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Effects of electron radiation on shielded space triple-junction GaAs solar cells*

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The displacement damage dose methodology for analysing and modelling the performance of triple-junction $InGaP_2$/GaAs/Ge solar cells in an electron radiation environment is presented. Degradations at different electron energies are correlated with displacement damage dose (D_d). One particular electron radiation environment, relative to a geosynchronous earth orbit (GEO), is chosen to calculate the total D_d behind the different thicknesses coverglasses to predict the performance degradation at the end of the 15-year mission.

Keywords: nonionizing energy loss, displacement damage dose, solar cell

PACC: 7170J, 8750G, 8630J

1. Introduction

The space environment is composed of many different types of charged particles varying over a wide energy range. The dominant particles in the space environment are electrons, protons or their combinations, depending on the orbit. Exposure to these charged particles typically degrades the electrical performance of semiconductor devices, especially less-shielded space solar arrays. Therefore, an understanding of the radiation response of the device is extremely important for accurate prediction of the expected mission lifetime.

Because of the rapid development of new solar cell types, satellite designers and space cell manufacturers have to continually qualify new cell technologies or new generations of existing technologies. This can be an extremely expensive and time-consuming process, since solar cells have to be irradiated by many different particle energies and fluences to simulate the real space environment with a quasi-continuous energy spectrum.

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 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, the cell performance in space can be predicted for a given radiation environment. If the energy dependence of the DCs for a given parameter could be calculated it would reduce the number of experiments required and, hence, significantly reduce costs. The displacement damage dose (D_d) methodology, developed at the US Naval Research Laboratory (NRL), addresses this issue by providing a means for predicting on-orbit cell performance from a minimum of ground-test data.[1,2] The principle of the methodology is to use nonionizing energy loss (NIEL) to calculate the energy dependence of the DCs.

Although the use of NIEL for correlating proton-induced DCs in a variety of semiconductor devices and material types has been widely documented and has been shown generally to be successful,[3−10] the available data are limited to correlate electron-induced DCs. These results are especially important for the particular space orbits which are mainly composed of electrons, e.g. GEO. Such results obtained through the analysis of the electron radiation response of a new type of triple-junction $InGaP_2$/GaAs/Ge solar cell are presented in this paper.

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2. Experimental details

The type of GaAs cell used in this study was a 2 cm×2 cm p-n type triple-junction $InGaP_2$/GaAs/Ge solar cell grown by metal-organic chemical vapour deposition (MOCVD). The cells had no coverglass during irradiation. The cells were chosen to have almost the same beginning-of-life efficiencies. The irradiations were performed by the ILU-6 electron radiation facility located at the Lanzhou institute of physics. The solar cells were irradiated at room temperature by 0.8 MeV, 1 MeV and 2 MeV electrons. The solar cells were irradiated at a particular fluence level and then immediately characterized after each irradiation. The temperature was monitored during the irradiation, and it was no more than 30°C for all samples. The beam dosimetry was calibrated by B3 films from the GEX Corporation before each irradiation. Illuminated current–voltage measurements were performed under 1 sun, air mass zero (1 sun, AM0, 1367 W/m^2) conditions at 25 °C.

3. Results

3.1. Calculation of NIEL

NIEL is defined as the part of the energy lost per unit length by a particle moving in the material, through Coulomb (elastic), nuclear elastic, and nuclear inelastic interactions thereby producing initial displacement damage and excited phonons. This displacement damage creates defect energy levels in semiconductors that can act as trapping and recombination centres. It is these defect levels that degrade the photovoltaic response of a solar cell through a reduction in minority carrier diffusion length. The units of NIEL are typically MeV/cm or $MeV \cdot cm^2/g$. 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,[11−13] i.e.

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

where N_A is Avogadro's number, A is the atomic weight, and θ_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.

The Geant4 radiation transport toolkit is used as the basis of the simulation to calculate NIEL for an electron on GaAs, and the results are shown in Fig.1. Electron irradiation can induce damage not only to GaAs, but also to $InGaP_2$ and Ge, and it can also degrade the photovoltaic response of the triple-junction GaAs cells. However, in this paper, only the effect of electron irradiation on GaAs is considered, since the $InGaP_2$ and Ge sub-cell have better radiation-resistant performance than the GaAs sub-cell.[14] In fact, the majority of the degradation occurs due to diffusion length degradation in the GaAs sub-cell, and in all cases, this sub-cell becomes the current-limiting junction after irradiation.

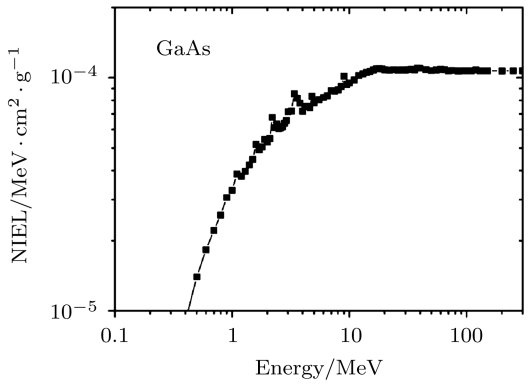


Fig.1. Calculated NIEL of GaAs based on the Geant4 radiation transport toolkit.

3.2. Displacement damage dose deposited

Solar cell response is typically characterized through photovoltaic parameters (i.e. short circuit current (I_sc), open circuit voltage (V_ac), maximum power (P_max), and fill factor (FF)). The methodology of displacement damage dose (D_d) can simplify the performance evaluation, therefore the displacement damage effect on the photovoltaic parameters for different particle energies can be correlated with D_d.

The amount of nonionizing radiation dose deposited by the irradiating particle is referred to as the displacement damage dose,[15] which is calculated by multiplying the particle fluence by the appropriate NIEL value for the given irradiating particle, energy

and target material as shown in Expression (2)

$$D_{\rm d} = \Phi(E)S(E)\left[\frac{S_(E)}{S(E_{\rm ref})}\right]^{(n-1)}, \qquad (2)$$

where $\Phi(E)$ is the fluence level for electrons, $S(E)$ is the NIEL value for electrons incident on the target material, $S(E_{\rm ref})$ is the NIEL for reference energy electrons, and $D_{\rm d}$ is the resulting effective displacement damage dose. The reference energy for an electron is usually taken to be 1 MeV. The quantity in square brackets accounts for a nonlinear dependence on NIEL. For any value of n other than unity, the $D_{\rm d}$ represents an effective $D_{\rm d}$ for the given particle and reference energy ($E_{\rm rer}$). The available data[5,15,16] suggest that when the active region is primarily composed of p-type materials the electron DCs often follow a quadratic dependence on NIEL ($n = 2$), whereas when it is composed of n-type materials they follow a linear dependence ($n = 1$), and for the most part, the DCs follow a power law dependence on NIEL with an exponent varying between 1 and 2.

Figure 2 shows the data for the normalized maximum power (normalized to the pre-irradiation value) measured on the triple-junction GaAs solar cells as a function of electron fluence for three different electron energies indicated by the solid symbols. For a given degradation level, the fluence level decreases with the increase of electron energy, indicating that the higher energy electrons do more damage.

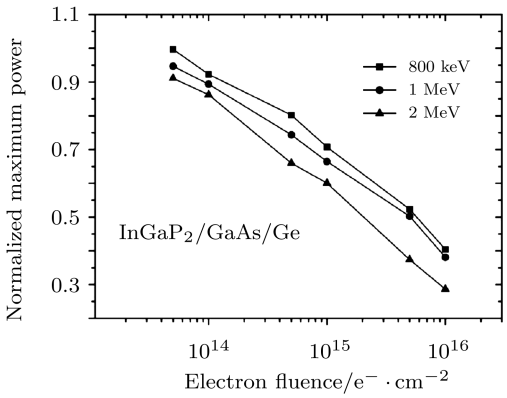


Fig.2. Curves for normalized maximum power as a function of electron fluence for 0.8 MeV, 1.0 MeV and 2 MeV electrons on $InGaP_2/GaAs/Ge$ solar cells.

If the normalized maximum power data are plotted as a function of effective 1 MeV electron $D_{\rm d}$ given by expression (2), the data will collapse into a single characteristic curve as shown in Fig.3. The photocurrent and photovoltage were also shown to fall on a single curve, but they are not shown here. In order to cause the data to collapse into a single curve a nonlinear least squares fitting of expression (2) is used to determine the best value of n. Since the triple-junction cell degradation is primarily controlled by the response of the GaAs sub-cell, the GaAs NIEL is used to calculate $D_{\rm d}$. The best correlation is obtained with $n = 1.51$, where $E_{\rm ref}$ is set to be 1 MeV. This value of n suggests significant photoresponse from both the p-type emitter and n-type base regions.

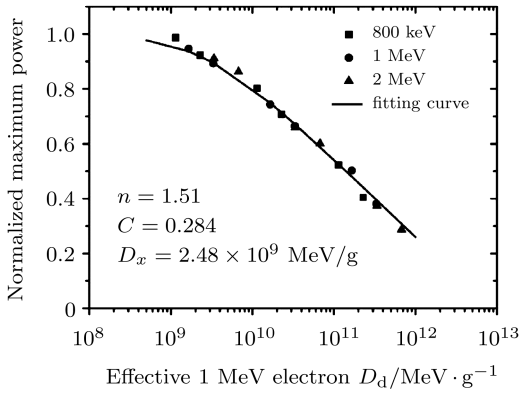


Fig.3. Normalized maximum power as a function of effective 1 MeV electron $D_{\rm d}$. The solid symbols represent the experimental data and the solid line represents the fitting curve for the triple-junction cell.

For solar cells, the superposed degradation curves shown in Fig.3 can be fitted by using the semi empirical equation[7]

$$N(E) = 1 - C\log\left(1 + \frac{D_{\rm eff}(E)}{D_x}\right), \qquad (3)$$

where $N(E)$ represents the normalized parameter of interest, $D_{\rm eff}(E)$ is the effective dose given by expression (2), and C and D_x are fitting parameters to be determined. The solid line represents the characteristic curves generated by using expression (3) for the cells. The fitting parameters are characteristic of this solar cell structure, and the best correlation is obtained with $C = 0.28$ and $D_x = 2.48 \times 10^9$ MeV/g.

Once correlated with $D_{\rm d}$, 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 a particle spectrum, and it can be seen that only a few experimental data are required to determine the characteristic parameters of the curve. In contrast, if the normalized maximum power data are correlated with $D_{\rm d}$ (a product of $\Phi(E)$ and $S(E)$), not effective $D_{\rm d}$ in expression (2), in many cases the curve will not fall

on a single curve, and in this case the data are dispersive, which is not shown here, as can be induced by a nonlinear dependence of the DCs on NIEL.[5,15,16] In the case of protons, the characteristic curve could be determined from measurements at a single energy, because the value of n can be simply considered to be unity. In the electron case, since the value of n can vary between 1 and 2, it must be determined through experimental data. So generally electron data at two energies are required, except that the DCs have a linear dependence on NIEL.

3.3. Effects of particular electron environments in GEO on the solar cells

In this section, we will calculate the total displacement damage dose deposited in the triple-junction GaAs solar cells for the particular electron environments in GEO (altitude 35870 km, inclination 0°).

Within the $D_{\rm d}$ methodology, the analysis of electron effects in space begins with the analysis of the space radiation environment. The integral electron spectrum encountered in a GEO for a 15-year mission is shown in Fig.4. This is an omni-directional spectrum based on AE8MAX. Typically, the solar cell is shielded from this incident spectrum by the coverglass in the front and the solar array substrate in the rear. To account for this shielding, the calculated slowed-down integral spectra for the fused silica coverglasses with different thicknesses are also shown in Fig.4; again they are omni-directional spectra obtained based on the Geant4 radiation transport toolkit. For the present example, only front side irradiation through the coverglass will be considered. The primary difference between the incident spectra and the slowed-down spectra is that the fluence of electrons below 1 MeV is significantly reduced. It will be noted that the energy dependences of the slowed-down spectra are similar for different coverglass thicknesses, although the absolute magnitude varies.

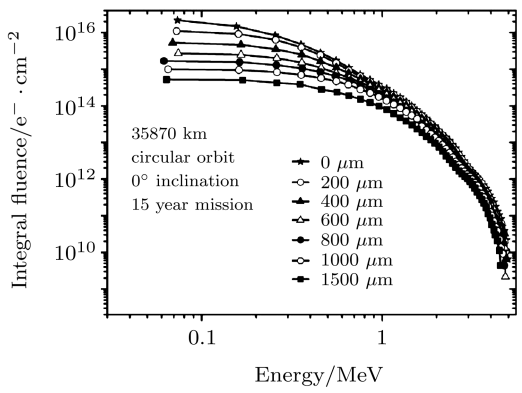


Fig.4. Calculated integral slowed-down spectra behind the fused quartz coverglass with several different thicknesses in a GEO for a 15-year mission.

The total effective dose deposited will be calculated as a function of fused silica coverglass thickness subjected to the electron environment, according to expression (2). The results are shown in Fig.5. As expected, the thicker the shielding material is, the lower the value of the $D_{\rm d}$ deposited in solar cells will be. The $D_{\rm d}$ deposited can be reduced by at least 50% by using a 500 μm thick coverglass. In the case of a proton, the calculation based on Geant4 radiation transport toolkit shows that the $D_{\rm d}$ can be reduced by at least one order of magnitude by the same thick coverglasses, indicating that an electron can penetrate more deeply in silica than a proton at the same energy. A further reduction in $D_{\rm d}$ can be achieved by increasing the coverglass thickness, but this would result in an increase in the overall weight of the solar array. Thus there exists a tradeoff between the higher electrical power and the lighter weight.

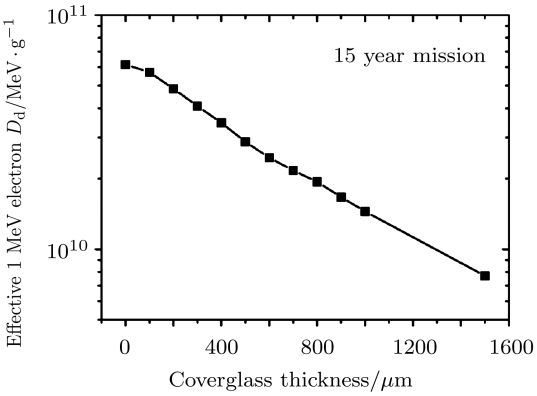


Fig.5. Effective 1 MeV electron $D_{\rm d}$ as a function of the coverglass thickness in a GEO for a 15-year mission.

Using the characteristic curve in Fig.3, the relation between effective $D_{\rm d}$ and coverglass thickness can be converted into that between normalized maximum power and coverglass thickness as shown in Fig.6. It can be seen that the normalized maximum power at the end of the 15-year mission in a GEO increases with the increase of thickness of the solar array coverglass. The power of the triple-junction cell will decrease to about 60% of the original power if the cell is uncovered by silica glass, while the use of a 500 μm thickness of silica glass will increase the end power of the 15-year

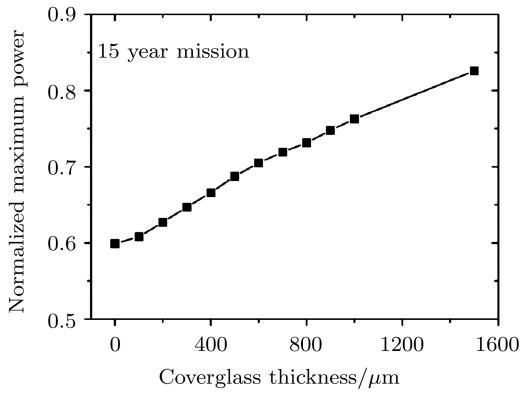


Fig.6. Normalized maximum power as a function of the coverglass thickness in a GEO for a 15-year mission.

mission to about 70% of the original power. However, the effects of the coverglass thickness and electron radiation-induced colour centres on the transmittivity of sunlight are not included in the analysis. In addition, the effect of the solar proton event on the total dose deposited on the cell is not considered in this work: this is relatively rare and occurs most often during the solar maximum phase of the 11-year solar cycle.[17,18]

4. Conclusion

In this paper, a comprehensive radiation damage analysis and modelling methodology for triple-junction GaAs solar cells based on displacement damage dose ($D_{\rm d}$) is presented. The result seems to suggest that the NIEL approach can be used to establish the energy dependence of electron DCs but the exponent dependence on NIEL must be first experimentally determined. The best value of exponent n is found to be 1.51, i.e. $n = 1.51$ for this type of cell. Degradation at different electron energies is correlated with $D_{\rm d}$, and an empirical equation can be used for predicting on-orbit cell performance. The methodology for the cell structure still needs to be validated through on-orbit data from space flight experiments.

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