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Displacement Damage Characterization of Electron Radiation in Triple-Junction GaAs Solar Cells

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The effect of space radiation environments on the degradation of triple-junction $InGaP_2$/GaAs/Ge cells was studied to provide the reference for solar array design. The irradiations were performed by the irradiation line-based unit-6 electron radiation facility. The solar cells were irradiated at room temperature with 0.8, 1, and 2 Mev electrons. For a given degradation level, the fluence level decreases for an increasing energy, indicating the higher energy electrons do relatively more damage. Degradation at different electron energies has been correlated with displacement damage dose. The performance of the triple-junction cells with various thicknesses of silica coverglass in a geostationary Earth orbit radiation environment is presented. The power of the triple-junction cells will decrease to about 60% of the original value if uncovered by silica glass, while the use of a 500-μm-thick glass will decrease the endpower of the 15-year mission by 30% of the original power. A 100-μm-thick silica glass (thickness usually used in space solar array) is not enough for blocking the electron radiation on the solar cells.

Nomenclature

A	=	atomic weight
D_d	=	displacement damage dose
$D_{\text{eff}}(E)$	=	effective displacement damage dose
I_{sc}	=	short circuit current, A/cm^2
n	=	degree of linear correlation
N_A	=	Avogadro's number
Pmax	=	maximum power output
$S(E)$	=	nonionizing energy loss for electron incident on target material
$S(E_{\text{ref}})$	=	nonionizing energy loss for reference energy electrons
T	=	recoil energy of target atoms
V_{oc}	=	open circuit voltage
$\Phi(E)$	=	electron fluence

I. Introduction

THE space environment consists of many different types of charged particles varying over a wide energy range. The dominant particles in the space environment are electrons, protons, or a combination of the two, depending on the orbit. Exposure to these charged particles typically degrades the electrical performance of semiconductor devices, especially less-shielded space solar arrays. Therefore, understanding the radiation response of the device is extremely important for accurate predictions 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 at many different particle energies and fluences to simulate the real space environment with a quasi-continuous energy spectrum.

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, predictions of the cell performance in space can be determined 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 D_d methodology, developed at the U.S. Naval Research Laboratory, addresses this issue by providing a means for predicting onorbit cell performance from a minimum of ground-test data [1,2]. The principle of the methodology is the use of 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 shown, generally, to be successful [3–10], there is a very limited amount of data for correlating electron-induced DCs. These results are especially important for the particular space orbits that are mainly composed of electrons, e.g., geostationary Earth orbit (GEO). This paper presents such results through analysis of the electron radiation response of new types of triple-junction $InGaP_2$/GaAs/Ge solar cells.

II. Experimental Details

The type of the GaAs cells used in this study was the 2×2 cm p-n type triple-junction $InGaP_2$/GaAs/Ge solar cells grown by metal–organic chemical vapor deposition. The cells had no coverglass during irradiation. The cells were chosen such that the beginning-of-life efficiency was almost identical. The irradiations were performed by the irradiation line-based unit-6 electron radiation facility located in the Lanzhou Institute of Physics. The solar cells were irradiated at room temperature with 0.8, 1, and 2 MeV. The solar cells were irradiated at a particular fluence level and immediately characterized after each irradiation. The temperature was monitored during the irradiation and was no more than 30°C for all samples. The beam dosimetry was calibrated by the B3 films from GEX Corporation before each irradiation. Illuminated current-voltage measurements were performed under one sun, air mass zero (space sunlight at Earth orbit, $1367\ W/m^2$) conditions at 25°C.

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III. Results

A. Calculation of Nonionizing Energy Loss

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 the initial displacement damage and excited phonons. 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 degrades the photovoltaic response of a solar cell through a reduction in the minority carrier diffusion length. The units of NIEL are typically MeV/cm or MeV 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 solid angle [11–13]; that is,

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

The Geant4 radiation transport toolkit is used as the basis of the simulation to calculate NIEL for electron on GaAs, and the results are shown in Fig. 1. Electron irradiation can induce damage on not only GaAs but on $InGaP_2$ and Ge that 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 subcells have better radiation-resistant performance than the GaAs subcell [14]. In fact, the majority of the degradation occurs due to diffusion length degradation in the GaAs subcell and, in all cases, this subcell becomes the current-limiting junction after irradiation.

B. Displacement Damage Dose Deposited

Solar cell response is typically characterized through the photovoltaic parameters (i.e., short circuit current I_{sc}, open circuit voltage V_{oc}, maximum power P_{max}, and fill factor). The methodology of displacement damage dose D_d 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 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 Eq. (2):

$$D_d = \Phi(E)S(E)\left[\frac{S(E)}{S(E_{\mathrm{ref}})}\right]^{(n-1)} \qquad (2)$$

The reference energy for the electron is usually taken as 1 MeV. The quantity in square brackets accounts for a nonlinear dependence on NIEL. For any value of n other than unity, the D_d represents an effective D_d for the given particle and reference energy E_{ref}. The available data [5,15,16] suggest that when the active region is primarily composed of p-type material, the electron DCs often follow a quadratic dependence on NIEL ($n = 2$), whereas the active region for n-type material follows a linear dependence ($n = 1$) and, for the most part, the DCs follow a power law dependence on NIEL, with an exponent varying between the value of one and two.

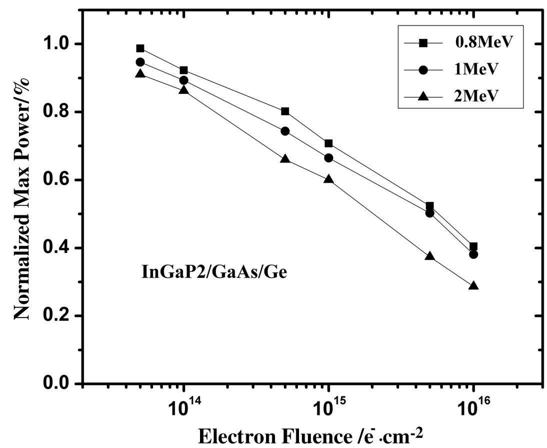

Fig. 2 Normalized maximum power of the triple-junction cells as a function of electron fluences.

Figure 2 shows the data for the normalized maximum power (normalized to the preirradiation values) 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 for increasing electron energy, indicating that the higher energy electrons do relatively more damage.

If the normalized maximum power data are plotted as a function of effective 1 MeV D_d, given by Eq. (2), the data will collapse to a single characteristic curve, as shown in Fig. 3. The solid symbols represent the experimental data and the solid line represents the fitting curve for the triple-junction cell. The photocurrent and photovoltage were also seen to fall on a single curve, but this is not shown here. 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. Since the triple-junction cells degradation are primarily controlled by the response of the GaAs subcell, the GaAs NIEL will be used to calculate D_d. The best correlation is obtained with $n = 1.51$, where E_{ref} is set to 1 MeV. This value of n suggests significant photoresponse from both the p-type emitter and n-type base regions.

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

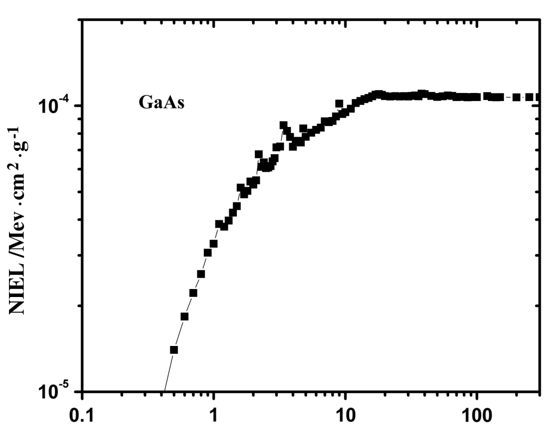

Fig. 1 The calculated NIEL of GaAs based on the Geant4 radiation transport toolkit.

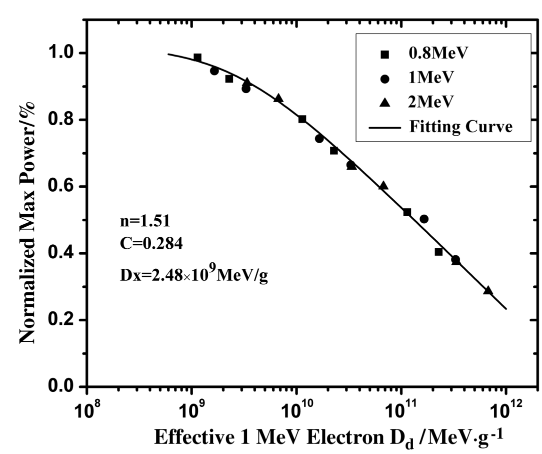

Fig. 3 Normalized maximum power as a function of effective 1 MeV D_d.

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

where C and D_x are 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 $C = 0.28$ and $D_x = 2.48 \times 10^9$ MeV/g.

Once correlated in terms of D_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. On the contrary, if the normalized maximum power data are correlated with D_d [a product of $\Phi(E)$ and $S(E)$], and not effective D_d in Eq. (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. This 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 simply be considered as unity. In the electron case, since the value of n can vary between one and two, it must be determined through experimental data. So, generally, electron data at two energies are required, except the DCs have a linear dependence on NIEL.

C. Effects of the Particular Electron Environments in Geostationary Earth Orbit 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 35,870 km, inclination 0°).

Within the D_d methodology, analysis of electron effects in space begins with an analysis of the space radiation environment. The integral electron spectrum encountered in a GEO, on solar cells behind various thicknesses of coverglass, for a 15-year mission is shown in Fig. 4. This is an omnidirectional spectrum based on AE8MAX. Typically, the solar cell is shielded from this incident spectrum by the coverglass on the front and the solar array substrate in the rear. To account for this shielding, the calculated slowed-down integral spectra for the different thicknesses of fused silica coverglass are also shown in Fig. 4, again an omnidirectional spectrum based on 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 dependence of the slowed-down spectra is similar for different coverglass thicknesses, although the absolute magnitude varies.

The total effective dose deposited will be calculated as a function of fused silica coverglass thickness subjected to the electron

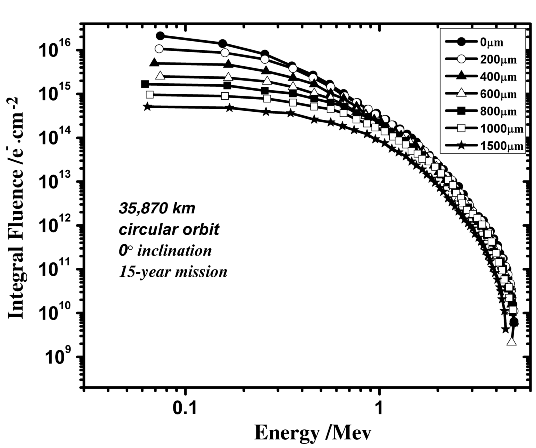

Fig. 4 The calculated integral slowed-down spectra behind the various thicknesses of the coverglass.

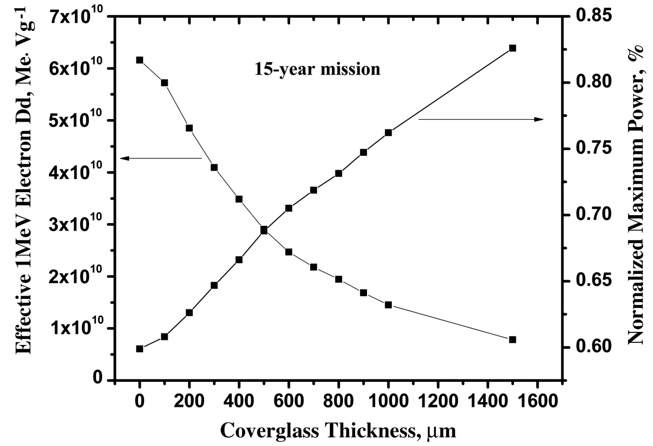

Fig. 5 The effective 1 MeV D_d and the normalized maximum power as a function of the coverglass thickness.

environment, according to Eq. (2). The results were shown in the left side of Fig. 5. As expected, the thicker the shielding material, the lower the value of Dd deposited in the solar cells. The Dd deposited can be reduced by at least 50% by using a 500 μm thickness of coverglass. While in the case of the proton, the calculation based on the Geant4 radiation transport toolkit shows that the D_d can be reduced at least one order of magnitude by the same thickness of coverglass, indicating that the electron can penetrate deeper in silica than the proton does at the same energy. A further reduction in the D_d can be achieved by increasing the coverglass thickness, but it would result in an increase of the overall weight of the solar array. This is a tradeoff between the higher electrical power and the lighter weight.

Using the characteristic curve in Fig. 3, the relation of the effective D_d with the coverglass thickness can be converted to that of normalized maximum power with the coverglass thickness, as shown in the right side of Fig. 5. It can be seen that the normalized maximum power at the end of the 15-year mission in GEO increases with the increasing thickness of the solar array coverglass. The power of the triple-junction cell will decrease to about 60% of the original power if uncovered by silica glass, while the use of a 500 μm thickness of silica glass will increase the endpower of the 15-year mission to about 70% of the original power. However, the effects of the coverglass thickness and electron radiation-induced color centers on the transmittivity of sunlight were not included in the analysis. In addition, the effect of the solar proton event on the total dose deposited on the cell was not considered in this work, which is relatively rare and occurs most often during the solar maximum phase of the 11-year solar cycle [17,18].

IV. Conclusions

In this paper, a comprehensive radiation damage analysis and modeling methodology for the triple-junction GaAs solar cells based on displacement damage dose D_d has been presented. The result seems to suggest that the NIEL approach can be applied to correlate the energy dependence of electron DCs, but that the exponent dependence on NIEL must first be experimentally determined. The best value of the exponent was obtained with $n = 1.51$ for this type of cell. Degradation at different electron energies has been correlated with D_d, and an empirical equation can be used for predicting onorbit cell performance. The methodology for the cell structure still needs to be validated through onorbit data from space flight experiments.

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