Nuclear Instruments and Methods in Physics Research B 307 (2013) 362–365

Contents lists available at SciVerse ScienceDirect

Nuclear Instruments and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb

Displacement damage dose approach to predict performance degradation of on-orbit GaInP/GaAs/Ge solar cells

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ARTICLE INFO

Article history:
Received 23 August 2012
Received in revised form 8 November 2012
Accepted 13 November 2012
Available online 25 January 2013

Keywords:
GaInP/GaAs/Ge solar cells
Displacement damage dose
Non-ionizing energy loss
Proton irradiation
Electron irradiation

ABSTRACT

The displacement damage dose approach for analyzing and modeling the performance degradation of triple-junction GaInP/GaAs/Ge solar cells in a space radiation environment is presented. The irradiation effects of protons and electrons on GaInP/GaAs/Ge solar cells are analysed and then correlated with the displacement damage dose. On this basis, on-orbit expected mission lifetime of GaInP/GaAs/Ge solar cells shielded with silica coverglass at various thicknesses in circular orbits of 5000 km with 60° inclination and 20,000 km with 0° inclination is predicted, respectively.

1. Introduction

The space radiation environment is a dynamic mixture of protons and electrons that varies with orbital altitude and inclination. Exposure to these energetic charged particles typically degrades the electrical performance of solar cells. Therefore, it is necessary to investigate solar cells radiation effects and to predict the on-orbit expected mission lifetime of solar cells.

The displacement damage dose (D_d) approach [1], developed at the U.S. Naval Research Laboratory (NRL), provides a means for predicting on-orbit cell performance from a minimum of ground-test data. D_d equals the product ($D_d = \Phi \times$NIEL) of particle fluence Φ and the respective non-ionizing energy loss (NIEL) which here refers to the rate of energy loss caused by atomic displacements. Thus, the displacement damage effects on solar cells for protons and electrons with different energies and fluences can be correlated with D_d.

Our works had shown the radiation effects on homemade GaInP/GaAs/Ge solar cells with protons and electrons ground-radiation tests [2–5]. The aim of this study is to predict on-orbit homemade GaInP/GaAs/Ge expected mission lifetime in an actual space radiation environment from the ground-test data using the D_d approach.

2. Experiments and results

GaInP/GaAs/Ge space solar cells were fabricated by metalorganic chemical vapor deposition (MOCVD). Solar cells mainly consist of three sub-cells: GaInP top cell, GaAs middle cell, and Ge bottom cell. Their dimensions are respectively about 1.2, 2.9, and 176 μm in thickness. The detailed structure of the solar cells is shown in Ref. [2].

The GaInP/GaAs/Ge 3 J solar cells were irradiated with 0.32, 1.00, and 3.00 MeV protons and 1.0, 1.8, and 11.5 MeV electrons, respectively. The fluence ranged from 3×10^9 to 1×10^{12} cm^{-2} for protons and 1×10^{12} to 3×10^{15} cm^{-2} for electrons. I-V characteristics of the solar cells before and after irradiations were measured at 25 °C under AM0 using a solar simulator with an illumination of 136.7 mWcm^{-2}.

The measured results for maximum power (P_{max}) degradation of GaInP/GaAs/Ge 3 J solar cells are shown in Fig. 1. The set of solid curves on the right of Fig. 1 are the original protons and electrons datum plotted against fluence using the abscissa along the top of the figure. The superposed dot curve on the left of Fig. 1 is plotted versus D_d using the below abscissa. The essence of the D_d method is the calculation of the nonionizing energy loss (NIEL) as a function of either protons or electrons energy for a cell material. Because GaInP/GaAs/Ge solar cells degradation is primarily controlled by the radiation response of the GaAs sub-cell [2,3], thus the NIEL(E) of GaAs material was used to calculate D_d. For the proton calculation, the adjusted NIEL(E) has been adopted [4], because protons

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0168-583X/$ - see front matter
http://dx.doi.org/10.1016/j.nimb.2012.11.060

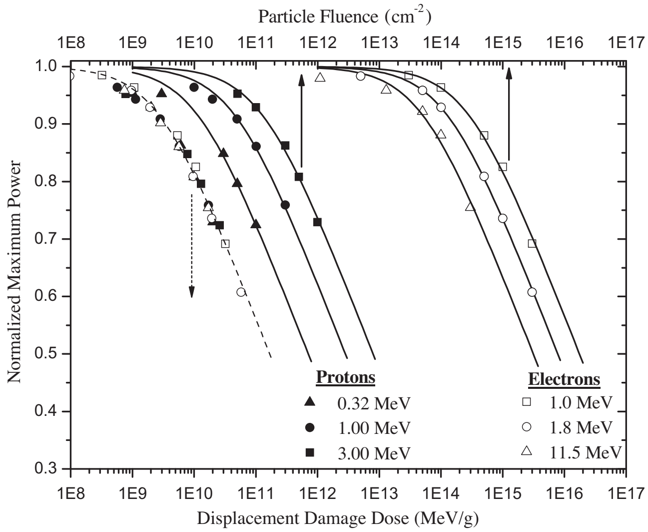

Fig. 1. The set of solid curves on the right are the original data against fluence, while the dot curves on the left is against D_d.

Table 1
Fitting parameters for proton and electron D_d curves of P_{max} degradation.

Protons irradiation		Electrons irradiation	
k	D_x (MeV/g)	k	D_x (MeV/g)
0.27	2.46×10^9	0.27	6.06×10^9

with relatively low energy can produce a non-uniform vacancies production rate distribution at the active region of the GaAs subcell. For the electron calculation, the actual dose is redefined in term of an equivalent dose, because electrons with sufficient energy usually produce point defects and do not produce recoils to generate the cascade defects caused by protons [6]. Thus, each data set about electrons and protons is described by a single characteristic degradation curve given by the following expression [7]:

$$\frac{P_{max}}{P_{max_0}} = 1 - k\log\left(1 + \frac{D_d}{D_x}\right) \qquad (1)$$

where P_{max0} and P_{max} are the maximum power of solar cells before and after irradiation, and k and D_x are fitting parameters whose values are shown in Table 1. To collapse the electron and proton curves, an electron to proton damage ratio (R_{ep}) is applied, R_{ep} is defined as the ratio (=0.406) of D_{xp}/D_{xe}. The electron curve by multiplying the parameter R_{ep} can be made to coincide with the proton curve [5]. Thus, the superposed dot curve on the left of Fig. 1 shows that all the measured electrons and protons datum can be represented by a single characteristic degradation curve using the D_d approach.

3. Slowed-down proton and electron differential spectra

The slowed-down spectra shown in Fig. 2 and Fig. 3 were calculated by applying the continuous slowing down approximation [8,9] and the proton and electron differential fluence spectra in different orbit. The differential fluence spectra from the NASA space model AP8MAX [10] and AE8MAX [10] were employed, corresponding to a circular orbit at 5000 km with 60° inclination in Van Allen inner radiation belt and 20000 km with 0° inclination in Van Allen outer radiation belt after five years. For omnidirectional proton radiation, the expression for the slowed-down differential energy spectrum $f(\varepsilon)_p$ with taking into account all angle of an omnidirectional flux, is as follows:

$$f(\varepsilon)_p = \frac{g(E)_p}{2} \times \int_0^{\pi/2} \sin\theta\cos\theta \frac{AaE^{a-1} + BbE^{b-1}}{Aa\varepsilon^{a-1} + Bb\varepsilon^{b-1}} d\theta \qquad (2)$$

where $g(E)_p$ is the incident proton differential energy spectrum, E is the incident energy, ε is the energy emerging through the shield coverglass, θ is the angle between incident direction and normal to the surface at the point of incidence, there are constants for $A = 7.019$ $a = 0.8542$, $B = 7.925$, $b = 1.824$ from a fit of equation $R(E) = AE^a + BE^b$ to experimental measurements of the energy dependence of the range of protons in silica [8]. For omnidirectional electron radiation, the $f(\varepsilon)_e$ is as follows:

$$f(\varepsilon)_e = \frac{g(E)_e}{2} \times \int_0^{\pi/2} \sin\theta\cos\theta \frac{a\varepsilon^{b+c\ln\varepsilon}\left(\frac{c\ln\varepsilon}{\varepsilon} + \frac{b+c\ln\varepsilon}{\varepsilon}\right)}{aE^{b+c\ln E}\left(\frac{c\ln E}{E} + \frac{b+c\ln E}{E}\right)} d\theta \qquad (3)$$

where $g(E)_e$ are the incident electron differential energy spectrum, E is the incident energy, ε is the energy emerging through the coverglass, θ is the angle between incident direction and the normal to the surface, there are constants for $a = 2145.14$, $b = 1.22617$, $c = -0.06936$ from a fit of equation $R(E) = aE^{b+c\ln E}$ to experimental measurements of the energy dependence of the range of electrons in silica as compiled by Seltzer et al., and tabulated in the computer code ESTAR [11].

The slowed-down proton and electron differential spectra with different silica coverglass thicknesses were calculated by

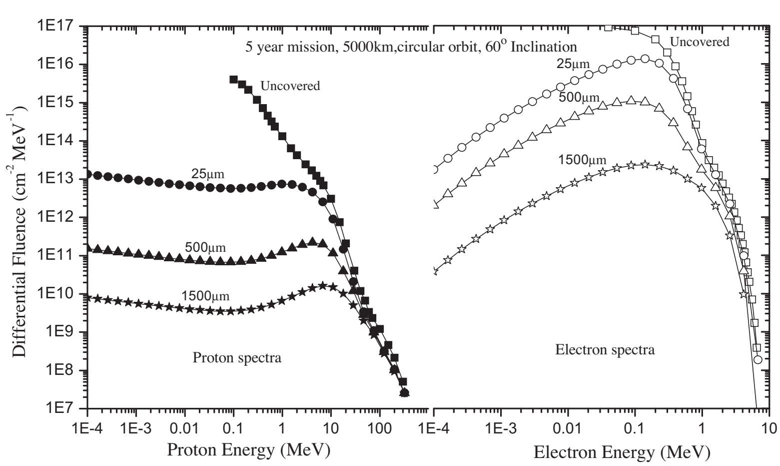

Fig. 2. Incident and slowed-down proton and electron differential spectra through silica coverglasses at 5000 km with 60° inclination after 5 years.