Evaluation and prediction of the degradation of space Si solar cells induced by a low-earth-orbit radiation environment

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Abstract: Space-graded silicon solar cells are evaluated by 1 MeV and 2 MeV electron-irradiation. The mean degradation of the maximum power ($P_{\rm max}$) is presented and analyzed. The degradation at both electron energies has been correlated with the displacement damage dose ($D_{\rm d}$). A good linearity between the electron $D_{\rm d}$ and the mean $P_{\rm max}$ degradation is obtained. The concept of $D_{\rm d}$ has also been used to predict the Si solar cell response in a low-earth-orbit (Altitude 799 km, Inclination 99°) radiation environment, considering the shielded effect of a 120 μm-thick silica coverglass on reducing the radiation. Compared with the on-orbit data from a Si solar array of a Chinese satellite (duration from April 2007 to July 2010), a good match can be found between the on-orbit data and the predicted results using $D_{\rm d}$ methodology, indicating the method is appropriate for evaluating the radiation damage of the solar cells, and also to provide a new technique for studying radiation effects on the optoelectronic detectors used in many high energy physics applications, where harsh radiation environments produce damage in optoelectronic device materials.

Key words: radiation, displacement damage dose, Si solar cell, LEO

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1 Introduction

The radiation environment is known to be a major cause of the failure of electronic devices in space, consisting mainly of protons and/or electrons. Extensive research has been conducted on the total-ionizing dose and single-event effects [1]. More recently, the displacement damage effects have been shown to be responsible for the failure of optoelectronic devices in flight [2]. These energetic particles in space degrade the electrical performance of the devices, and the change of the optoelectronic devices during irradiation is one of the most important questions for the application of the optoelectronic detectors in high energy physics experiments. Therefore, understanding the radiation response of the device is extremely important for accurate predictions of performance degradation.

In order to predict the degradation of the electrical parameters 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 the 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 can be determined for a given radiation environment. The displacement damage dose methodology, developed at the U.S. Naval Research Laboratory, addresses this issue by providing a means for predicting on-orbit cell performance from a minimum of ground-test data [2–5]. The principle of the methodology is the use of nonionizing energy loss (NIEL) to calculate the energy dependence of the DCs.

In this paper, results are presented about the performance degradation of a back surface reflection Si cell induced by electron irradiation. The $D_{\rm d}$ methodology was employed to predict the solar cell response in a LEO space mission. To validate the $D_{\rm d}$ method-

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ology in the application of electron irradiation to simulate the LEO space mission predominated with proton radiation, the prediction results of cell performance have been compared with the space flight data obtained from a Si solar array of the China satellite (Altitude 799 km, Inclination 99°, duration from April 2007 to July 2010).

2 The experimental method

The type of cell used in this study was a 2 cm×4 cm n^+p type Si solar cell manufactured in China. The cells had no coverglass during irradiation. The cells were chosen so that the beginning-of-life efficiency was almost identical. The irradiations were performed by the ILU-6 electron radiation facility located in the Lanzhou Institute of Physics. The solar cells were irradiated at room temperature with 1 MeV and 2 MeV electrons, respectively, to a particular fluence level and immediately characterized after each irradiation. The temperature was monitored during the irradiation and was no more than 30 ℃ throughout all sample irradiations. The beam dosimetry was calibrated by the B3 films from GEX Corporation before each irradiation [6]. Illuminated current-voltage measurements were performed under 1 sun, air mass zero (one solar spectral irradiance, AM0, 1367 W/m^2) conditions at 25 ℃ using a solar simulator from the Oriel Corporation.

3 Results and discussion

3.1 Electron irradiation results

Figure 1 shows the data for the normalized maximum power (normalized to the pre-irradiation values) measured on the Si solar cells as a function of electron fluence for two different electron energies, the short circuit current (I_{sc}) and open circuit voltage (V_{oc}) data are not shown here. It can be found that for a given degradation level, the fluence level decreases with increasing electron energy indicating that the higher energy electrons do relatively more damage. For example, a degradation of max power to 80% of the initial value will require a fluence of about 1.17×10^{15}/cm^2 for a 1 MeV electron, while for a 2 MeV electron, only a fluence of 2.73×10^{14}/cm^2 is required.

3.2 Calculation of NIEL

NIEL is defined as the part of the energy, lost per unit length by a particle moving in the material through the nuclear elastic, and nuclear inelastic interactions, thereby producing the initial displacement damage and excited phonons. NlEL is a direct analog of the linear energy transfer or stopping power for ionization events. This displacement damage creates defect energy levels in semiconductors that can act as trapping and recombination centers. It is the introduction of these defect levels that degrade the photovoltaic response of a solar cell through a reduction in the minority carrier diffusion length. The unit of NIEL is typically MeVcm^2/g. NIEL is a calculated quantity that takes into account the various interactions of an incident particle with a target atom/material. NIEL can be written as an integral over a solid angle [7, 8], i.e.

$$\mathrm{NIEL}(E) = \frac{N_\mathrm{A}}{A}\int_{\theta_{\min}}^{\pi}\left[\frac{\mathrm{d}\sigma(\theta,E)}{\mathrm{d}\Omega}\right] \times T(\theta,E)L\left[T(\theta,E)\right]\mathrm{d}T, \qquad (1)$$

where N_A is Avogadro's number, A is the atomic weight, and $\theta_{\min}$ is the scattering angle for which the recoil energy equals the threshold for atomic displacement. $\mathrm{d}\sigma/\mathrm{d}\Omega$ is the total differential cross section (elastic and inelastic) for atomic displacements. T is the recoil energy of the target atoms and $L(T)$ is the so-called partition factor which partitions the energy into ionizing and nonionizing events.

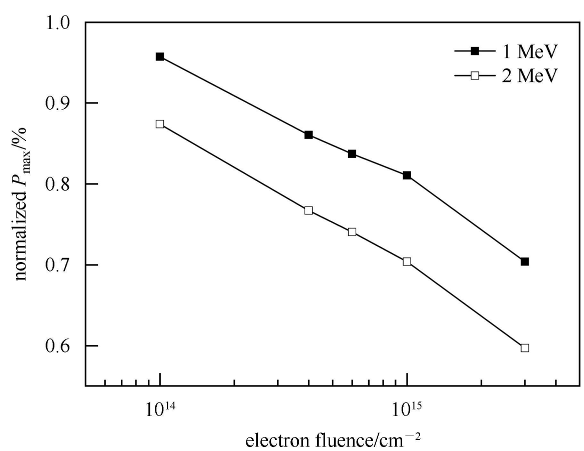

Fig. 1. The normalized maximum power of Si solar cells as a function of electron fluence for 1.0 MeV and 2 MeV electrons.

The Geant 4 radiation transport toolkit is used as the basis of the simulation to calculate NIEL for electrons and proton in silicon, and the results are shown in Fig. 2.

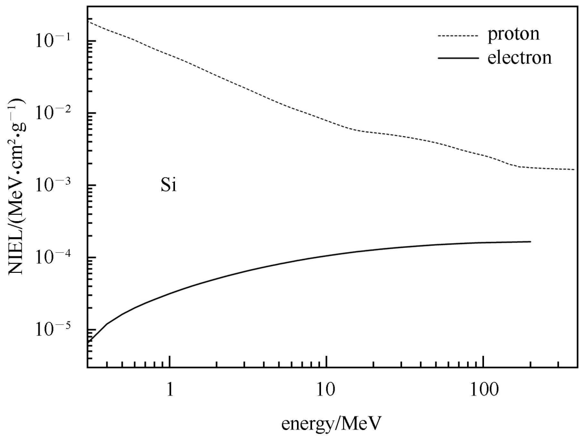

Fig. 2. The calculated NIEL of the electrons and protons in silicon based on the Geant4 radiation transport toolkit.

3.3 The displacement damage dose deposited

The response to radiation by a solar cell is typically characterized by the photovoltaic parameters (i.e., I_{sc}, V_{oc}, $P_{\max}$). The amount of the non-ionizing radiation dose deposited by the irradiating particle is referred to as the displacement damage dose [9]. The methodology of the 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 value for the given irradiating particle, energy and target material. However, D_{d} is usually expressed in the form of the effective displacement damage dose, as shown in Eq. (2)

$$D_{\mathrm{deff}}=\Phi(E)S(E)\left[\frac{S(E)}{S(E_{\mathrm{ref}})}\right]^{(n-1)}, \tag{2}$$

where $\Phi(E)$ is the fluence level for electrons, $S(E)$ is the NIEL value for electrons incident on the target material, $S(E_{\mathrm{ref}})$ is the NIEL for reference energy electrons, and D_{deff} is the resulting effective displacement damage dose. The reference energy for the 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, D_{d} represents an effective D_{d} (i.e. D_{deff}) for the given particle and reference energy (E_{ref}).

If the normalized maximum power data shown in Fig. 1 are plotted as a function of effective 1 MeV electron D_{d} given by Eq. (2), the data will collapse to a single characteristic curve, as shown in Fig. 3. The photocurrent and photovoltage are also seen to fall on a single curve, but are not shown here. In order to cause the data to collapse to a single curve, a nonlinear least squares fitting of Eq. (2) is used to determine the best value of n. The best correlation is obtained with n=2.56, where E_{ref} is set to 1 MeV. This value of n suggests a significant photoresponse from both the p-type emitter and n-type base regions.

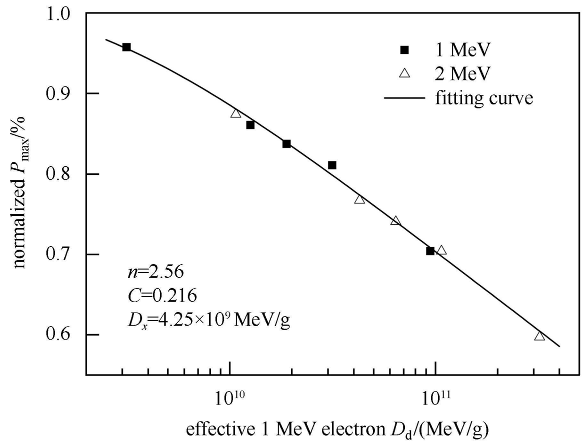

Fig. 3. The normalized maximum power as a function of the effective 1 MeV electron D_{deff}. The symbols represent the experimental data and the solid line represents the fitting curve for the cell.

For solar cells, the superposed degradation curves shown in Fig. 3 can be fitted using the semi empirical equation [10]

$$N(E)=1-C\log\left(1+\frac{D_{\mathrm{deff}}(E)}{D_x}\right), \tag{3}$$

where $N(E)$ represents the normalized parameter of interest, $D_{\mathrm{deff}}(E)$ is the effective dose given by Eq. (2), C and D_x are the fitting parameters to be determined. The solid line represents the characteristic curves generated using Eq. (3) for the cells. The fitting parameters are characteristic for this solar cell structure, and the best correlation is obtained with C=0.216 and D_x=4.25×10^9 MeV/g.

Once correlated in terms of D_{deff}, the radiation data for a given particle fall on a single curve. The characteristic curve can be used to predict the cell response to irradiation by any particle energy or by the particle spectrum, and it can be seen that only a few experimental data points are required to determine the characteristic parameters of the curve.

3.4 The degradation of the Si cells in an LEO radiation environment

The simulation was executed about the performance degradation of the Si cells with 120 μm thicknesses of shielded silica coverglass in the LEO (Altitude 799 km, Inclination 99°) radiation environment, using the displacement damage dose methodology for analyzing and modeling.

Within the D_{d} methodology, the analysis of electron effects in space begins with an analysis of the space radiation environment. The integral electron and proton spectra encountered in the LEO earth orbit for a 1y mission are shown in Fig. 4, an omni directional spectrum based on AE8MAX and AP8MAX. Typically, the solar cell is shielded from this incident spectrum by the coverglass on the front and the solar array substrate in the rear. For the present example, only the front side irradiation through the coverglass will be considered. To account for this shielding, the calculated slowed-down integral spectra for a 120 μm thickness of fused silica coverglass are also shown in Fig. 4. It can be seen that the proton spectrum less than several MeVs of the LEO environment has been enormously attenuated by the 120 μm thick silica coverglass, while it does not look very different to the pre-shielded one in the case of the electron spectrum, due to the fact that an electron can penetrate deeper in silica than a proton does at the same energy.

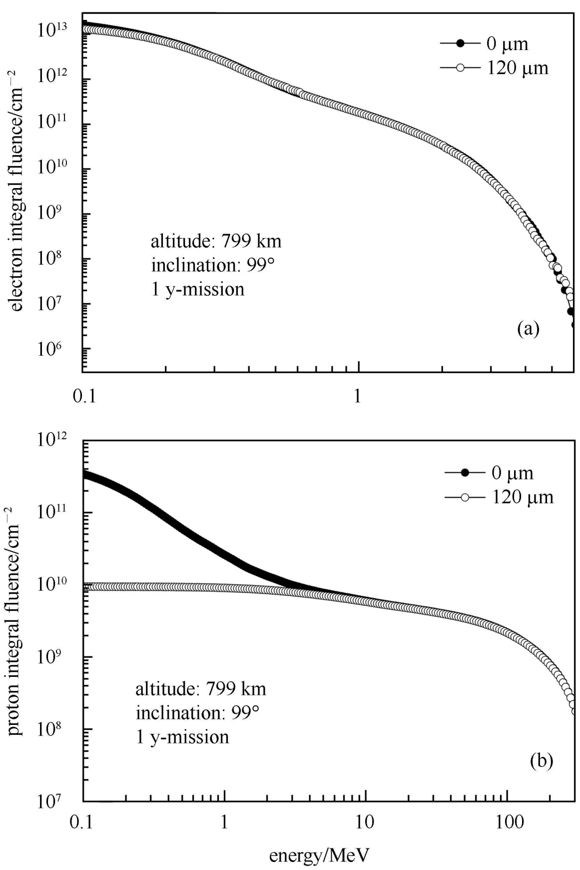

Fig. 4. The calculated electron (a) and proton (b) integral slowed-down spectra behind a 120 μm-thick coverglass in LEO.

The amount of displacement damage induced by the irradiating continuous spectrum can be determined by summing the product of the differential fluence spectrum with NIEL, so Eq. (2) can also be rewritten as the integral:

$$D_{\mathrm{deff}} = \int_0^{\infty} \mathrm{SDS}(E) \cdot S(E) \cdot \left[\frac{S(E)}{S(E_{\mathrm{ref}})}\right]^{(n-1)} \mathrm{d}E, \quad (4)$$

where $\mathrm{SDS}(E)$ is the differential fluence spectrum, replacing $\Phi(E)$ in Eq. (2). The total D_{d} deposited before and behind a 120 μm thick coverglass was calculated for the LEO radiation environment, according to Eq. (2). The results are listed in Table 1. It can be found that D_{d} deposited by an electron before shielding is reduced from 7.16×10^{7} MeV/g to 6.24×10^{7} MeV/g, only about a 12.8% drop of D_{d} using a 120 μm thick coverglass. However in the case of the proton, D_{d} can be enormously decreased from 6.60×10^{10} MeV/g to 1.36×10^{8} MeV/g, a reduction more than two orders of magnitude by the same thickness of coverglass. The use of the coverglass is of vital importance for shielding the radiation from the low energy proton. A further reduction in the D_{deff} can be achieved by increasing the coverglass thickness but would result in an increase of the overall weight of the solar array. The calculation results indicate that the D_{d} received by the unshielded solar cells will come mainly from the proton radiation of the LEO environment; on the other hand, despite a considerable lowering in fluence density by a shielded coverglass, the proton radiation will still dominate the D_{d} received by the shielded solar cells, due to a higher value of proton NIEL shown in Fig. 1.

Table 1. The calculated D_{d} from the LEO radiation environment with or without a coverglass in a 1 y-mission.

particle species	unshielded D_{deff}/(MeV/g)	shielded D_{deff}/(MeV/g)
electron	7.16×10^{7}	6.24×10^{7}
proton	6.60×10^{10}	1.36×10^{8}

Using the characteristic curve in Fig. 3, the relationship between the normalized max power and D_{deff} can be converted into that between the normalized max power and the on-orbit years. As the D_{d} mainly comes from proton radiation in the LEO environment, the equivalent relationship must be obtained between the proton D_{d} and effective 1 MeV electron D_{deff}, so as to use the electron characteristic curve in Fig. 3 to predict the behavior of the Si solar array in the LEO orbit. Research work [11, 12] shows that a proton does about ten times more damage to Si cells than an electron does at the same effective 1 MeV electron D_{deff}. According to the relationship, the normalized max power of the cells will be seriously degraded if unshielded, theoretically degrading to about 55.6% of the initial value by the accumulating proton dose at the end of a 1-year-mission, while in the case of using a 120 μm thick coverglass, the normalized max power can be increased to 97.4% of the initial value.

To validate the D_{d} methodology, predictions of on-orbit performance have been compared with the space flight data obtained from a Si solar array of a China satellite (launched in April 2007, altitude 799 km, inclination 99°). A summary of the results is shown in Fig. 5. The selected flight data from April 2007 to July 2010 are the mean monthly max output power of the solar array, and only the data represented by solid characters is listed in Fig. 5 for clear sight. These data points are normalized to the initial value, i.e., that in April 2007. A dose causing ten times more damage than that of the electron dose in Fig. 3 was adopted to predict the degradation of the solar array in the proton radiation environment. In this case, the predicted data represented by the dashed line matches the space flight data very well, indicating the methodology is appropriate for using electron irradiation to evaluate the effects of the proton radiation environments on a Si solar array. The results are especially important for the particular space orbits which are mainly composed of protons, e.g., the LEO earth orbit. This methodology will be beneficial to save expensive costs of proton irradiation experiments, and to avoid the use of higher energy proton irradiation facilities, considering an important portion of ~100 MeV protons in LEO.

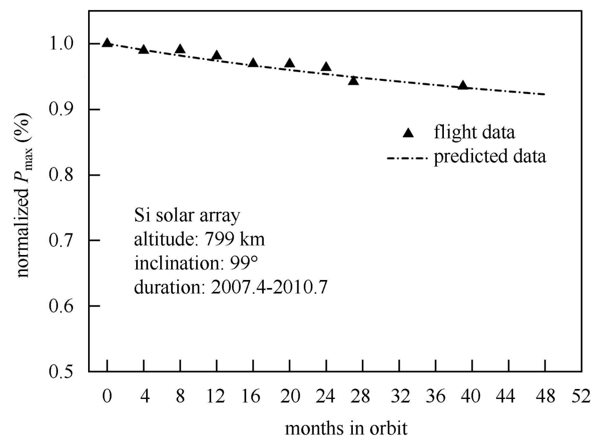

Fig. 5. Comparison of data from space flight mission with predictions made with the D_{d} model.

4 Conclusion

In this paper, a modeling methodology for the Si solar cells based on a displacement damage dose has been employed to predict the behavior of home-made Si cells in a LEO radiation environment. Degradation at different electron energies has been correlated with D_{d}. A good match can be found between the on-orbit data of a China satellite and the predicted results by D_{d} methodology, indicating that the methodology can provide a valuable reference for solar array design.

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