Evaluating electron induced degradation of triple-junction solar cell by numerical simulation*

LI Jun-wei (李俊炜)[1], WANG Zu-jun (王祖军)[2], SHI Cheng-ying (石成英)[1], XUE Yuan-yuan (薛院院)[2], NING Hao (宁浩)[3], and XU Rui (徐瑞)[3]**

1. Xi'an Research Institute of High-Technology, Xi'an 710025, China

2. Northwest Institute of Nuclear Technology, Xi'an 710024, China

3. School of Materials Science and Engineering, Xiangtan University, Xiangtan 411105, China

(Received 24 June 2020; Revised 23 July 2020)

In this paper, the degradation related parameters of GaInP/GaAs/Ge triple-junction solar cell induced by electron irradiation are carried out by numerical simulation. The degradation results of short-circuit current, open-circuit voltage, maximum power have been investigated, and the degradation mechanism is analyzed. Combining the degradation results, the degradation of normalized parameters versus displacement damage dose is obtained. The results show that the degradation increases with the increase of the electron fluence and electron irradiation energy. The degradation normalized related parameters versus displacement damage dose can be characterized by a special curve that is not affected by the type of irradiated particles. By calculating the annual displacement damage dose and the on-orbit operation time of special space orbit, the degradation of normalized parameters can be obtained with the fitting curve in the simulation. The study will provide an approach to estimate the radiation damage of triple-junction solar cell induced by space particle irradiation.

Document code: A **Article ID:** 1673-1905(2021)05-0276-7

DOI https://doi.org/10.1007/s11801-021-0107-5

GaInP/GaAs/Ge triple-junction solar cell is an important type of multi-junction solar cell, and it is made up of GaInP top cell, GaAs middle cell and Ge bottom cell[1-4]. The band gap width of each sub-cell is different, and it has a specific absorption wavelength range which increases the absorption range of triple-junction solar cell. Triple-junction solar cell has the advantages of high conversion efficiency, good stability, wide absorption solar spectrum and long service time, which is widely used as a power source in spacecraft[5-8]. However, when the triple-junction solar cell on the spacecraft works in the space orbit, they will be irradiated by space particles, such as electrons, protons and a small number of heavy ions. It would lead to the performance degradation of triple-junction solar cell and even functional failure finally[9-12].

At present, a great number of studies have been carried out to investigate the performance degradation of triple-junction solar cell induced by space electron irradiation[13-15]. The studies mainly focus on the experimental research about the related parameters degradation of triple-junction solar cell and analyze the degradation mechanism induced by particle irradiation with different energy and fluence[7,8,10]. The triple-junction solar cell particle irradiation studies indicate that the degradation of related parameters has a significant difference after different electron irradiation. However, owing to the limitation of experimental accelerator condition and other experimental limitation, the degradation related parameters and degradation mechanism of the triple-junction solar cell is not clearly induced by electron irradiation with multi-energy spectrum. Solar cell numerical simulation is an important method to simulate and analyze the parameters degradation induced by particle irradiation, which has the advantages of high accuracy, a great number of data, short time completion and operability[16,17]. Cappelletti et al[18] simulated the performance degradation of single-junction GaAs solar cell after 1 MeV electron irradiation with different fluence, and the effect of base doping concentration on radiation resistance of GaAs sub-cell induced by electron irradiation with PC1D simulation software had been studied. However, due to the structure of the triple-junction solar cell is more complex than that of the single-junction solar cell, few studies about the degradation behavior of triple-junction solar cell are reported induced by particle irradiation with simulation[19,20].

* This work has been supported by the National Natural Science Foundation of China (Nos.11875223 and 11805155), the Strategic Priority Research Program of Chinese Academy of Sciences (No.XDA15015000), the Innovation Foundation of Radiation Application (No.KFZC2018040201), and the Foundation of State Key Laboratory of China (No.SKLIPR1803, 1903Z).

** E-mail: wangzujun@nint.ac.cn

It is necessary to study the parameters degradation of triple-junction solar cell induced by electron irradiation with various energy and fluence, in the meanwhile, the main reason on parameter degradation of the triple-junction solar cell is the displacement damage caused by particle irradiation[8]. Combining with the parameters degradation induced by proton irradiation, the degradation parameters of the triple-junction solar cell versus displacement damage dose are obtained, which are not affected by the type of irradiated particles finally.

In the paper, to clarity the parameters degradation with different electron irradiation environments, the degradation of triple-junction solar cell induced by electron irradiation with different energy and fluence has been carried out by numerical simulation. The related electrical parameters of the triple-junction solar cell are investigated, and the degradation mechanism is analyzed induced by electron irradiation. The degradation of related parameters with displacement damage dose caused by proton and electron irradiation is analyzed. This research will provide an approach to analyze the degradation of triple-junction solar cell induced by different space particle irradiation with displacement damage dose method.

The numerical simulation studies are based on the solar cell simulation software-wxAMPS[21]. Fig.1 shows the flowchart of the proposed numerical simulation procedures. It is made up of modeling, simulating, theoretical calculating and producing results mainly. The modeling procedure consists of triple-junction solar cell model and electron irradiation defects with various energy fluence and fluence. The schematic structure of the triple-junction solar cell model is shown in Fig.2, the band gap of GaInP and GaAs sub-cell is 1.85 eV and 1.43 eV respectively, and the model has been successfully used in our previous numerical simulation to study the degradation of triple-junction solar cell induced by proton irradiation[22].

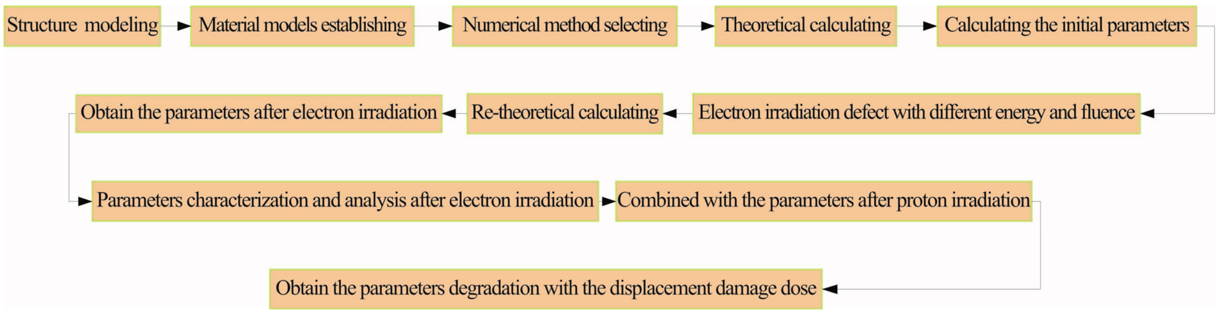

Fig.1 Flowchart of the numerical simulation procedures

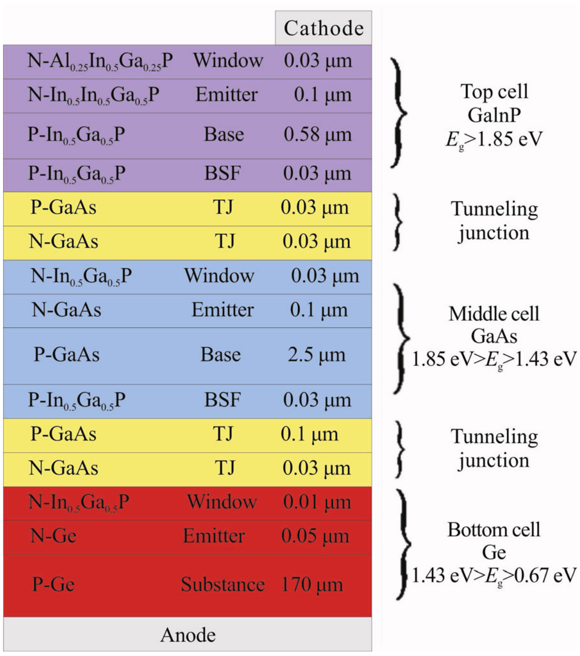

Fig.2 The schematic structure of the triple-junction solar cell[22]

The triple-junction solar cell model is composed of GaInP, GaAs and Ge sub-cell, which is connected by GaAs/GaAs tunneling junction. Here, the AM0 standard spectrum (H_0=1 367 W/cm^{-2}) is used as the light source in this study. When the electron interacts with the atoms of the lattice, electron irradiation causes atoms to dislodge from their normal lattice location, leading to a great number of vacancies, complexes formed with impurities and interstitial atoms. These are called irradiation-defects. The irradiation-defects which induced by electron irradiation are produced in GaInP/GaAs/Ge triple-junction solar cell including the emitter, the depletion region and the base. The defects result in donor-like and acceptor-like traps within the band gap. The traps will lead to the reduction of carrier lifetime, which is the main reason for the degradation of triple-junction solar cell induced by electron irradiation[23]. The displacement damage dose can be expressed as multiplying the particle non-ionization energy loss (*NIEL*) and irradiation fluence. In order to model the degradation induced by particle irradiation, the defects measured by deep level transient spectrum (DLTS) are introduced in numerical simulation. In the meanwhile, to model the degradation induced by particle irradiation with different energy and fluence, the defects concentration is proportional to displacement damage dose induced by particle irradiation approximately in simulation[12]. However, in term of the displacement damage dose induced by electron irradiation with the different energy, the displacement damage dose (DDD) could not by multiplying *NIEL* and fluence directly.

Besides, the DDD of electron irradiation with different energy needs to be equivalent to 1 MeV electron irradiation. The equivalent formula can be expressed as[24]

$$D_e = \Phi_e(E_e) NIEL(E_e) \left[\frac{NIEL(E_e)}{NIEL(1\,\mathrm{MeV}|_e)} \right]^{n-1}, \quad (1)$$

where E_e is the electron energy, $\Phi_e(E_e)$ is the electron fluence, $NIEL(1\ \mathrm{MeV}|_e)$ is the 1 MeV electron non-ionization energy loss and n ($1<n<2$) is the equivalent coefficient of electron with different energy. Tab.1 and Tab.2 are the defects parameters corresponding to DLTS measurement in GaInP and GaAs sub-cell induced by 1 MeV electron irradiation. E is the defect energy level position, N_T is the recombination center concentration, σ_n and σ_p are the electron and hole capture cross-section, which represents the ability of recombination center to capture an electron and hole. The Ge sub-cell current of the triple-junction solar cell is the maximum value and does not affect the output current after electron irradiation. Therefore, the degradation of Ge sub-cell is not analyzed induced by electron irradiation.

Tab.1 GaInP defect parameters after 1 MeV electron irradiation with the fluence of 3×10^{16} cm^{-2}[25]

Deep level	E (eV)	N_T (cm^{-3})	$\sigma_{n/p}$ (cm^{-2})
H1	E_v+0.20 eV	5×10^{16}	3.1×10^{-17}
H2	E_v+0.50 eV	1.6×10^{15}	4.2×10^{-16}
H3	E_v+0.71 eV	1.3×10^{15}	5.2×10^{-16}
E1	E_c−0.20 eV	8×10^{14}	9.9×10^{-16}
E2	E_c−0.36 eV	3.5×10^{15}	3.3×10^{-17}
E3	E_c−0.72 eV	2.5×10^{15}	2.5×10^{-17}

Tab.2 GaAs defect parameters after 1 MeV electron irradiation with the fluence of 3×10^{16} cm^{-2}[26]

Deep level	E (eV)	N_T (cm^{-3})	$\sigma_{n/p}$ (cm^{-2})
H1	E_v+0.06 eV	2.4×10^{16}	1.6×10^{-16}
H2	E_v+0.29 eV	1.2×10^{16}	5×10^{-15}
H3	E_v+0.41 eV	5×10^{16}	2.0×10^{-16}
H4	E_v+0.71 eV	6×10^{15}	1.2×10^{-14}
E1	E_c−0.045 eV	4.5×10^{16}	2.2×10^{-15}
E2	E_c−0.14 eV	4.5×10^{16}	1.2×10^{-13}
E3	E_c−0.30 eV	1.2×10^{16}	6.2×10^{-15}
E4	E_c−0.76 eV	2.4×10^{15}	3.1×10^{-14}
E5	E_c−0.96 eV	3×10^{15}	1.9×10^{-12}

By calculating the Poisson's equation and the continuity equation of electrons and holes, the related parameters of the triple-junction solar cell can be solved. In the non-equilibrium state, the continuity equation of electron and hole is[27]

$$D_n \frac{d^2 \Delta n_p}{dx^2} - \frac{\Delta n_p}{\tau_n} + G_n(x) = 0, \quad (2)$$

$$D_p \frac{d^2 \Delta p_n}{dx^2} - \frac{\Delta p_n}{\tau_p} + G_p(x) = 0, \quad (3)$$

where τ_n and τ_p are the average lifetime of minority carriers (electrons) in p region and minority carriers (holes) in n region respectively, D_n and D_p are the diffusion coefficients of electrons and holes, and $G_n(x)$ and $G_p(x)$ are the generation rates of electrons and holes. In order to simulation the non-radiation in semiconductor band gap induced by electron irradiation, the Shockley-Reed-Hall (SRH) recombination model is used and can be expressed as[27]

$$R_{SRH} = \sum_{\alpha=1}^{m} R_A + \sum_{\beta=1}^{n} R_D, \quad (4)$$

$$R_A = \frac{pn - n_i^2}{\tau_p \left[n + g n_i \exp(\frac{E_t - E_i}{kT}) \right] + \tau_n \left[p + \frac{1}{g} n_i \exp(\frac{E_i - E_t}{kT}) \right]}, \quad (5)$$

$$R_D = \frac{pn - n_i^2}{\tau_p \left[n + \frac{1}{g} n_i \exp(\frac{E_t - E_i}{kT}) \right] + \tau_n \left[p + g n_i \exp(\frac{E_i - E_t}{kT}) \right]}, \quad (6)$$

where R_{SRH} is SRH recombination rate, R_A and R_D are acceptor defects and donor defects recombination rate, m and n are the numbers of acceptor defects and donor defects respectively. The n_i is the intrinsic carrier concentration, k is the Boltzmann constant, T is the absolute Kelvin temperature, g is the degradation factor, and E_i and E_t are the intrinsic carriers Fermi level and the defect energy level respectively.

The degradation of normalized short-circuit current (I_{sc}) versus the fluence with different energy electron irradiation is shown in Fig.3.

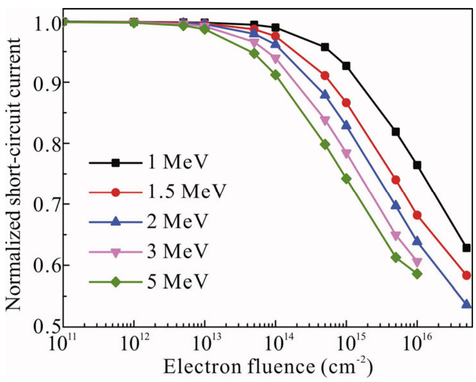

Fig.3 The degradation of normalized short-circuit current versus the fluence with different energy electron irradiation

As shown in Fig.3, the short-circuit current of triple-junction solar cell decreases gradually with the increase of electron fluence. When the electron fluence is less than

1×10^{14} cm^{-2} approximately, slight degradation of normalized I_{sc} has happened induced by electron irradiation. However, when the electron fluence is more than 1×10^{14} cm^{-2}, the degradation of I_{sc} is serious, and the degradation of normalized I_{sc} is proportional to the logarithm of electron fluence. The degradation of I_{sc} increases as the electron energy increases after the electron irradiation with the same fluence. Electron irradiation leads to the degradation on the diffusion length of minority carriers, which leads to the I_{sc} decrease of the triple-junction solar cell. The decrease of minority carrier diffusion length makes it difficult for the photo-generated carriers at the top of the emitter region and the bottom of the base region to diffuse to the depletion region and be collected by the built-in electric field. It results in the indirect recombination of minority carriers increasing and the number of electron-hole pairs decreasing, which is collected and separated by the built-in electric field induced by electron irradiation. The relationship between the minority carrier diffusion length and the electron fluence can be expressed as[27]

$$\frac{1}{L^2}=\frac{1}{L_0^2}+K_L\Phi \quad , \tag{7}$$

where L_0 and L are the minority carrier diffusion length before and after irradiation respectively, and K_L is the minority carrier diffusion length damage coefficient. As can be seen in Eq.(7), the minority carriers' diffusion length decreases with the increase of electron fluence. For the electron irradiation with different energy, the electron irradiation with different energy is mainly reflected in the different K_L values in Eq.(7). Fig.4 shows the electron and proton *NIEL* values in GaAs. In the figure, the electron *NIEL* increases as the electron energy increases, which leads to the increase of displacement damage. On the contrary, the degradation trend of proton *NIEL* (>0.1 MeV) with proton energy is opposite to that of different electron energy. The damage coefficient of proton irradiation is approximately proportional to the *NIEL* value. However, the displacement damage coefficient of electron irradiation is not proportional to the *NIEL* value[28]. Eq.(1) is used to modify the actual displacement dose of electron irradiation with different energy and to make the displacement damage coefficient in proportion to the electron *NIEL* value, the n value in Eq.(1) is approximately 1.7[29]. The modified displacement damage dose is the equivalent displacement damage dose. By calculating the displacement damage dose under different electron irradiation conditions in Eq.(1) and combining the results in Fig.3, the degradation of normalized I_{sc} versus the electron displacement damage dose is shown in Fig.5(a). Meanwhile, the degradation of normalized I_{sc} versus the proton displacement damage dose in our previous study is also shown in Fig.5(a). The relationship between the normalized parameters (including I_{sc}, V_{oc} and P_{max}) versus the particle fluence can be fit as[30]

$$\frac{X}{X_0}=1-C\log(1+\frac{D}{D_0}) , \tag{8}$$

where X_0 and X are the remaining electrical parameter values before and after particle irradiation, D is displacement damage dose, and c and D_0 are constants. D_0 is the displacement damage dose at which the normalized electrical parameters start to change to a linear function with the logarithm of the displacement damage dose. According to Eq.(8), the degradation of normalized short-circuit current versus the displacement damage dose can be expressed as:

$$\frac{I}{I_0}=1-0.186\log(1+\frac{D}{1.075\times10^{10}}) \quad . \tag{9}$$

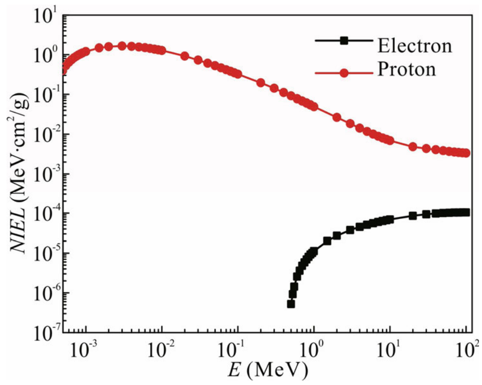

Fig.4 Electron and proton *NIEL* values in GaAs[28]

In Fig.5, the degradation of normalized I_{sc} induced by electron and proton irradiation is different after the same displacement damage dose. To obtain the degradation of normalized I_{sc}, which only versus displacement damage dose and is not affected by the type of irradiated particles, the displacement damage dose of electron irradiation needs to be equivalent. The equivalent formula can be expressed as[29]

$$D_{e/p}=\frac{1}{R_{ep}}\Phi_e(E_e)NIEL(E_e)\left[\frac{NIEL(E_e)}{NIEL(1\ \mathrm{MeV}|_e)}\right]^{n-1} , \tag{10}$$

where R_{ep} is the equivalent coefficient. By dividing the DDD of electron irradiation by R_{ep}, the result of normalized I_{sc} induced by electron irradiation is approximately the same as that of induced by proton irradiation. The R_{ep} is approximately equal to 3.2 in this simulation. The degradation on normalized I_{sc} of induced by DDD of equivalent electron and proton are shown in Fig.5(b). According to the degradation results of normalized I_{sc} with the DDD of equivalent electron and proton irradiation, the degradation of normalized I_{sc} versus the DDD, which is not affected by the type of irradiated particles, is obtained in Fig.5(b).

The degradation of normalized open-circuit voltage (V_{oc}) versus the fluence with different energy electron irradiation is shown in Fig.6.

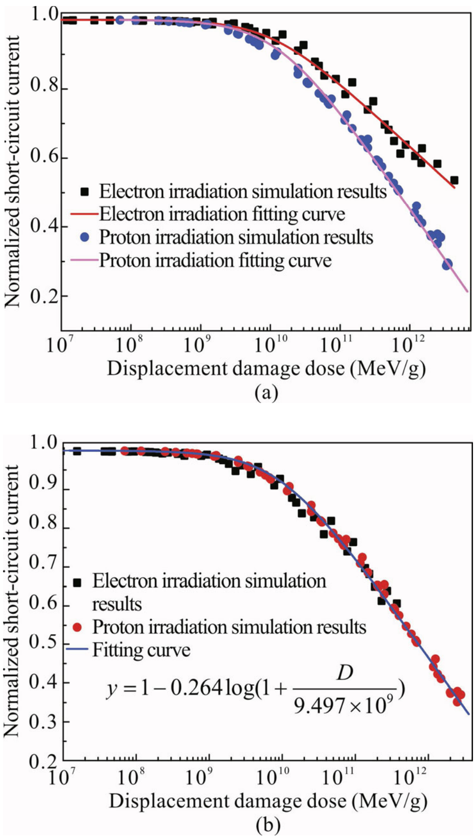

Fig.5 The degradation of normalized short-circuit current versus the displacement damage dose: (a) The displacement damage dose of electron irradiation and proton irradiation[22]; (b) The displacement damage dose of equivalent electron irradiation and proton irradiation

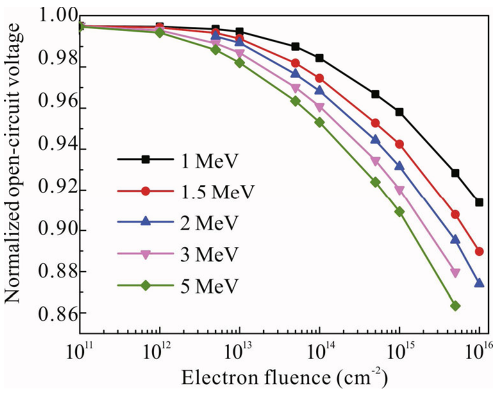

Fig.6 The degradation of normalized open-circuit voltage versus the fluence with different energy electron irradiation

Similar to the degradation of short-circuit current with irradiation fluence, the V_{oc} of the triple-junction solar cell decreases gradually with the increase of electron fluence, and the degradation trend induced by electron irradiation increases as the electron energy increases. Assuming that all impurities are ionized where $N_A \approx p_p$, $N_D \approx n_n$, the V_{oc} of each sub-cell can be expressed as[31]

$$V_{oc_{\text{sub-cell}}} = \frac{kT}{q} \ln \frac{n_n p_p}{n_i^2} . \quad (11)$$

The V_{oc} decrease is caused by the removal of the majority carrier induced by electron irradiation. The majority carrier concentration versus the fluence can be expressed as[31]

$$n = n_0 \exp(\frac{-R_c \Phi}{n_0}) , \quad (12)$$

where n_0 and n are majority carrier concentration before and after proton irradiation, and R_c is the removal rate of majority carriers.

The majority carrier concentration decreases with the increasing of electron fluence which leads to the decrease of built-in electric potential in junction region. In same to the trend of K_L value with electron energy, R_c decreases as the electron energy increases, which leads to the degradation of V_{oc} is serious with the increase of electron energy under the same irradiation fluence. Fig.7(a) shows the degradation of normalized V_{oc} versus the displacement damage dose of electron and proton irradiation in our previous study[22]. By using Eq.(8), the fitting curves of normalized open-circuit voltage versus the displacement damage dose of electron and proton are obtained. According to Eq.(10), the value of normalized V_{oc} versus displacement damage dose of equivalent electron and proton irradiation is obtained in Fig.7(b). The degradation of normalized V_{oc} versus the DDD which is not affected by the type of irradiated particles can be expressed as

$$y = 1 - 0.039 \log(1 + \frac{D}{4.673 \times 10^8}) . \quad (13)$$

Maximum power is the critical parameter that reflects the triple-junction solar cell conversion efficiency of the solar spectrum directly. The degradation of normalized maximum power versus the fluence induced by electron irradiation with different energy is shown in Fig.8. The related parameter degradation trend induced by electron irradiation with different energy in numerical simulation is similar to the related parameter degradation in the experiment method[3], and there is a slight error between the simulation and experiment results due to the different structure for the triple-junction solar cell in simulation and experiment. The normalized maximum power decreases with the increase of electron fluence. The degradation trend increases as the electron energy increases. By using the degradation of maximum power induced by electron and proton irradiation in our previous study and Eq.(8), the degradation curve of maximum power with the DDD which is not affected by the type of irradiated particles is fitted in Fig.9(b). When the total DDD is lower than 3.586×10^9 MeV/g, the slight degradation of maximum power has happened. The remaining normalized maximum power is more than 90%. When the total DDD is more than 3.586×10^9 MeV/g, the serious degradation of maximum power is caused. The degradation of normalized maximum power is proportional to the change of displacement damage dose induced by proton and equivalent electron irradiation.

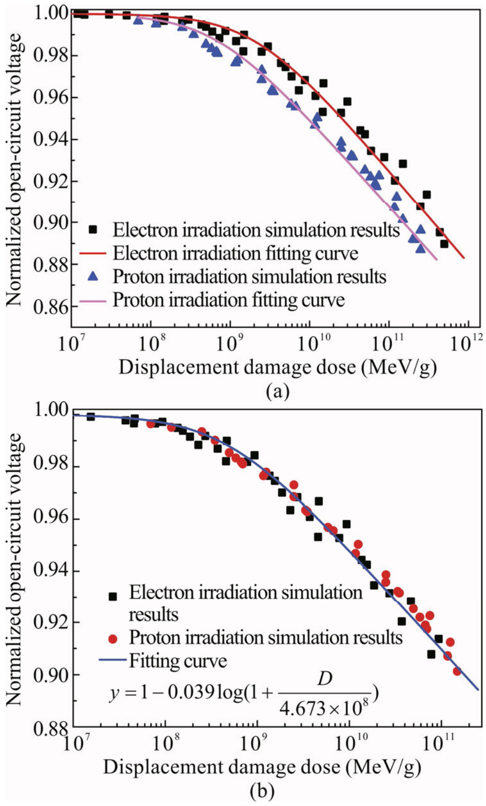

Fig.7 The degradation of normalized open-circuit voltage versus the displacement damage dose: (a) The displacement damage dose of electron irradiation and proton irradiation[22]; (b) The displacement damage dose of equivalent electron irradiation and proton irradiation

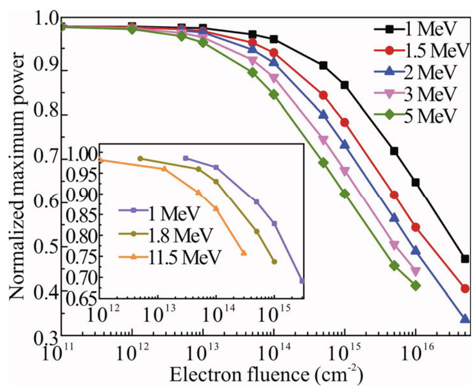

Fig.8 The degradation of normalized maximum power versus fluence induced by electron irradiation with different energy (inset: The degradation of normalized maximum power versus fluence according to the experiment method[3])

By using the degradation simulation results of related parameters (I_{sc}, V_{oc}, P_{max}) induced by electron and proton irradiation with various irradiation conditions, the fitting curves of the degradation on related parameters versus the displacement damage dose can be obtained. By calculating the displacement damage dose of space radiation and fitting the curve, the normalized degradation of the related parameters can be obtained directly. At the same time, the displacement damage dose of solar cell in orbit can be calculated for[29]

$$D_{space}=\int\frac{\mathrm{d}\Phi(E_p,t)}{\mathrm{d}E_p}NIEL(E_p)\mathrm{d}E_p+\frac{1}{R_{ep}}\int\frac{\mathrm{d}\Phi(E_e,t)}{\mathrm{d}E_e}NIEL(E_e)\left[\frac{NIEL(E_e)}{NIEL(1\ \mathrm{MeV}|_e)}\right]^{n-1}\mathrm{d}E_e\ . \quad (14)$$

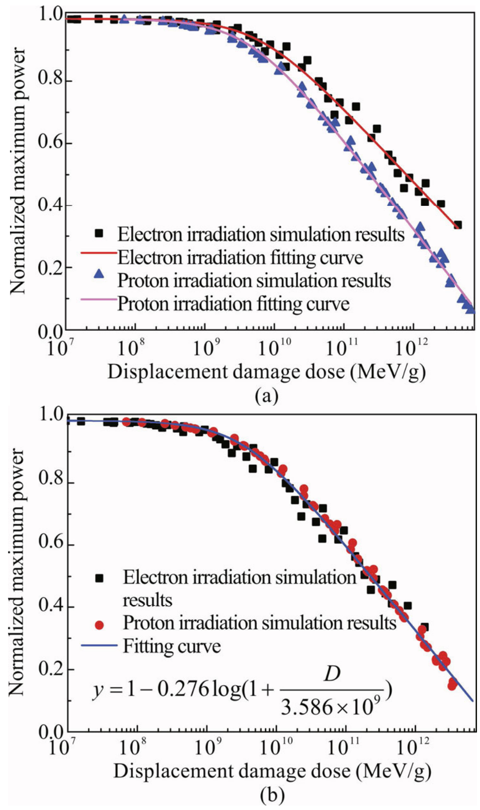

Fig.9 The degradation of normalized maximum power versus the displacement damage dose: (a) The displacement damage dose of electron irradiation and proton irradiation[22]; (b) The displacement damage dose of equivalent electron irradiation and proton irradiation

The annual displacement damage dose of the triple-junction solar cell is calculated by Eq.(14), the D_0 in Eq.(8) is divided by the annual displacement damage dose (D_{year}), and the D_0 is converted into this number of space service years. By combining Eq.(8), the degradation of related electrical parameters versus space service time can be obtained:

$$\frac{X}{X_0}=1-C\log\left(1+\frac{t_{service}}{\frac{D_0}{D_{year}}}\right)\ . \quad (15)$$

In this paper, the degradation of short-circuit current, open-circuit voltage and maximum power of triple-junction solar cell induced by electron irradiation is simulated. The degradation trend of related parameters increases with the increase of electron irradiation fluence. There is a critical value of irradiation fluence. When the irradiation fluence is less than this value, the degradation of the normalized electrical parameters is slight. However, when the irradiation fluence is more than this value, the normalized electrical parameters are seriously, and the degradation of the normalized related parameter is proportional to the logarithm of the change of electron fluence. According to the degradation of related parameters induced by proton irradiation in our previous and equivalent treatment displacement damage dose of electron irradiation (R_{ep}), the degradation of related parameters versus displacement damage dose could be characterized with a single curve, which is not affected by the type of irradiated particles. This provides a way to analyze the degradation of related parameters induced by space particle irradiation by numerical simulation.

References

[1] M. Wiemer, V. Sabnis and H. Yuen, Proc. SPIE **8108**, 810804 (2011).

[2] M. Yamaguchi, Sol. Energy Mater. Sol. Cell. **75**, 261 (2003).

[3] Wang R, Lu M, Yi T C, Yang K and Ji X X, Chin. Phys. Lett. **31**, 103 (2014).

[4] Sato S, Miyamoto H, Imaizumi M, Shimazaki K, Morioka C, Kawano K and Ohshima T, Sol. Energy Mater. Sol. Cell. **93**, 768 (2009).

[5] Qi J H, Hu J M and Sheng Y H, Acta Phys. Sin. **64**, 108802 (2015). (in Chinese)

[6] Ochoa M, Yaccuzzi E, Espinet-Gonzalez P, Barrera M, Barrigon E, IbarraM L, Yedileth C, Garcia J, Lopez E, Alurralde M, Algora C, Godfrin E, Rey-StolleI and Pia J, Sol. Energy Mater. Sol. Cell. **159**, 576 (2017).

[7] Zhang Y Q, Huo M X, Wu Y Y, Sun C Y, Zhao H J, Geng H B, Wang S, Liu R B and Sun Q, Chin. Phys. B. **26**, 088801 (2017).

[8] Yan Y Y, Fang M H, Tang X B, Chen F D, Huang H, Sun X Y and Ji L L, Nucl. Instr. Meth. Phys. Res. B. **451**, 49 (2019).

[9] Yuan Z H, Li X N and Huang J, Optoelectronics Letters **9**, 11 (2013).

[10] Xu Y, Hei N M, Shen X B, Aierken A, Zhao X F, Sailai M, Lu W, Tan M, Wu Y Y, Lu S L, Li Y D and Guo Q, Jpn. J. Appl. Phys. **58**, 032008 (2019).

[11] Song M H, Wang D X and Bi J F, Acta Phys. Sin. **52**, 168 (2017). (in Chinese)

[12] J. C. Bourgoin and M. Zazoui, Semicond. Sci. Technol. **17**, 453 (2002).

[13] X. Jing, G. Min, L. Ming, H. Hu, Y. Guang and X. Jianwen, Materials **11**, 944 (2018).

[14] Wu R, Wang J L and Ling Y L, Atom Energ. Sci. Technol. **69**, 098802 (2018). (in Chinese)

[15] Elahidoost A, Fathipour M and Mojab A, Modelling the Effect of 1 MeV Electron Irradiation on the Performance Degradation of a Single Junction $Al_xGa_{1-x}As$/GaAs Solar Cell, 2012 20th Iranian Conference on Electrical Engineering, 2012.

[16] Leem J M, Yu J S, Kim J N and Noh S K, J. Korean Phys. Soc. **64**, 1561 (2014).

[17] Daniel Schiavo, 2012 Modeling Radiation Effects on a Triple Junction Solar Cell using Silvaco ATLAS (MS dissertation) (Monterey: Naval Postgraduate School).

[18] Cappelletti M A, Casas G A and Morales D M, Semicond. Sci. Technol. **31**, 115020 (2016).

[19] Turowski M, Bald T, Raman A, Fedoseyev A, Warner J H, Cress C D and Walters R J, IEEE Trans. Nucl. Sci. **60**, 2477 (2013).

[20] J. Cubas, S. Pindado and M. Victoria, J. Power Sources **247**, 467 (2014).

[21] Liu Y M, Sun Y and Rockett A, Sol. Energy Mater. Sol. Cell. **98**, 124 (2012).

[22] Li J W, Wang Z Z and Shi C Y, Acta Phys. Sin. **69**, 098802 (2020). (in Chinese)

[23] Guo H L, Shi L F, Wu Y Y, Sun Q, Yu H, Xiao J D and Guo B, 2018 Nucl. Instr. Meth. Phys. Res. B. **431**, 1 (2018).

[24] Messenger S R, Summers G P and Burke E A, Prog. Photovoltaics **9**, 103 (2001).

[25] Khan A, Yamaguchi M, Dharmaso N, Bourgoin J, Ando K and Takamoto T, Jpn. J. Appl. Phys. **41**, 1241 (2002).

[26] M. Mbarki, G. C. Sun and J. C. Bourgoin, Semicond. Sci. Technol. **17**, 453 (2002).

[27] Silvaco Atlas User's Manual http://www.silvaco.com.cn

[28] Baur C, Gervasi M and Nieminen P, NIEL Dose Dependence for Solar Cell Irradiated with Electrons and Protons, Proceedings of the 14th ICATPP Conference, 692 (2013).

[29] Wu Y Y, Yue L and Hu J M, Acta Phys. Sin. **9**, 723 (2011). (in Chinese)

[30] Anspaugh B E, GaAs Solar Cell Radiation Handbook, JPL Publication Jet Propulsion Laboratory, California, 1996.

[31] Zuleeg R and Lehovec K, IEEE Trans. Nucl. Sci. **27**, 1343 (1980).