different $Al_xGa_{1-x}As$ window and p⁺ GaAs thicknesses.

p⁺ (AlGaAs/GaAs) thickness (μm)	AlGaAs thickness (μm)	State	J_{sc} (mA/cm²)	V_{oc} (V)	FF	η%
0.53	0.09	Initial	23.86	1.01	0.88	15.60
		Degraded	14.36	0.678	0.730	5.23
	0.3	Initial	21.83	1.01	0.88	14.26
		Degraded	15.72	0.682	0.737	5.80
	0.4	Initial	20.97	1.01	0.88	13.70
		Degraded	14.67	0.687	0.737	5.40
AlGaAs thickness (μm)	p⁺ GaAs thickness (μm)					
0.09	0.44	Initial	23.86	1.01	0.88	15.60
		Degraded	14.36	0.678	0.730	5.23
	0.2	Initial	23.86	1.01	0.88	15.60
		Degraded	17.41	0.682	0.733	6.40
	0.1	Initial	23.85	1.01	0.88	15.58
		Degraded	17.56	0.683	0.727	6.41

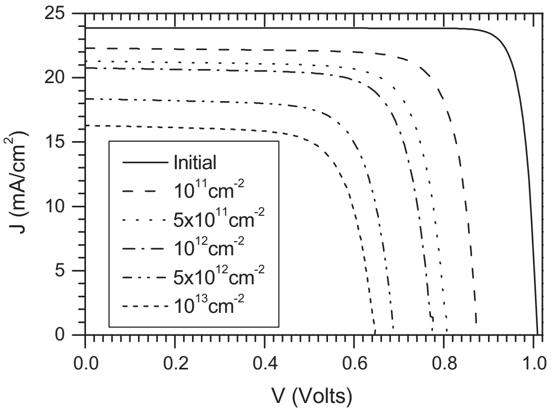

Fig. 3. The illuminated *J–V* characteristic of the p⁺n GaAs solar cell: solid line; before proton irradiation and dotted lines; 10^{11}, 5×10^{11}, 10^{12}, 5×10^{12}, 10^{13} cm^{-2} fluences.

Table 7
The output parameters, extracted from Fig. 3, of the p⁺n GaAs solar cell before and after 1 MeV proton irradiation for different fluences.

Fluence (cm^{-2})	J_{sc} (mA/cm²)	V_{oc} (V)	FF	η%
Initial (10^{10})	23.86	1.01	0.88	15.60
10^{11}	22.29	0.876	0.796	11.43
5×10^{11}	21.29	0.806	0.763	9.74
10^{12}	20.75	0.773	0.751	8.98
5×10^{12}	18.36	0.688	0.743	6.85
10^{13}	16.29	0.646	0.723	5.60

The output parameters of the solar cell decrease with increasing fluence, in consistence with other studies [13–18]. The remaining values of these parameters at the final fluence (10^{13} cm^{-2}) are found to be 0.68, 0.64, 0.82 and 0.36 for J_{sc}, V_{oc}, FF and η respectively. Unfortunately, we have not found experimental studies that give a detailed effect of 1 MeV proton irradiation on the outputs of a GaAs based cell. In [25,26] only the normalized maximum power is provided. It decreases approximately to

Table 8
The output parameters of the p⁺n GaAs solar cell before (initial) and after 1 MeV electron irradiation (degraded with a fluence of 10^{13} cm^{-2}) for different $Al_xGa_{1-x}As$ window and p⁺ GaAs thicknesses.

p⁺ (AlGaAs/GaAs) thickness (μm)	AlGaAs thickness (μm)	State	J_{sc} (mA/cm^2)	V_{oc} (V)	FF	η%
0.53	0.09	Initial	23.86	1.01	0.88	15.60
		Degraded	16.29	0.646	0.723	5.60
	0.3	Initial	21.83	1.01	0.88	14.26
		Degraded	16.89	0.648	0.726	5.84
	0.4	Initial	20.97	1.01	0.88	13.70
		Degraded	16.00	0.646	0.725	5.50
AlGaAs thickness (μm)	p⁺ GaAs thickness (μm)					
0.09	0.44	Initial	23.86	1.01	0.88	15.60
		Degraded	16.29	0.646	0.723	5.60
	0.2	Initial	23.86	1.01	0.88	15.60
		Degraded	18.48	0.651	0.72	6.37
	0.1	Initial	23.85	1.01	0.88	15.58
		Degraded	18.50	0.652	0.711	6.30

0.45 at 10^{12} cm^{-2} proton fluence. According to this, one expects that the normalized maximum power reaches a value below 0.45 at 10^{13} cm^{-2} proton fluence. Another study on the displacement damage of proton in GaAs has presented the degradation measurement of the photocurrent as a function of proton fluence normalized to the pre-irradiation values for 2 MeV [1]. According to this study the normalized photocurrent decreases to 0.47 at 10^{13} cm^{-2} [1]. It is also expected that for 1 MeV, the normalized photocurrent should be higher.

In Table 8 we present the effect of both the p⁺ AlGaAs window and p⁺ GaAs emitter thicknesses on the solar cell degradation by proton irradiation. The effect is almost similar to that produced by electron irradiation although J_{sc} shows higher values at the degraded state while V_{oc} shows lower values. When the p⁺ GaAs emitter thickness is decreased to 0.2 μm, the degraded value of J_{sc}, V_{oc}, and FF are 18.48 mA/cm^2, 0.651 V and 0.72, respectively. The corresponding efficiency is 6.37%.

For a p⁺ GaAs emitter thickness of 0.1 μm, FF is more affected in comparison with electron irradiation. Its degraded value is 0.711 while J_{sc} and V_{oc} are 18.50 mA/cm^2 and 0.652 V respectively. The corresponding efficiency in this case is 6.30%. Thus, the optimum thicknesses of the p⁺ AlGaAs window and the p⁺ GaAs emitter layers are 0.09 and 0.2 μm respectively.

4. Discussion

It was found that the solar cell efficiencies at the degraded state by electron and proton irradiation are almost similar: 5.23% and 5.60% respectively. Despite the similarity of the efficiencies at the degraded states by electron and proton irradiation, the effect on the other parameters is quite different. J_{sc} is more affected by electron irradiation than by proton irradiation. It decreases from 23.86 to 14.36 mA/cm^2 by 10^{16} cm^{-2} electron irradiation fluence, and to 16.29 mA/cm^2 by 10^{13} cm^{-2} proton irradiation fluence. However, V_{oc} is a bit more affected by proton irradiation than by electron irradiation respectively. It decreases from 1.01 to 0.678 by 10^{16} cm^{-2} electron irradiation fluence and to 0.64 V by 10^{13} cm^{-2} proton irradiation fluence. A possible explanation of these differences may be due to the type and depth in the energy gap of the defects created by each irradiation type. The electron irradiation (Table 2) creates five electron traps in the n-type GaAs and four hole traps in the p-type. The three deep traps E5, E4 (n-type) and H3 (p-type) can be considered as recombination centers. E5 the deepest one with the greatest capture cross section (1.9×10^{-12}) is responsible of the serious degradation of J_{sc}. On the other hand the two very shallow traps E1 and H0 can be regarded as doping levels. Thus, they may increase the barrier potential at the p⁺n interface. It is well known that the open circuit voltage of a solar cell is related to the barrier built-in voltage. Hence the increase in the barrier will compensate the reduction of V_{oc} by electron irradiation. For proton irradiation (Tables 3 and 4), there are two recombination centers PR1 and PR2 which affect J_{sc} but with reduced effect than in the case of electron irradiation. However, there are no shallow traps to compensate the effect on V_{oc}. Therefore, V_{oc} is more sensitive to proton irradiation than electron irradiation.

The increase of the $Al_xGa_{1-x}As$ window thickness from 0.09 to 0.3 μm while the whole p^+ layer is kept constant at 0.53 μm, gives little improvement in efficiency at the degraded state; 5.80% in the case of electron irradiation and 5.84% in the case of the proton irradiation. However, the improvement of the degraded efficiency is more important by decreasing the p^+ GaAs emitter thickness. J_{sc} and V_{oc} exhibit an optimum values at a p^+ GaAs emitter thickness of 0.1 μm for both electron and proton irradiations. Contrarily, FF decreases at this thickness, in particular for proton irradiation. The effect of FF is crucial since it provides different optimum p^+ GaAs emitter thicknesses for electron and proton irradiation. For the electron irradiation, the optimum p^+ GaAs emitter thickness is 0.1 μm for which the degraded efficiency is 6.41%. However, for proton irradiation, the optimum p^+ GaAs emitter thickness is 0.2 μm for which the efficiency is 6.37%.

Thus, a better hardness to irradiation is achieved by using a gradual window. This ensures on one hand the splitting of the solar spectrum which improves the photovoltaic response for the short wavelengths. On the other hand, it reduces the discontinuity in the energy bands which is produced between GaAs and an AlGaAs abrupt window. In addition, the reduction of the emitter thickness will minimize recombination. Our design may have the same idea as that of Ref. [31] which uses a graded doping design of InP solar cells. Our design is a graded band gap AlGaAs window. Despite the difference in the design, both designs may have the same effect, i.e. creating an internal electric field which helps in collecting carriers more efficiently by drift.

5. Conclusion

Numerical simulation was used to compare the degradation of a p^+n GaAs solar cell by energetic electrons and protons. Electron and proton irradiations have nearly the same effect on the efficiency of the GaAs solar cell. For the two cases of irradiation, the efficiency degradation is related to the degradation of J_{sc} and V_{oc}, while FF is the least affected parameters. J_{sc} shows a strong degradation from 23.86 to 14.36 mA/cm^2 by electron irradiation at $10^{16}\,cm^{-2}$ fluence, which gives a remaining value of 0.6. This degradation is related mainly to the presence of E_5, the deepest recombination center. V_{oc} decreases from 1.01 to 0.687 V which gives a remaining value of 0.67. Therefore J_{sc} is more sensitive to electron irradiation than V_{oc}. For proton irradiation at $10^{13}\,cm^{-2}$ fluence, we have obtained remaining values of 0.68 for J_{sc} and 0.64 for V_{oc}. Thus V_{oc} is a little bit more sensitive to proton irradiation.

A better hardness to irradiation is achieved by using a thin gradual window AlGaAs (0.09 μm) with a reduced p^+ GaAs emitter thickness. For electron irradiation, the optimum p^+ GaAs emitter thickness is 0.1 μm for which the efficiency is 6.41% at the degraded state. However, for proton irradiation the efficiency at the degraded state is 6.37% for the optimum p^+ GaAs emitter thickness of 0.2 μm. This difference is related to the remaining value of FF at the degraded state when the p^+ GaAs emitter thickness is reduced. For proton irradiation, it was found that FF is more degraded for a p^+ GaAs emitter thickness of 0.1 μm, since it decreases to 0.711. However, it decreases only to 0.727 by electron irradiation.

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