Nuclear Inst. and Methods in Physics Research B 451 (2019) 49–54

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research B

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

Effect of 150 keV proton irradiation on the performance of GaAs solar cells

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ARTICLE INFO

Keywords:
GaAs
Minority carrier lifetime
Proton irradiation
Radiation damage

ABSTRACT

In this paper, the effects of a 150 keV proton radiation on a GaAs sub-cell of GaInP/GaAs/Ge trip junction solar cells and its radiation damage were studied. The degradation behavior of the solar cells was analyzed by theoretical device modeling combined with electro-optical characterization techniques such as external quantum efficiency, *IV* measurements, and photoluminescence (PL). The degradation of cell output parameters by protons was plotted as a function of the displacement damage dose. The results show that the short-circuit currents degrades less than open-circuit voltages because the base region of GaAs is severely damaged. The PL results indicated that proton irradiation exerted destructive effect on the photoelectric properties of the material. Such destructiveness was due to the numerous defects introduced by proton irradiation, which destroys the integrity of the lattice space, resulting in a decrease in the diffusion length of the minority and an increase in the surface recombination velocity. By COMSOL simulation analysis, it is found that the reason of radiation degradation of GaAs is the decrease of minority carrier time after irradiation and simulation results show that the PL results are in good agreement with the simulation results which can provide a method for the calculation of internal defects and minority carriers in multi-junction solar cells.

1. Introduction

Triple-junction solar cells, such as GaInP/GaAs/Ge, have been commonly used in space as their primary energy systems due to their high conversion efficiency and low temperature coefficient [1–4]. However, when the solar cells are exposed to the radiation of particles, they will degrade because of the displacement damage induced by the space particles that penetrate the device. A large number of studies have shown that, GaAs as the intermediate layer of triple-junction solar cell, its irradiation damage is more serious than that of other two cells, and once the intermediate GaAs sub cell is damaged by irradiation, photovoltaic parameters are significantly reduced. The detailed mechanism of the performance degradation is still unknown, therefore, it is necessary to perform a separate radiation damage study on the interlayer GaAs to predict its service behavior in space.

At present, there are many researches on GaAs sub-cell of triple-junction solar cell. This research is mostly focused on the selection of irradiated particles with different energy and fluence. After the irradiation experiment, the test of performance includes two aspects: macroscopic performance parameters include short-circuit currents (*Isc*), open-circuit voltages (*Voc*), fill factors (*FF*), microscopic properties include deep levels, defect densities [5–9]. The analysis of the microscopic properties of the sub cell is usually performed using the Deep Level Transient Spectroscopy (DLTS) [10–13], which depends on the test conditions and the sample. Because of the high requirements of DLTS test, researchers have used physical software such as TCAD, COMSOL or SILVACO® Virtual Wafer Fabrication Software to obtain the output of solar cells under irradiation conditions. These simulation methods strongly rely on DLTS test results, and the deep-level test results have great influence on the simulation results. Therefore, this paper proposes a COMSOL simulation method to analyze the minority carrier lifetime in the solar cell after proton irradiation.

In this study, we performed a 150 keV proton irradiation experiment on GaAs sub-cell of a GaInP/GaAs/Ge triple junction cell and analyzed its irradiation effect. Through the *I-V* performance, spectral response and photoluminescence spectra test of GaAs solar cells, the effects of proton irradiation on the electrical and optical properties of GaAs cells were studied. The solar cell was simulated using multi-physics analysis software COMSOL and the experimental results were analyzed.

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https://doi.org/10.1016/j.nimb.2019.04.065
Received 8 July 2018; Received in revised form 21 March 2019; Accepted 23 April 2019
0168-583X/

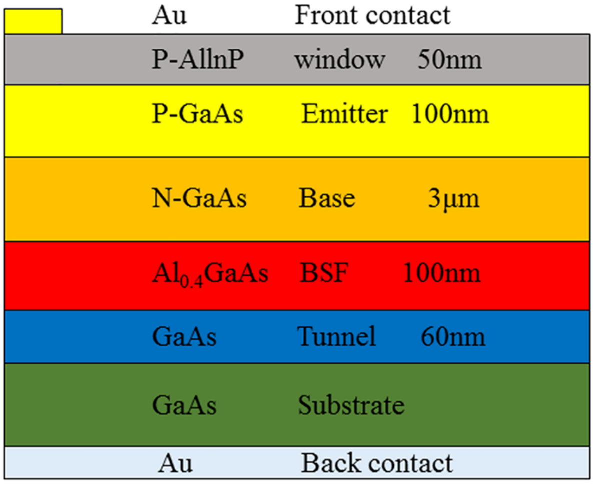

Fig. 1. Configuration of the GaAs solar cells.

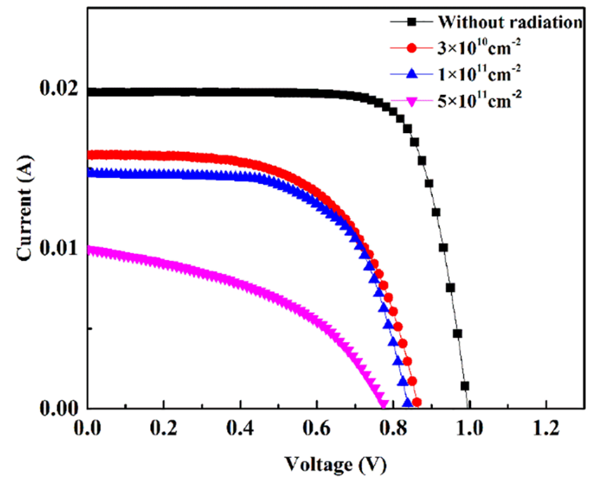

Fig. 2. Current-voltage curves of GaAs before and after radiation.

2. Experiment and simulation

2.1. Experiment and device characterization

The space-use GaInP/GaAs/Ge triple-junction solar cells and GaAs solar cells were prepared by metal organic chemical vapor deposition (MOCVD). The GaAs solar cell was grown on a highly doped p-type GaAs substrate while the other solar cells were grown on Ge substrates. The GaAs structure is shown in Fig. 1.

150 keV proton irradiation was performed on a positive ion irradiation simulation system at the National Key Laboratory of Space Environmental Material Behavior and Evaluation Technology, Harbin Institute of Technology. The flux was $1 \times 10^{9}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, the irradiation fluence was from $3 \times 10^{10}\,\mathrm{cm}^{-2}$ to $5 \times 10^{11}\,\mathrm{cm}^{-2}$.

I-V curves were measured under AM0, 1 sun condition (136.7 mW/cm^2) at 25 °C. Three identical wafers were selected for each fluence, and the three irradiated cells were tested and each cell was tested three times. The spectral response was conducted at Shanghai Institute of Space Power. The equipment used was a solar cell quantum efficiency meter. The photoluminescence of the solar cell before and after irradiation was tested using a LabRam HR 800 Raman Spectrometer.

2.2. COMSOL simulation

A GaAs solar cell PN structure is modeled in order to simulate the operation modes with and without trap levels appearing with proton irradiance. Numerical simulations are carried out with a finite element resolution using COMSOL Multi-physics software [14]. This modeling is done with a multi-physics parametric non-linear resolving using semiconductor and optics modules.

First, we use the semiconductor module. This module is used to model single junction GaAs solar cell. The established one-dimensional GaAs PN junction model includes carrier generation and Shockley-Reed-Hall recombination. An analytical doping model was used for the doping carrier concentration in the base region, and the doping of the front surface of the cell was described using a geometric doping model. Shockley-Read-Hall recombination are used to describe trap combinations produced in solar cells. The front and rear surfaces of the cell are metal contacts to characterize the electrodes of the solar cell. The PN junction parameters were obtained from the sample parameters. The base of the PN junction was an analytical doping model that was the base region N-type, with a doping concentration of $1 \times 10^{17}\,\mathrm{cm}^{-3}$. The front surface of the model is P-type doped with a junction depth of 0.5 μm.

The ray optical interface is used to define the spectral irradiance, and the spectral irradiance is used to define the carrier generation rate:

$$G= \int \alpha(\lambda)\,(1-R(\lambda)\Phi(\lambda))\exp(-i\alpha(\lambda)z)d\lambda \tag{1}$$

$\alpha(\lambda)$ is the absorption coefficient of light from a solar cell material. In optical theory, it is usually expressed as:

$$\alpha(\lambda) = \frac{4\pi\kappa(\lambda)}{\lambda} \tag{2}$$

$\kappa(\lambda)$ is the imaginary part of the refractive index of solar cells in GaAs, $\Phi(\lambda)$ is the generation rate of light, it can be obtained from the following formula:

$$\Phi(\lambda) = \lambda F(\lambda)/hc \tag{3}$$

Here, we assume that the characteristic output of the cell is proportional to the incident optical power density (irradiance). The reference irradiance $H_0 = 1353\,\mathrm{W/m^2}$ is used in this model.

3. Results and discussion

3.1. Degradation of electrical performance

The *I-V* curves of GaAs irradiated by 150 keV protons with different fluences are shown in Fig. 2. The short-circuit current (*Isc*), open-circuit voltage (*Voc*), and fill factor (*FF*) of GaAs solar cells after radiation are shown in Table 1.

The electrical properties of the cell are similar before irradiation. Under 150 keV proton irradiation, the *Isc* and *Voc* of solar cells decrease with increasing irradiation fluence. When the irradiation fluence is less than $1 \times 10^{11}\,\mathrm{cm}^{-2}$, the *Isc* decays less, especially when the fluence reaches up to $5 \times 10^{11}\,\mathrm{cm}^{-2}$, *Isc* decays to 50% of the original cell, and the damage of the solar cell is severe. The electrical performance parameters of the solar cell in Table 1 are in good agreement with the literature [24], the degradation rate of parameters is basically consistent with 170 keV proton radiation. Radiation damage caused by particles can be divided into emitters, bases and the junction region. Mainly damages the base regions, and this causes the electrical properties to decrease.

The degradation of the above two electrical parameters (*Isc*) (*Voc*) is expressed by the relation of the remaining factor (the ratio of the

Table 1
Electrical parameter summary of solar cells after radiation.

Fluence (cm^{-2})	3×10^{10}	1×10^{11}	5×10^{11}
Isc (mA)	15.90 ± 0.3	14.67 ± 0.2	9.96 ± 0.1
Voc (V)	0.86 ± 0.1	0.84 ± 0.1	0.78 ± 0.2
FF	83.67 ± 1.3	60.04 ± 2.4	45.78 ± 2.3

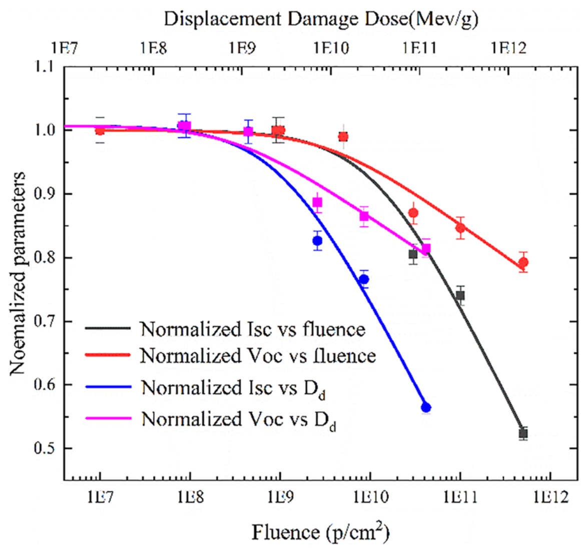

Fig. 3. Normalized electric-properties vs. fluence and displacement damage dose for GaAs solar cell irradiated by 150 keV protons.

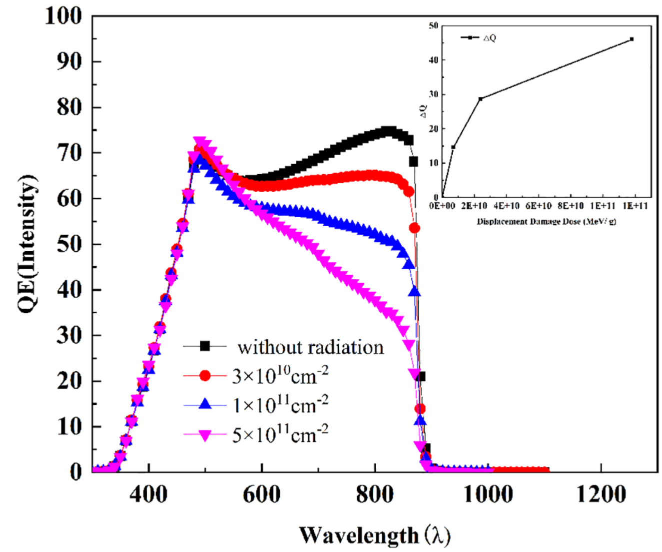

Fig. 4. External Quantum Efficiency measurements of the GaAs solar cell before and after 150 keV proton irradiation. (inset: Relationship between quantum efficiency degradation ΔQ (at wavelength of 870 nm) and displacement damage dose.)

decayed value to the initial value) with respect to the irradiation fluence and the displacement damage dose (*Dd*) [16]. The degradation characteristics of *Isc* and *Voc* in Fig. 3 are obtained by fitting the following formula:

$$\frac{X}{X_0} = 1 - C\ log\left(1 + \frac{\Phi}{\Phi_0}\right) \tag{4}$$

where X is the electrical performance value of the cell after irradiation, X_0 is the electrical performance value before irradiation, Φ is the radiated particle fluence, Φ_0, C are constants.

$$Dd = \Phi(E) \times NIEL(E) \tag{5}$$

where $\Phi(E)$ is the particle fluence with energy E.

From Fig. 3, it can be seen that the *Isc* of the solar cell after irradiation is more severely decayed than the *Voc*. In a single junction solar cell, the *Voc* can be derived from the following formula:

$$Voc = \frac{\mathrm{kT}}{q}\ln\left(\frac{Isc}{I_0} + 1\right) \tag{6}$$

where q is the electron charge constant, k is the Boltzmann constant, T is the absolute Kelvin temperature, and I_0 represents the reverse saturation current of the PN junction.

As in Eq. (6), the *Voc* of solar cell is theoretically determined by the built-in barrier voltage of the PN junction. Compared to *Isc*, with the increase of irradiation fluence, the decrease of *Voc* is smaller, which indicates that proton irradiation damage mainly occurs in the base region of the solar cell [15]. The result is in agreement with the results obtained from Monte Carlo simulation. The energy of 150 keV protons is about 1.1 μm in GaAs, completely penetrating the PN junction region of the cell, and the final range is in the base region of the cell. When the solar light illuminates the solar cell, photo-generated carriers are generated in the emitter, base, and junction regions. Proton irradiation can introduce deep-level defects in solar cells, increase the number of recombination centers of photo-generated carriers, and reduce the diffusion length of carriers, which will cause a part of photo-generated electron-hole pairs cannot reach the junction region to be separated by electric field, and this will decrease the performance of the solar cell.

3.2. Analysis of quantum efficiency

Spectral response is an effective method used to evaluate the damage of solar cells after irradiation. The change in the spectrum is a change in the cell performance. Fig. 5 shows the variation of the spectral response of GaAs solar cells radiated with 150 keV protons with different radiation fluences. The yield of sample Q was subtracted from the yield of non-radiated sample Q_0, $\Delta Q = Q_0 - Q$. The figure interpolated in Fig. 4 shows the relationship between quantum efficiency degradation and displacement damage dose.

The spectral response results show that after 150 keV proton radiation, GaAs solar cells have almost no degradation in the short wavelength, significantly decreases in the wavelength range from 500 to 900 nm, and the degradation peak appears at 860 nm. The spectral response curve of the cell begins to decline at a wavelength of 450 nm, and as the wavelength increases, the degradation increases. When fluence reaches up to $5 \times 10^{11}\ cm^{-2}$, the response degradation at wavelength 800 nm reaches 50%. The change in spectral response peaks may be related to the radiation-induced defects, which reduce the diffusion length of light-generated carriers and thus have an impact on the carrier collection efficiency [17].

For the short wavelength of light, the photons are almost absorbed by the p region in front of the cell, which are mainly absorbed by the window layer and emitter in front of the cell. The carrier lifetime and the depth of the PN junction are the main factors affecting the spectral response of the cell for wavelength between 400 nm and 800 nm. When wavelength is more than 800 nm, the photons have a long penetration depth in GaAs, the surface recombination rate of the cell will have a major effect on the performance of the cell.

When the proton fluence is less than $10^{11}\ cm^{-2}$, the response of the cell in the short-wavelength spectrum is less, and SRIM simulation shows that the range of 150 keV is in the base region of GaAs cell. When 150 keV proton with low fluence radiates the cell, less damage occurs in the cell's emitter and p-region. After photons enter the p-GaAs layer through the window layer, most of them are absorbed in the layer to generate photo-generated carriers. Whether these carriers can diffuse into the junction region and are separated by the electrostatic field of the PN junction, and photocurrent is generated across the p-n junction is the most important factor determining the efficiency of solar cell. As shown in Fig. 4, with the increase of displacement damage dose of the cell, the ΔQ value increases. This indicates that as the proton fluence increases, although the proton range is in the base region of solar cell, due to more defects in the base region, the ability of trapping carrier is improved and the carrier lifetime is reduced.

For a single junction solar cell, the defects of solar cells are usually tested by deep level measurements, but the deep level test is more demanding for its sample condition, and for the triple junction solar cell, because of its structural complexity, there are few tests can direct measure the defect information of the triple junction solar cell, which is difficult for the study of multi-junction solar cells. Thus, the following sections focus on the above two problems, using photoluminescence test combined with COMSOL simulation, the defect information of single-junction GaAs solar cells and its minority carrier lifetime are characterized, which lays a foundation for the research of multi-junction cells.

3.3. Analysis of minority carrier lifetime and radiation defect

Photoluminescence (PL) fluoresces semiconductor materials by exciting them with shorter wavelength lasers. PL relative luminous intensity and half-peak width are important parameters to characterize the quality of epitaxial materials. The stronger luminous intensity indicates that there are fewer non-irradiation recombination centers in the material, and more exciting numbers, the higher the luminous efficiency. The smaller the half peak width, the better the flatness of the material [18].

Photoluminescence spectra of GaAs solar cells irradiated with protons of different fluence were compared. The results are shown in Fig. 5. As can be seen from Fig. 5, the photoluminescence spectrum before irradiation has a strong sharp peak at wavelength of 870 nm. The intensity falls after irradiation, indicating that the 150 keV proton irradiation has a destructive influence on the optical performance of the irradiated GaAs solar cell, and the crystal lattice of GaAs is affected. As the fluence increases, the characteristic peak position of the GaAs material shifts to the right, the peak height decreases and the half width widens.

After the low-energy proton irradiation, the intensity of the photoluminescence peak of the cell is weakening, and the peak position has also undergone a significant change. This is due to the fact that in semiconductor crystals, the atoms are regularly arranged in a lattice according to certain rules. At the lowest energy state, the system is the most stable. When the solar cells are irradiated, the irradiated particles will collide, displacing the lattice atoms, and the primary off-site atoms may initiate secondary shifts, forming many defects (Frankel defects), and the vacancy and interstitial atoms generated by irradiation are disturbed. The integrity of the lattice, resulting in greatly reduced photoluminescence intensity.

Radiation introduces non-radiative recombination center, thus, decreases of PL intensity. As a result, PL intensity, I, which is proportional

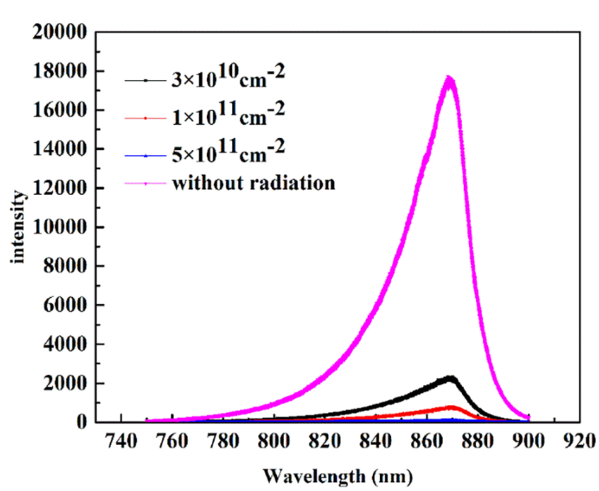

Fig. 5. Photoluminescence spectra of GaAs solar cells irradiated by different fluence of 150 keV protons.

Table 2
Values of the parameters obtained from the fits of the PL experimental data, combined with formula (8–11).

Fluence (cm^{-2})	τ_{nr}(s)	Leff (cm)	σ(cm^2)	Nt(cm^{-3})
3×10^{10}	9.96E−10	1.68E−4	8.36E−15	2.72E14
1×10^{11}	2.95E−10	9.15E-−5	8.48E−15	9.07E14
5×10^{11}	3.05E−11	2.94E−5	1.64E−14	4.53E15

to radiation efficiency η, can be written as [19]:

$$I\propto \eta = \left(1 + \frac{\tau_r}{\tau_{nr}}\right)^{-1} = (1 + \tau_r \sigma v N)^{-1} \tag{7}$$

where $\tau_r$and τ_{nr} denote the radiative and nonradiative recombination, respectively, k is the introduction rate of non-radiation recombination centers, σ is the minority carrier capture cross section, v is the thermal velocity of carriers, N is the concentration of non-radiation recombination centers concentration.

It can be seen from the literature [20] that formula (8) can also be expressed as:

$$\eta = (1 + \alpha\Phi)^{-1} \tag{8}$$

$$\alpha = k\sigma v/BN \tag{9}$$

where B is the radiative recombination probability which is independence of irradiation fluence, N is the doping concentration and is equal to 10^{17} cm^{-2} in n-type base layer for GaAs solar cells.

Therefore, in combination with the formula (8)–(10), we will get the non-radiative minority carrier lifetime τ_{nr} after irradiation with different radiation fluence (Table 2). As the irradiation fluence increases, the non-radiative minority carrier lifetime in the solar cell is significantly reduced, resulting in degradation of performance of solar cell. The lifetime of the minority carrier is decreased, and the effective minority carrier diffusion length Leff in the solar cell is also inevitably decreased. For solar cells, the minority carrier lifetime is related to the minority carrier diffusion length as follows:

$$\mathrm{Leff} = \sqrt{D\tau} \tag{10}$$

where D is the carrier diffusion coefficient of GaAs [14].

The defect concentration Nt in GaAs after irradiation is usually expressed by the following formula:

$$\mathrm{Nt} = \mathrm{k}\Phi \tag{11}$$

where Nt is the trap concentration, which is associated with the introduction rate of the recombination centers k and the fluence Φ.

So, combined with formula (8)–(12), the change of defect trapping cross section σ in GaAs after irradiation is shown in Table 2. It is known from Table 2 that after different fluence of proton irradiation, the trapping cross section of the defect increases, and the ability to trap carriers is enhanced, resulting in a decrease in the minority carrier lifetime, thereby reducing the minority diffusion length. And the output performance of solar cell is significantly reduced. According to [21], under low-energy proton irradiation, a 0.71 energy level defect is generated in the solar cell, and the defect concentration is between 10^{13} and 10^{14} cm^{-3}, and the defect causes the minority carrier lifetime in the solar cell to decrease to 10^{-11} and 10^{-9} s. The simulation results for the defect parameters in this paper are coincidence with n the literature.

According to the results of PL, the results of minority carrier lifetime, defect concentration and capture cross section in GaAs after different fluence proton irradiation were obtained. In the following, according to the established COMSOL simulated single junction solar cell model, the minority carrier lifetime, defect concentration and minority carrier lifetime obtained from the PL test results are verified, and the results are as follows.

Table 3
Comparison of simulated and experiment values of cell output before proton irradiation.

Output parameters	Simulated	Experimental
Isc(mA)	18.1	19.4
Voc (V)	0.92	0.99
FF	82.61	75.49

This part simulates the deep-level defects in PN junction of GaAs cells. The simulation part was performed using the finite element analysis software COMSOL Multi-physics. The model uses two modules: semiconductor and ray optics.

For reference, solar cells with no proton radiation are first simulated. The simulation process does not consider electron and hole traps in the solar cell. Table 3 shows the comparison of the simulated and measured output performance of the cell before irradiation. The reason for the deviation between results is mainly due to the existence of surface recombination, non-radiation recombination and other composite systems in the solar cell. In the simulation process, the surface recombination model of GaAs is not considered, which results in the difference between the simulated value and the experimental value. The results of the simulation are in agreement with the results of the experimental test, with the maximum difference being 8% of the experimental value.

In order to study the influence of the defects produced on the solar cell under the irradiation of low energy protons, we simulated the defects mainly including: electron defects and hole defects. The parameters of these defects are the defects generated in GaAs after proton irradiation in the literature [21], as shown in the following Table 4. Among the following defects, since the 0.71 eV energy level is close to the intrinsic Fermi energy level of the solar cell, the energy level that has a greater influence on the solar cell is $E_c - 0.71$ and $E_v + 0.71$. The main reason for the decrease of the output of solar cell after irradiation is the EL2 type defects generated after the cell is irradiated. These defects are usually complex centers in the cell [22]. Therefore, in this paper, COMSOL simulates the defect level with a uniform reference level of 0.71 E_V, neglects the effect of shallow level defect on the cell, and simulates the electrical properties of the irradiated GaAs. The relationship between the lifetime of a minority carriers and the performance of solar cell is deduced.

The output performance of GaAs with different radiation fluence was simulated in this paper. The results are shown in Fig. 6. The figure shows that the error between the experimental value and the analog value is within 8%. The relationship between the minority lifetime of the solar cell and irradiation fluence after proton irradiation is shown in Fig. 7.

It can be seen from Fig. 7 that after low-energy proton irradiation, the minority carrier lifetime in the battery is basically $\sim 10^{-9}$ s, which is similar to the literature results [21]. The lifetime of the minority carrier in the irradiated solar cell is significantly reduced. After the irradiation, not only the single void defect but also the complex defects of multiple voids are generated in GaAs. These defects form a new defect energy level in the solar cell. Recombination of the minority

Table 4
Characteristics of electron and hole traps observed for 150 keV proton irradiation GaAs solar cells.

Proton fluence(cm^{-2})	Electron traps		Electron traps	
	E	Et(eV)	H	Et(eV)
1×10^{11}	E3	Ec-0.20	H1	Ev + 0.17
	E7	Ec-0.71	H10	Ev + 0.71
5×10^{11}	E3	Ec-0.20	H1	Ev + 0.17
	E7	Ec-0.71	H8	Ev + 0.52

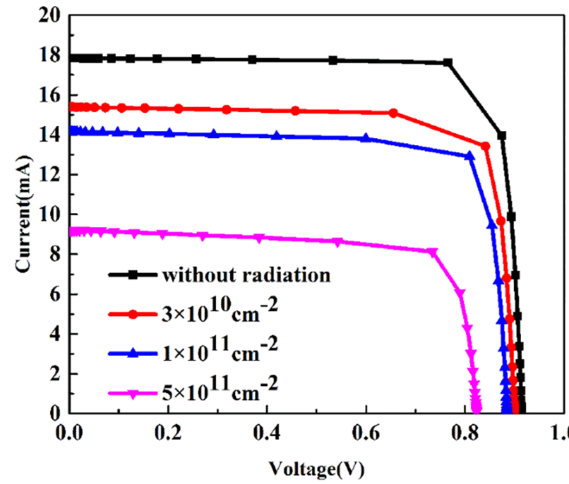

Fig. 6. COMSOL Simulation of *I-V* Curve after Proton irradiation with different fluence.

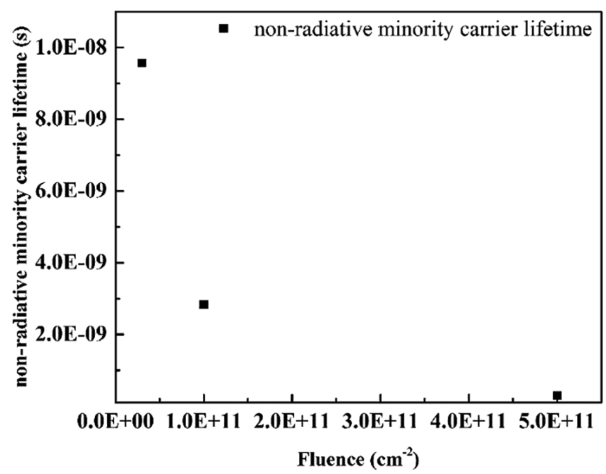

Fig. 7. Minority Carrier Lifetime of GaAs irradiated by Proton with different fluence.

carriers results in a decrease in the minority carrier lifetime. Therefore, the concentration of defects produced in the solar cell after proton irradiation has an important effect on the recombination of a few carriers in the solar cell. The analysis of the defect concentration generated in the irradiated GaAs has a great effect on the radiation damage of the solar cell. According to the COMSOL simulation results of minority carrier life time in the solar cell irradiated by different fluence, the defect concentration in the cell is obtained from formula (12) as shown in Fig. 8.

As shown in Fig. 8, according to the simulation results, the defect concentration after irradiation is in the order of 15, which is basically consistent with the results of deep energy level measurements in the literature [23] which is $0.7 \times 10^{15}\,cm^{-3}$–$0.7 \times 10^{15}\,cm^{-3}$, and consistent with the results of PL measurements. With the increase of irradiation flux, the defect concentration in GaAs increases, which leads to cell performance attenuation. Because of its deep energy level, large trapping cross section, and the increase of defect concentration in the cell after radiation, this kind of defect will lead to the direct attenuation of the performance and affect its lifetime.

4. Conclusion

The effects of 150 keV proton irradiation on the performance of GaAs cells were investigated by experiments and finite element

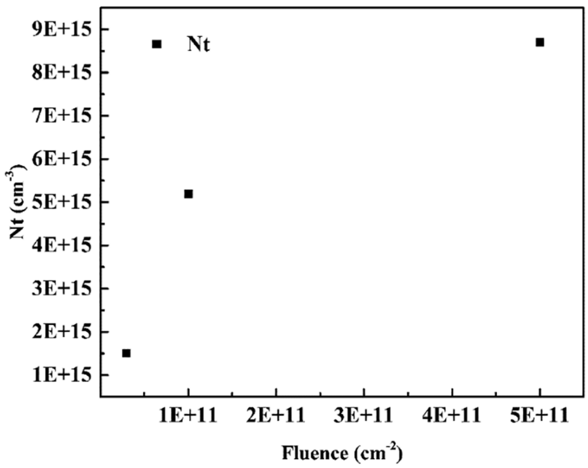

Fig. 8. Relationship between defect concentration and irradiation fluence in Proton irradiated solar cell.

COMSOL simulations. Under 150 keV proton irradiation, the short-circuit current and open-circuit voltage of the GaAs cell decreased as the irradiation fluence increased. Quantum efficiency tests show that after low-energy proton irradiation, the quantum efficiency of GaAs cells is less attenuated in the short-band, especially in the long-band attenuation. It is attributed to the generation of solar cell defects that lead to a decrease in minority carrier lifetime. The photoluminescence test also showed that the characteristic peak intensity of the photoluminescence spectrum of the battery after proton irradiation was reduced, and both the peak position and the half-width of the peak were changed, mainly due to defects and recombination centers generated in the irradiated cell. The information of minority carrier, defect concentration and trapping cross section of irradiated battery are deduced by PL results. The results of COMSOL simulation show that the PL results are in good agreement with the simulation results which can provide a method for the calculation of internal defects and minority carriers in multi-junction solar cells.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (Grant No. 11705087), the National Natural Science Foundation of China (Grant No. 11405085), the Natural Science Foundation of Jiangsu Province (Grant No. BK20170776), the Shanghai Aerospace Science and Technology Innovation Project (Grant No. SAST2015035) and the Foundation of Graduate Innovation Center in NUAA (Grant No. kfjj20170603).

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