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A study on the effects of the proton flux on the irradiated degradation of GaAs/Ge solar cells

Hu Jianmin [a,b,*], Wu Yiyong [a], Yang Dezhuang [a], He Shiyu [a], Zhang Zhongwei [c], Qian Yong [c], Zhang Mengyan [c]

[a] School of Materials Science and Engineering, Harbin Institute of Technology, Harbin 150001, China
[b] A Cheng College, Harbin Normal University, Harbin 150301, China
[c] ShangHai Institute of Space Power Sources, Shanghai 200233, China

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Abstract

Low-energy proton irradiation is one of the important factors which affect applications of GaAs solar cells in space. The proton flux encountered in orbit is much lower than that used during ground-base radiation experiments, thus ground-based experiments are a so-called accelerated simulating process. In this paper, effects of the proton flux on the degradation of GaAs/Ge solar cells using *I–V* measurements are investigated. The results indicate that low-energy irradiation seriously damages the solar cells. Regardless of the proton energy, the radiation flux shows no influence on the degradation process of the solar cell. The mechanisms for these effects are discussed in detail here.

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Keywords: GaAs solar cell; Proton radiation; Flux

1. Introduction

GaAs solar cells are being used in the space industry due to their good properties such as high quantum efficiency and good irradiation tolerance. It is thus essential to investigate their behavior under space radiation. There are many published papers which have reported the radiation properties of GaAs solar cells, but most have studied solar cell degradation processes under high-energy particle radiation, such as 1 MeV electrons or 10 MeV protons. In these cases, efforts were made to investigate the influence of high-energy particles on the degradation of electrical properties of the solar cells [1–5]. For low-energy proton irradiation, there are less data reported and fewer investigations of the damage processes and changes in properties of solar cells. Theoretically, the proton-induced displacement damage increases with decreasing energy and reaches a maximum near the threshold (around 200 eV) for atomic displacement. Thus, low-energy proton radiation would result in more serious degradation of the solar cell compared to that of higher-energy proton (>200 keV) radiation [6,7]. Summer et al. [8] had reviewed the degradation effects of low-energy protons in space orbits. In practice, when solar cells are irradiated with ground-based accelerators they are always irradiated at a much greater flux rate than experienced in space. Cells irradiated with electrons to fluences between 1×10^{15} and $1 \times 10^{16}/cm^2$ are usually irradiated with fluxes in the order of 1×10^{11} e/cm^2 s, so that the radiation times are no more than a few hours [1].

Loo et al. [9,10] reported the influence of electron flux on the degradation process of a GaAs solar cell. Their results

* Corresponding author. Address: School of Materials Science and Engineering, Harbin Institute of Technology, Harbin 150001, China. Tel.: +86 451 86412462; fax: +86 451 86415168.
E-mail address: hujianmin@hit.edu.cn (H. Jianmin).

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indicated that the power degradation showed no difference to changes in the electron flux (2×10^9 and 1×10^{11} e/cm^2 s). It should be noted that the irradiation temperature should be kept at room temperature, otherwise the electron radiation at higher temperature can anneal out some defects [11,12]. It was also reported that as-irradiated at 80 °C and at both fluxes of 2×10^9 and 2×10^{11}/cm^2 s, the GaAs cell presented the same degradation process up to a fluence of 6×10^{14} e/cm^2 [13]. However, to the authors' knowledge, no literature was found to report the effects of the proton flux on the degradation process of GaAs solar cells. In this paper, the degradation of a single-junction GaAs cells was investigated after low-energy proton irradiation with various fluxes. The mechanism on the effects of the proton fluxes was also analyzed in detail.

2. Experimental details

As shown in Fig. 1, single-junction p+/n-type GaAs/Ge solar cells were used in the experiments with dimensions of 2×1.5cm^2. A 3 μm-thick n-base GaAs was epitaxially grown and doped by Si with a concentration of (1–1.5) $\times 10^{17}$ cm^{-3}. The GaAs emitter layer is 0.5 μm thick doped by Zn with a concentration of 3×10^{18} cm^{-3}. On the top of the cell, there is an anti-reflective coating to increase the optical transmittance. The as-received cells were measured to have an efficiency around 18.0–19.5% under 1 AM0 illumination.

The proton irradiation test was carried out in a ground-based space-environment simulator. The proton energies were selected as 40, 70, 100 and 170 keV, so that the ranges of incident protons were in the regions of the emitter, junction and base respectively. The proton fluences were in the range of 2×10^{10} to 1×10^{13} cm^{-2} for analysis, while the influence of proton flux was investigated by varying it in the range from 6×10^9 to 1.2×10^{11} cm^{-2} s^{-1}. During the experiments, the sample temperature was kept at 300 K and the irradiation chamber was at a vacuum of 10^{-4} Pa.

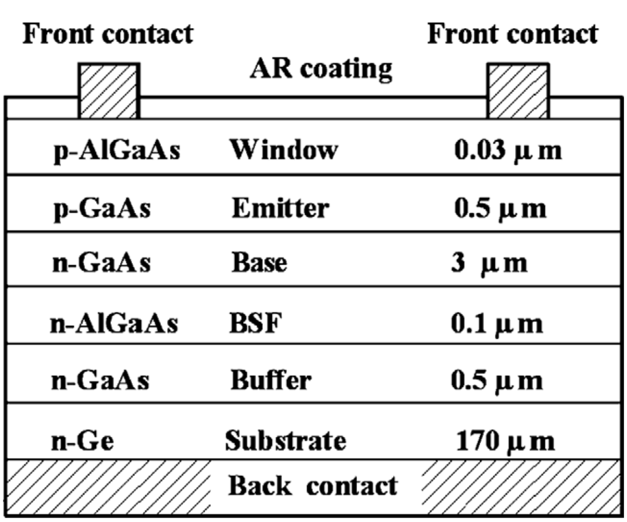

Fig. 1. Schematic of GaAs/Ge solar cell structure.

With reference to the PRC national standard (GB/T 6494-1986) the electrical properties, such as short circuit current (I_{sc}) and open-circuit voltage (V_{oc}), were measured in situ during irradiation, on the AM0 solar spectrum condition (using a standard solar simulator).

3. Results and discussions

3.1. Electrical properties of the solar cells after irradiation

As reported in our previous paper [7], the ranges of the incident proton with energies of 40, 70, 100 and 170 keV are calculated using the computer code SRIM [14] as 0.35, 0.57, 0.80 and 1.36 μm into the solar cell, respectively. Compared with the solar cell configuration shown in Fig. 1 this implies that the incident protons are stopped in regions of the emitter, the junction and the base for energies of 40 keV, 100 keV and 170 keV, respectively, while 70 keV protons are stopped around the interlayer between the emitter and junction.

Fig. 2 shows the effects of proton fluxes on the change of normalized short circuit current I_{sc}, open-circuit voltage V_{oc}, maximum output power P_{max} and filled factor FF versus fluences of 100 keV protons. The results indicate that the electrical properties of the solar cells decrease with increasing fluence, consistent with our previous study [7]. Moreover, changes in the proton fluxes shows almost no influence on the degradation process of the solar cells. Hence, proton fluxes change in the range from 6×10^9 to 1.2×10^{11} cm^{-2} s^{-1}. According to SRIM the range of 100 keV protons is located near the junction region of the GaAs solar cell and thus causes the damage mainly in the junction.

On the other hand, as protons with energies of 40 keV and 170 keV penetrate into the emitter and the base region of the solar cells (according to SRIM), the electrical properties of the cells show some typical degradation, as shown in Fig. 3. Similarly, a change in proton flux causes no effect on the damage process of the cells. These results in Figs. 2 and 3 imply that both proton energy and fluence cause important effects on the cell degradation process. Nevertheless, the proton flux shows no influence on the degradation process even when the protons penetrate into and damage different functional regions (namely emitter, junction and base region), at the experimental temperature. It is understandable that a change in proton energy results in different distributions and concentrations of displacement damage, while a change in fluence causes a concentration change of the damage, thus changing the electrical properties. Hence, the mechanisms of the proton flux effects will be discussed using the classical mode in the following discussion.

3.2. Discussion

Proton flux is defined as the proton number passing through unit area (such as cm^{-2}) during unite time (such as s^{-1}). The proton and electron fluxes are much lower

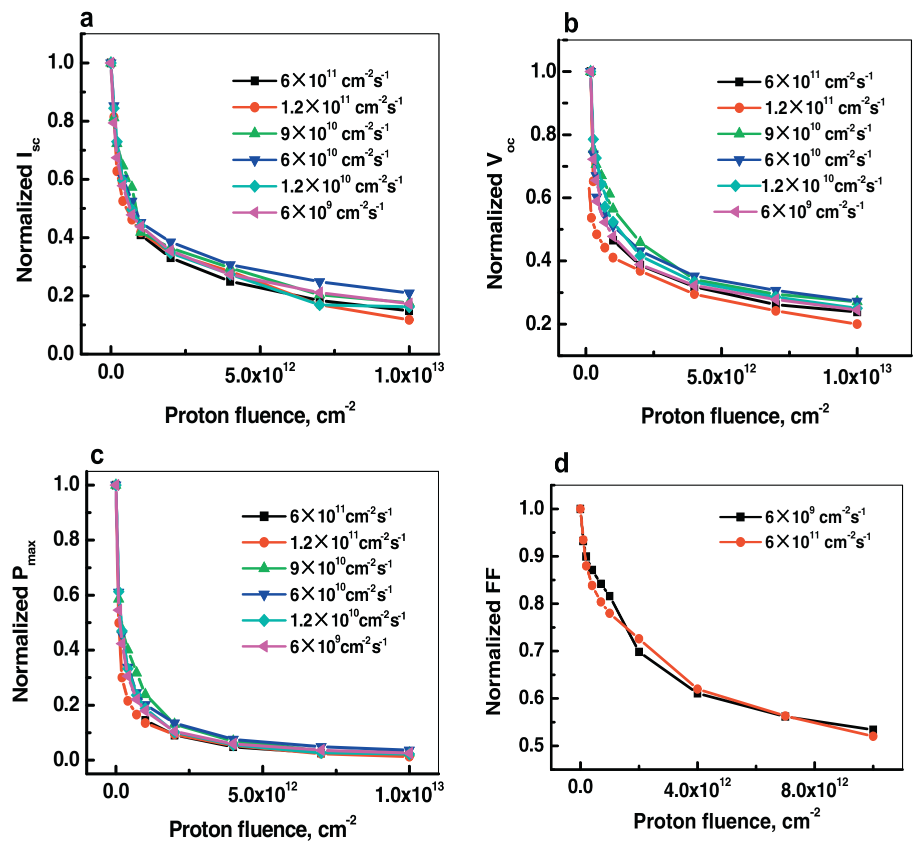

Fig. 2. Effects of proton fluxes on the normalized short circuit current I_{sc} (a), open-circuit voltage V_{oc} (b), maxim output power P_{max} (c) and filled factor FF (d) versus fluences of 100 keV protons.

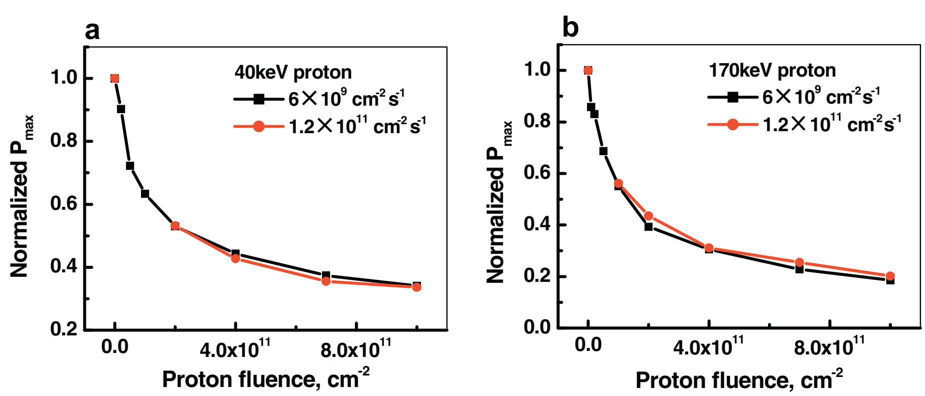

Fig. 3. Effect of proton fluxes on the normalized maxim output power P_{max} versus fluences of (a) 40 keV and (b) 170 keV protons.

than those selected in the ground-based experiments, so we apply a classical model of the particle transportation and radiation damage processes to analyze the effects of the irradiated proton flux.

Proton radiation can result mainly in ionization and displacement in materials. Ionization results from inelastic–collision process of the incident protons with orbital electrons. Ionization is the primary mechanism for energy loss for energetic proton traversing a solar cell. After ionization the corresponding electrons (atoms) will be excited to higher-energy states or even become free ones. These unstably-excited electrons (atoms) would be recovered through recombination or photo(thermal)-emission. In this case, the life time of the excited state is on a time scale of 10^{-14} to 10^{-8} s [15].

The displacement phenomena occur during irradiation mainly through elastic collisions of the protons with lattice atoms. Furthermore, the initially displaced atoms (so-called recoiled atoms) can further impact the next lattice atom, possibly producing a second displacement, and so on. The collision can produce many vacancies and interstitials in the solar cells, becoming lattice-defects. These defects cause a decrease in the life time and diffusion free path length of the minority carriers in the solar cell. On the other hand, the newly-formed vacancies and interstitials can also combine and recover to the originally stable state, but some complex defects such as a bi-vacancy, tri-vacancy or vacancy-doped atom complex can form during radiation or post-annealing, depending on thermal conditions. It takes a time in the range of 10^{-6} to 10^{3} s [15] from the beginning of interaction between incident proton and the lattice atoms to the formation of a stable defect.

Radiation-induced degradation of a solar cell is mainly due to displacement effects. The flux influence of the protons may depend on the correlation characteristic between the interaction time of neighbouring incident protons with the lattice atoms and the life time of the defect formation.

For protons with an energy less than 200 keV, we can treat the radiation process using a classical mechanics theory. For defining the correlated behaviors of the neighboring protons, one should consider two different cases: one is the neighboring protons which enter simultaneously into the solar cell, the other is those neighbors entering sequentially into the radiated cell.

3.2.1. Correlation for the neighbor protons simultaneously in to the cell

Given a proton mass m_p, proton energy E, its velocity v can be calculated as $v = \sqrt{\frac{2E}{m_p}}$. Assuming the incident proton distribution is homogeneous within the irradiated area of the cells, the proton concentration is n while the flux is φ. Using the classical transportation mode, the following relationship for the proton beam can be obtained:

$$vt \cdot S \cdot n = \varphi \cdot St,$$

where S is the projected cross-section area, t is the related time, thus one can get the proton concentration in a unit volume as $n = \frac{\varphi}{v}$. In this case, the average distance l (we assume that a proton takes up volume of a cube with edge length of l) between the neighboring protons simultaneously radiated in the cell can be calculated as:

$$l = \sqrt[3]{V_p} = \sqrt[3]{\frac{1}{n}} = \sqrt[3]{\frac{v}{\varphi}}. \tag{1}$$

Eq. (1) indicates that the distance between simultaneously-incident neighboring protons is related to the velocity (or energy) and flux of the incident protons. For the case of the experimentally-used flux of $1.2 \times 10^{11}\ \mathrm{cm^{-2}\,s^{-1}}$, the calculated distances are shown in Table 1. It is seen that the average distance between one proton to its neighbor (given they penetrate simultaneously in to the cell) is of the order of 10^6 nm, which is 10^7 times larger than the lattice constant (around 0.56 nm at room temperature) of the irradiated GaAs material. This implies that there is almost no probability for the two simultaneously-incident protons to impact a single lattice atom or even its neighbor at the same time, namely no interference between the simultaneous collision events. On the other hand, as the proton energy is in the range of 40–170 keV, the maximum lateral spreading width, determined using SRIM, of the protons is around 4×10^3 nm, which is 10^3 times lower than the above-calculated distance between the neighboring incident protons. This indicates that it is very low probability for the simultaneously-incident protons to interfere with each other in their penetration paths. Thus, one can make a conclusion that there is no correlation between the simultaneously-incident protons for a proton flux of less than $1.2 \times 10^{11}\ \mathrm{cm^{-2}\,s^{-1}}$.

3.2.2. Correlation for the neighbor protons sequentially in to the cell

For sequentially-incident protons, the important parameter is the time interval between one proton and the next to demonstrate the correlations. The time interval can be calculated using Eq. (1) as:

$$\Delta t = \frac{l}{v} = \sqrt[3]{\frac{v}{\varphi \cdot v^3}} = \sqrt[3]{\frac{1}{\varphi \cdot v^2}} \tag{2}$$

the symbols used are defined as above. From this formula the time interval between sequentially-incident protons decreases with increasing flux and its velocity (energy), implying that the correlation between them increases. Based on experimental parameters, the calculated time intervals are listed in Table 1. The time interval for two sequentially-incident protons is around 10^{-10} s. The slowing-down time is of order of 10^{-12} s [16] for a MeV proton penetrating a solid material, which is much shorter than the calculated interval above. Therefore, two sequentially-incident protons have no opportunity to collide with a single lattice atom. Hence the correlated effects of two sequentially-incident protons should also depend on the life time of a displaced atom. The life time of displacement defects in GaAs is on the time scale of 10^{-6} to 10^{3} s, much longer than the time intervals between the sequentially-incident protons. This indicates that there is a certain correlation between the sequential

Table 1
The calculated average distances between the simultaneously-incident protons and average time intervals between the sequentially-incident protons

Proton energy (keV)	Proton flux ($\mathrm{cm^{-2}\,s^{-1}}$)	proton-velocity ($\mathrm{m\,s^{-1}}$)	Distance l (nm)	Time intervals Δt (s)
40	1.2×10^{11}	2.77×10^{6}	1.32×10^{6}	4.77×10^{-10}
70	1.2×10^{11}	3.66×10^{6}	1.45×10^{6}	3.96×10^{-10}
100	1.2×10^{11}	4.38×10^{6}	1.54×10^{6}	3.52×10^{-10}
170	1.2×10^{11}	5.71×10^{6}	1.68×10^{6}	2.95×10^{-10}
1000	1.2×10^{11}	1.385×10^{7}	2.26×10^{6}	1.63×10^{-10}

protons in the material. However, there are two correlated effects for a second proton for the defects formed by the first proton. One is to decrease the recombination probability of the newly-formed displaced atom and the corresponding vacancy, due to impacting the atom away from the vacancy by the following incident proton. The other is to supply a certain energy to the displaced atom to facilitate recombination. When these two effects have the same probability, no correlation could be detected for two sequentially-incident protons during radiation.

For comparison, the situation for electron irradiation is different. When the electron flux is larger that $5 \times 10^{12}\,\mathrm{cm^{-2}\,s^{-1}}$, a kind of thermal-control coating of ZnO/K_2SiO_3 appears [17], decreasing its solar-absorption ratio $\Delta\alpha_s$ with increasing electron flux. The main mechanism for electron radiation to damage this thermal-control coating is ionization effects. Hence, considering the theory, we can obtain the velocity of the electron with energy E_e:

$$v_e = c\sqrt{1 - \left(\frac{m_e c^2}{E_e + m_e c^2}\right)^2}, \tag{3}$$

where E_e, m_e, v_e and c are the electron energy, electron static mass, the velocity and the light velocity in vacuum, respectively.

From Eq. (3), the velocity of 30 keV electrons can be calculated as $9.85 \times 10^7\,\mathrm{ms^{-1}}$. For an electron flux of $5 \times 10^{12}\,\mathrm{cm^{-2}\,s^{-1}}$, the distance between two simultaneously-incident electrons is 1.25×10^6 nm, while the time interval between two sequentially-incident electrons is 1.27×10^{-11} s. This time interval is comparable with the recovery lifetime of $10^{-14} \sim 10^{-8}$ seconds from excited ionization. Therefore, the ionization processes of the sequentially-incident electrons would be overlapped under experimental electron fluxes. This implies that there is a correlated character for the neighboring incident electrons, namely the flux affects the degradation properties of the thermal-control coatings.

Thus, the flux effects of proton irradiation on the degradation of GaAs solar cells depend on two factors: one is the distance l between simultaneously-incident protons; the other is the time interval Δt between sequentially-incident protons. Given that the distance l is of the same order as the lateral spreading width of the incident protons, and the time interval is of the same order as the slowing-down time (10^{-12} s) of protons, correlated effects would appear and so the proton flux exerts an influence on the degradation. Thus, one can calculate the limited flux ϕ_l for the case of simultaneously-incident protons to induce correlation effects (given that the proton energy is 1 MeV, its velocity would be in a scale of $10^7\,\mathrm{m\,s^{-1}}$), according to Eq. (1):

$$\varphi_l = \frac{v}{l^3} = \frac{10^7\ \mathrm{m\,s^{-1}}}{(4 \times 10^{-6}\ \mathrm{m})^3} = 1.56 \times 10^{19}\ \mathrm{cm^{-2}\,s^{-1}}.$$

In the meantime, the other limited flux $\phi_{\Delta t}$ for the case of sequentially-incident protons according to Eq. (2) is

$$\varphi_{\Delta t} = \frac{1}{\Delta t^3 v^2} = \frac{1}{(10^{-12}\ \mathrm{s})^3 (10^7\ \mathrm{m\,s^{-1}})^2} = 10^{18}\ \mathrm{cm^{-2}\,s^{-1}}.$$

Therefore, for GaAs solar cells in space applications, the two limited fluxes of ϕ_l and $\phi_{\Delta t}$ are much larger than the ground-based experimental flux range of 10^9 to 10^{13} $\mathrm{cm^{-2}\,s^{-1}}$ and also the orbital proton flux of less than 10^8 $\mathrm{cm^{-2}\,s^{-1}}$. The results imply that the change in proton flux shows no influence on the radiation damage of GaAs solar cells.

4. Summary

Under low-energy proton irradiation, GaAs solar cells are degraded mainly due to displacement effects. Furthermore, the degradation in electrical properties can be enhanced by increasing the proton energy and fluence. However, large changes in the proton flux show no influence on the damage process under the experimental conditions. This indicates that at room temperature the flux effects depend on the correlation of the collision processes between sequentially or simultaneously-incident protons and the life time of radiation-induced defects. The calculated results show that if proton irradiation was carried out at room temperature, a 1 MeV proton flux of less than $10^{18}\,\mathrm{cm^{-2}\,s^{-1}}$ would show no influence on the degradation. From a practical standpoint, although even the slow rate used in this experiment is one or two orders of magnitude higher than flux rates experienced in space, it is confirmed that rate effects are not a prime issue of concern for the ground-based experiments.

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