Performance Evaluation and Prediction of Single-Junction and Triple-Junction GaAs Solar Cells Induced by Electron and Proton Irradiations

Gao Xin, Feng Zhan-zu, Cui Xin-yu, Yang Sheng-sheng, and Zhang Lei

***Abstract*—Space-graded single-junction (SJ) and triple-junction (TJ) GaAs solar cells, produced by MOCVD, are evaluated through different energy electron- and proton-irradiations to compare radiation effects on these solar cells. Mean degradations of the short circuit current, open circuit voltage and maximum power are presented and analyzed. Compared to the radiation data of the single-junction GaAs cell, the triple-junction GaAs cell has a superior radiation-hardness performance at the same electron or proton energy and fluence. Degradations at different electron or proton energies have been correlated with displacement damage dose. Monte Carlo calculations were completed to analyze displacement damage dose deposited in the solar cell active regions by space radiation environments. The performance degradations of both solar cells in space were predicted. This study provides reference data for the design of these GaAs solar arrays in the typical space radiation environments to ensure the security and reliability of on-orbit spacecrafts.**

***Index Terms*—Displacement damage dose, GaAs, model prediction, radiation effect, solar cell.**

I. Introduction

THE space environment is composed of many different types of charged particles varying over a wide energy range, mainly including electrons and protons. Exposure to the environment degrades the electrical performance of semiconductor devices, especially solar cells, possibly resulting in the failure of the space mission. Therefore, to be used in space, an understanding of the radiation response of solar cells is extremely important for accurate prediction of the expected mission lifetime. In order to predict the degradation of a particular electrical parameter of a solar cell, e.g., maximum power, open circuit voltage, or short circuit current in a space radiation environment, it is necessary to know how that parameter responds to different electron and proton energies, i.e., the energy dependence of the damage coefficients (DCs). Once the energy dependence of the DCs is known, predictions of the cell performance in space could be determined for a given radiation environment. From the point of view of photovoltaic operation, the primary effect of particle irradiation of a solar cell is displacement damage where atoms in the semiconductor lattice are moved from their equilibrium position to form point defects like vacancies and interstitials or defect complexes like vacancy-impurity clusters [1]–[3]. The displacement damage dose (D_d) methodology, developed at the U.S. Naval Research Laboratory (NRL), can provide a means for predicting on-orbit cell performance from a minimum of ground-test data [4]–[10]. The principle of the methodology is the use of nonionizing energy loss (NIEL) to calculate the energy dependence of the DCs. However the methodology may not be appropriate for predicting the space radiation effects on the silicon-based devices having a thick active region over more than several tens of micrometers which results in a nonuniform damage by space radiation environment across the active regions [11], [12]. The performance degradations of the GaAs-based devices can be accurately evaluated and predicted because the displacement damage dose is deposited uniformly by high energy proton or electron irradiation [13].

With the rapid development of new solar cell types, satellite designers and space cell manufacturers need to continually qualify new cell technologies or new generations of existing technologies for the use of these solar cells in space. In this paper, results are presented on the performance of a new SJ and TJ GaAs cells induced by high energy electron and proton irradiation recently fabricated in Tianjin Institute of Power Sources. A Monte Carlo simulation was carried out to obtain the total D_d deposited in the active regions of the solar cells based on the GEANT4 radiation transport toolkit [14]. The NRL displacement damage dose methodology was employed to analyze and predict the radiation responses of the SJ and TJ solar cell in the typical space radiation environments.

II. Experimental Details

The types of the GaAs cells used in this study were 3 cm × 4 cm SJ GaAs/Ge and 2 cm × 2 cm TJ $GaInP_2/GaAs/Ge$ solar cells both grown by Metal-Organic Chemical Vapor Deposition (MOCVD). The cells had no coverglass during irradiation. The cells were chosen such that the beginning-of-life efficiency was almost identical. The typical values of short circuit current (I_{sc}), open circuit voltage (V_{oc}), maximum power (P_{max}) before irradiations are ~ 0.4 A, ~ 1.0 V, ~ 0.3 W and ~ 0.068 A, ~ 2.67 V, ~ 0.156 W for SJ and TJ cells, respectively. The electron and proton irradiations were performed at the ILU-6 elec-

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tron radiation facility located in the Lanzhou institute of physics, and at the EN Tandem Van De Graaff Accelerator in Peking University, respectively. The beam current was monitored through FARADAY cups and, in addition, the electron dose and energy was determined using B3 radiochromic films from GEX Corporation. The solar cells were irradiated at room temperature with 1.0 MeV, 1.5 MeV and 2.0 MeV electrons, and 3.0 MeV, 5.0 MeV, 8.0 MeV and 10.0 MeV protons. Each time, three samples were placed on sample plate in the vacuum chamber during irradiation and a mean value was used to characterize the device degradations. The solar cells were irradiated at a particular fluence level and immediately characterized after each irradiation. A temperature-controlled plate was used to eliminate the effect of thermal annealing on the cell degradations [15]. The temperature was monitored during the irradiation and was no more than 40 °C throughout all sample irradiations. Illuminated current-voltage measurements were performed both before and after irradiation at 25 °C using a Spectrolab X-25 solar simulator under AM0 condition (air mass zero, 1 sun).

III. Result and Discussion

Fig. 1 shows the normalized values of I_{sc}, V_{oc} and P_{max}, the ratio of the value after irradiation to the one before irradiation, measured on the SJ and TJ solar cells as a function of electron and proton fluences for different energies, indicated by the open symbols and by the solid symbols, respectively. For a given degradation level, the fluence level increases for decreasing electron energy indicating that the higher energy electrons do relatively more damage. This is correlated with nonionizing energy loss (NIEL) of electron and proton in semiconductor materials [4], [9]. NIEL represents displacement damage energy transferred to the target lattice by an irradiating particle. It can also be found that the fluence level was demanded higher for electron to give rise to the same degradation level than for proton, which can be attributed to the fact that NIEL of proton is far higher than that of electron at same energy.

A $GaInP_2/GaAs/Ge$ solar cell consists of three p-n junctions stacked on top of one another, separated by tunnel junctions to keep the overall polarity of the device the same so the subvoltages add. This "monolithic" approach does result in subcell current limiting, however. The radiation response of a TJ GaAs cell is primarily controlled by the most radiation sensitive subcell photocurrent. The quantum efficiency (QE) measurements of the TJ cell are shown in Fig. 2 before and after 1.0 MeV 1×10^{15} cm^{-2} and 5×10^{15} cm^{-2} electron irradiations. The integral of each of these curves with the incident illumination spectrum yields the photocurrent. Given the wide absorption range of the Ge sub-cell, it produces significantly more photocurrent than the top two junctions (even after irradiation), so it never limits the current. The ratio (J_{GaInP}/J_{GaAs}) of photocurrents between the top two sub-cells, is 0.996 quite closely matched before irradiation. However, after irradiation, the ratio increases to 1.25 for 1×10^{15} cm^{-2} and 1.31 for 5×10^{15} cm^{-2} electron irradiations, indicating that the GaAs sub-cell degrades much faster than the $GaInP_2$ sub-cell so that it limits the current.

It can also be noted in Fig. 1 that the TJ cells show a superior radiation-hardness performance over the SJ cells at the same irradiation condition. Indeed, current matching is the condition for maximum power output of TJ cell, and the TJ cells had been designed to achieve current matching at end-of-life, which sacrifices some of the beginning-of-life performance but results in optimum end-of-life performance. When top-cell limited at beginning-of-life, the degradation of a TJ cell will be controlled by the more radiation resistant $GaInP_2$ top-cell until a specific irradiation level is reached where the photocurrent of the GaAs sub-cell is degraded to the level of the top-cell leaving the device current unmatched.

Before beginning a space mission, satellite designers need to predict the expected degradation of the solar array in the

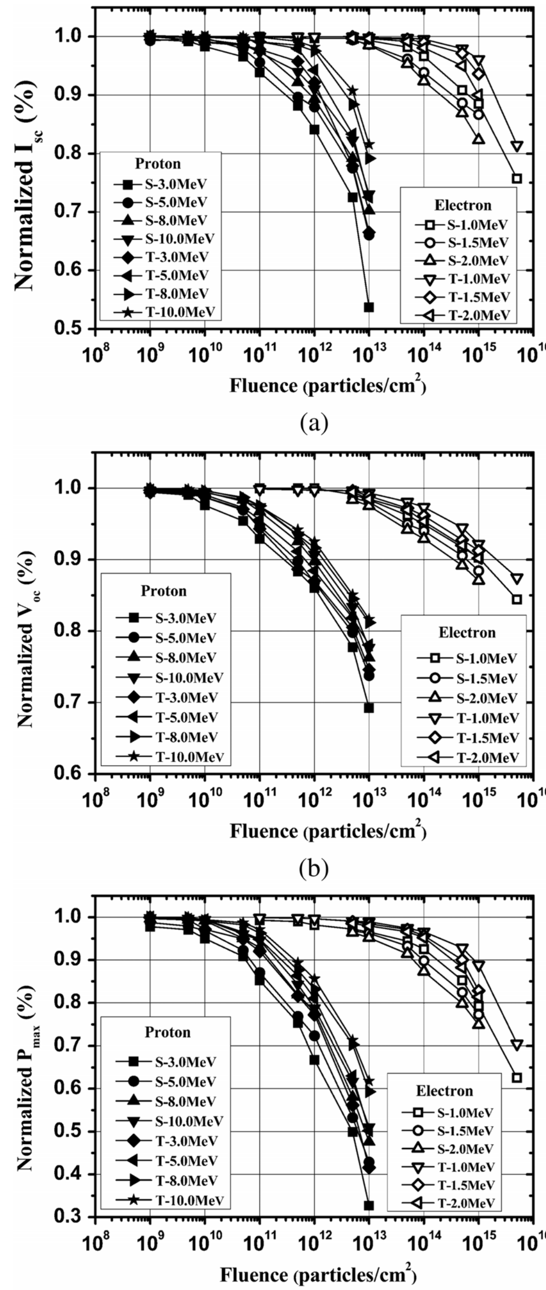

Fig. 1. Normalized parameters (a) I_{sc}, (b) V_{oc}, and (c) P_{max} of the solar cells as a function of electron and proton fluence under different energies. T: Triple-junction cell, S: Single-junction cell.

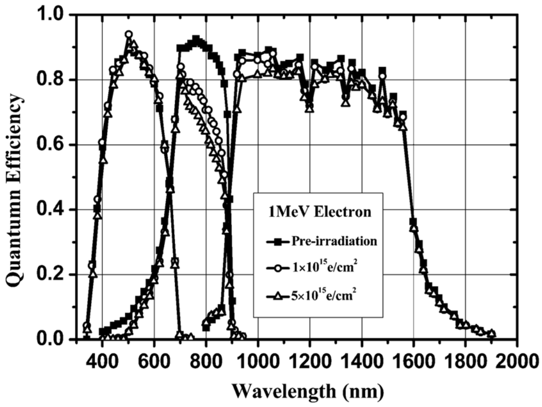

Fig. 2. Electron radiation-induced spectral response degradations of a triple-junction $GaInP_2/GaAs/Ge$ solar cell.

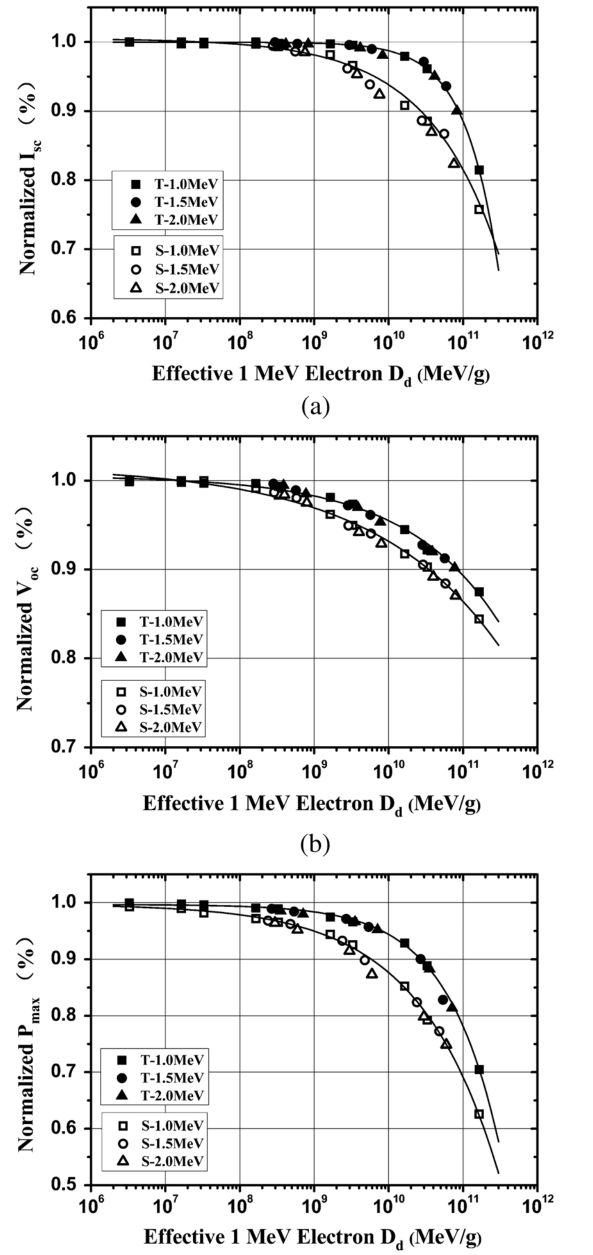

Fig. 3. Normalized parameters (a) I_{sc}, (b) V_{oc}, and (c) P_{max} as a function of the effective 1 MeV electron D_{deff}. The symbols represent the experimental data and the solid line represents the fitting curve for the cells.

space radiation environment. The methodology of displacement damage dose can simplify the performance evaluation since the displacement damage effects on the photovoltaic parameters for different particle energies can be correlated on the basis of D_d. The D_d can be calculated by multiplying the particle fluence by the appropriate NIEL for a given reference energy and D_d is usually expressed in the form of the effective displacement damage dose, as shown in Equation (1) [16]

$$D_d = \Phi(E)S(E)\left[\frac{S(E)}{S(E_{ref})}\right]^{(n-1)} \tag{1}$$

where $\Phi(E)$ is the fluence level for incident particles, $S(E)$ is the NIEL value for particles incident on the target material, $S(E_{ref})$ is NIEL for a given reference energy and D_d is the resulting effective displacement damage dose. The reference energy for electron is usually taken as 1 MeV. The exponent n accounts for a nonlinear dependence on NIEL. For any value of n other than unity, NIEL represents an effective NIEL for the given particle and reference energy, and as a result, the D_d represents an effective D_d. For solar cell analyses, the factor has been empirically determined to be 1 for proton, neutron and heavy ion radiation effects and to vary roughly between 0.5 and 3 for electron radiation effects [12], [17]. The factor can be determined through a nonlinear least squares fitting of (1) (where E_{ref} is set to 1 MeV) and can be used to collapse the electron data to a single curve as the equivalent 1.0 MeV electron D_d. The values of n for the SJ and TJ cells are listed in Table I.

If the normalized data shown in Fig. 1 are plotted as a function of effective 1 MeV electron D_d and proton D_d given by (1), respectively, then the data will collapse to a single characteristic curve, as shown in Fig. 3 and Fig. 4 for the respective electron and proton data.

The superposed degradation curves shown in Fig. 3 can be fitted using the semi empirical equation [18]

$$N(E) = 1 - C\log\left(1 + \frac{D_d(E)}{D_x}\right) \tag{2}$$

where N(E) represents the normalized parameter of interest, $D_d(E)$ is the effective dose given by (1), C and D_x are fitting parameters in Table I. The solid line in Fig. 3 and Fig. 4 represents the characteristic curves generated using (2) for the SJ and TJ cells.

The characteristic curve can be used to predict the cell response to irradiation by any particle energy or by a particle spectrum, and it can be seen that only a few experimental data are required to determine the characteristic parameters of the curve, as is often the case with new and emerging cell technologies.

As an example the end-of-life performance of SJ and TJ GaAs solar cells after a 5 year flight in typical electron-enriched GEO (35,870 km, 0°), electron/proton-combined GPS-like orbit (21,500 km, 55°) and proton-enriched LEO (799 km, 99°) radiation environments are predicted using the

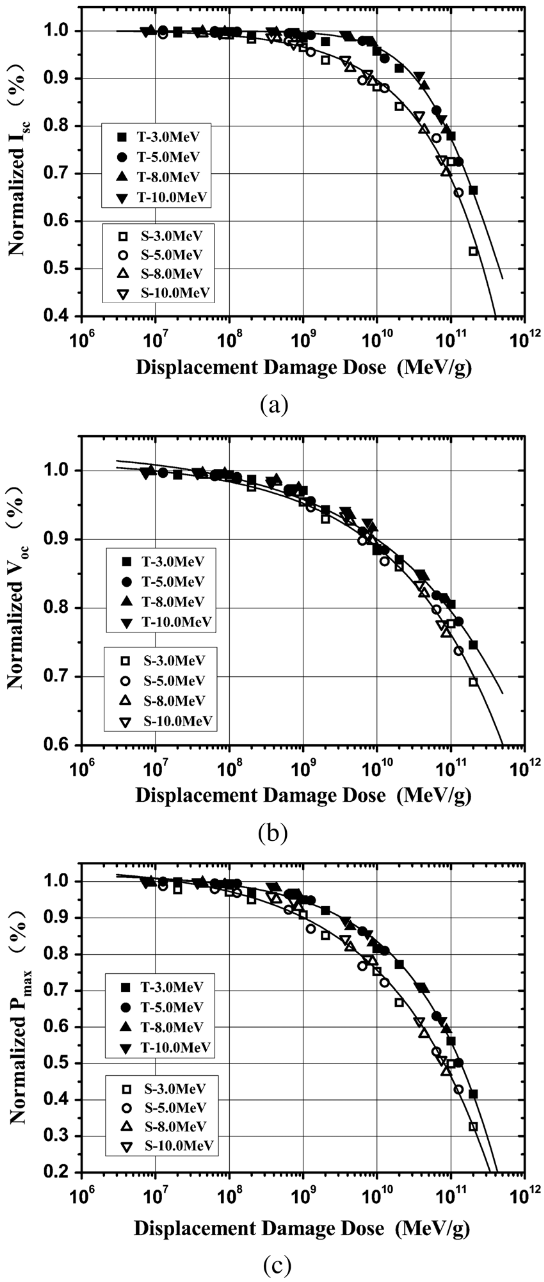

Fig. 4. Normalized parameters (a) I_{sc}, (b) V_{oc}, and (c) P_{max} as a function of proton D_d. The symbols represent the experimental data and the solid line represents the fitting curve for the cells.

displacement damage dose methodology. For earth-orbiting and near-earth systems, the primary source of these particles is from the geomagnetically trapped particles in the Van Allen belts. Damaging protons can also be encountered during periods of high solar activity when solar coronal mass ejections occur, but not included in this analysis.

The incident proton and electron fluence spectra are obtained according to the AP8 and AE8 radiation models. To account for a coverglass shielding, the omni-directional slowed-down fluence spectra is analyzed for 100 micrometer fused silica coverglass thicknesses for these radiation environments based on Geant4 radiation transport toolkit. Because the GaAs cell active layers are typically very thin, less than 5 μm for both the

TABLE I
THE VALUES OF FITTING PARAMETERS FOR THE ELECTRON AND PROTON IRRADIATION DATA OF THE SJ AND TJ GAAS SOLAR CELLS

Particles	Cells	Parameters	n	C	D_x
Electron	SJ	I_{sc}	1.75	0.18	8.16×10^{9}
		V_{oc}	1.86	0.06	6.32×10^{8}
		P_{max}	1.25	0.21	3.37×10^{10}
	TJ	I_{sc}	1.95	2.65	9.44×10^{11}
		V_{oc}	1.80	0.07	2.45×10^{9}
		P_{max}	1.62	0.35	2.69×10^{10}
Proton	SJ	I_{sc}	1.0	0.25	6.10×10^{9}
		V_{oc}	1.0	0.13	1.34×10^{9}
		P_{max}	1.0	0.28	1.23×10^{9}
	TJ	I_{sc}	1.0	0.55	6.36×10^{10}
		V_{oc}	1.0	0.11	1.23×10^{9}
		P_{max}	1.0	0.31	3.83×10^{9}

TABLE II
THE CALCULATED D_d DEPOSITED IN GAAS MATERIAL BEFORE AND BEHIND SILICA COVERGLASS AND THE PREDICTED P_{max} AFTER A 5-YEAR ON-ORBIT FLIGHT

Orbit type	Coverglass thickness μm	Effective 1MeV D_d (MeV/g)	Proton D_d (MeV/g)	Normalized P_{max}
GEO	0	1.09×10^{10}	-	0.87(SJ) 0 .94(TJ)
	100	7.50×10^{9}	-	0.90(SJ) 0.95(TJ)
GPS-like Orbit	0	3.46×10^{10}	9.30×10^{13}	0.0
	100	1.77×10^{10}	4.36×10^{8}	0.83(SJ) 0.92(TJ)
LEO	0	1.81×10^{8}	2.64×10^{10}	0.66(SJ) 0.74(TJ)
	100	7.80×10^{7}	1.43×10^{8}	0.95(SJ) 0.98(TJ)

cells, the slowed-down spectrum can be considered constant throughout the active region of the cells. Then the total D_d deposited in GaAs material behind 0 and 100 $\mu m - \text{thick}$ coverglass, can be calculated by integrating to (1),

$$D_d = \frac{1}{S(E_{ref})^{n-1}} \int \frac{d\varphi(E)}{dE} \cdot S(E)^n dE \qquad (3)$$

where $d\varphi(E)/dE$ is the differential slowed-down particle fluence spectrum.

The accumulated D_d and the predicted P_{max} after a 5-year on-orbit flight are presented in Table II, according to the characteristic curves in Fig. 3 and Fig. 4. For the combination radiation environment of electron and proton, one needs to convert the effective 1 MeV electron D_d to proton D_d using the following expression [17]:

$$D_{dp} = D_{xp}\left[\left(1+\frac{D_{de}}{D_{xe}}\right)^{\frac{C_e}{C_p}} - 1\right] \qquad (4)$$

where $(\mathrm{D_{xp}}, \mathrm{C_p})$ and $(\mathrm{D_{xe}}, \mathrm{C_e})$ are the fitting coefficients of the proton $\mathrm{D_d}$ and effective 1 MeV electron $\mathrm{D_d}$ curves, presented in Table I.

It can be found in Table II that the $\mathrm{D_d}$ deposited by electron before shielding can be reduced no more than 50% by using a $100\ \mu\mathrm{m}-\mathrm{thick}$ coverglass. However in the case of proton, the $\mathrm{D_d}$ can be significantly lowered by more than two orders of magnitude by the same coverglass. For the GPS-like orbit radiation environment the $\mathrm{D_d}$ received by the unshielded solar cells will be mainly contributed by the proton radiation, whereas the electron radiation will dominate the $\mathrm{D_d}$ received by the shielded solar cells. The use of the coverglass is vital important for shielding the damages induced by low energy proton.

IV. Conclusion

The irradiation experimental results were presented about SJ and TJ GaAs solar cells to compare radiation effects of electrons and protons on these solar cells, and also to provide experimental data for predictions of the cell performances. The research results show that the TJ GaAs cell has a superior radiation-hardness performance than the SJ cell does, which can be attributed to the TJ cell structure design for current matching at end-of-life that more significantly controls the radiation-response. A modeling methodology for the SJ and TJ GaAs solar cells based on $\mathrm{D_d}$ has been employed to predict the behaviors of the GaAs cells in typical GEO, GPS-like and LEO orbit radiation environments. The predicted results for the SJ and TJ cell structures still need to be validated through on-orbit data from space flight experiments.

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