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Adjusted NIEL calculations for estimating proton-induced degradation of GaInP/GaAs/Ge space solar cells

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ABSTRACT

The non-ionizing energy loss (NIEL) values for protons in solar cells should be modified by taking into account the distribution of the Bragg damage peak in the active region to calculate the corresponding displacement damage dose. In this paper, based upon a thin target approximation, a new approach is presented to modify NIEL values for protons on a GaAs sub-cell. Adjusted NIEL values can be used to estimate the degradation induced by protons on GaInP/GaAs/Ge triple-junction space solar cells.

1. Introduction

Solar cells have been used as the main power source by many satellites and play an important part in space missions. GaInP/GaAs/Ge triple-junction (3J) solar cells are the mainstream at present, they have very high conversion efficiency [1] and high radiation hardness. For space applications, it is extremely important to analyze the proton radiation response of the solar cells and predict their end-of-life (EOL) performance in space from results obtained by ground tests as accurately as possible.

The displacement damage dose approach [2], developed at the US Naval Research Laboratory (NRL), is applied to predict the performance degradation of solar cells. The displacement damage dose (D_d) equals the product of proton fluence and the respective non-ionizing energy loss (NIEL) which here refers to the rate of energy loss caused by atomic displacements when protons traverse a certain material. Thus, the performance degradation of solar cells due to proton radiation is determined as a function of D_d. If the particle energy remains constant across the active region, the NRL method can work well and the NIEL values are accurate. The 3J solar cell is a series-connected device, the photocurrent of which is limited to the least value of all sub-cells and its voltage is a summation of the photovoltage of each sub-cell. Generally, proton irradiation may affect the photovoltaic properties of each sub-cell differently, and it will preferentially degrade one of the three sub-cells, which might complicate the calculation of NIEL values, and thus hinder the application of D_d approach to 3J solar cells. This paper attempts to calculate NIEL values via a new approach compared with SRIM-derived NIEL values [3] and then make reasonable application of the D_d approach to investigate proton irradiation degradation on 3J solar cells.

2. Experiments and results

GaInP/GaAs/Ge 3J space solar cells were fabricated by metal–organic chemical vapor deposition (MOCVD). Solar cells without cover glass 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. [4].

Proton irradiation was performed using a 2 × 1.7 MV tandem accelerator (General Ionex Corporation, USA) in Beijing Normal University. The solar cells were irradiated with 0.32, 1.00, and 3.00 MeV, with fluences up to 1×10^{11}, 3×10^{11}, 1×10^{12} ions/cm^2, respectively. Current–voltage (I–V) characteristics under 25 °C, AM0, 1 Sun conditions (136.7 mW/cm^2) and quantum efficiencies (QE) were measured before and after proton irradiation to evaluate electrical properties.

Fig. 1 shows the maximum power degradation in solar cells. The set of curves on the right are the original data plotted against fluence using the abscissa along the top of the figure. The superposed curve on the left of Fig. 1 is the original data multiplied by

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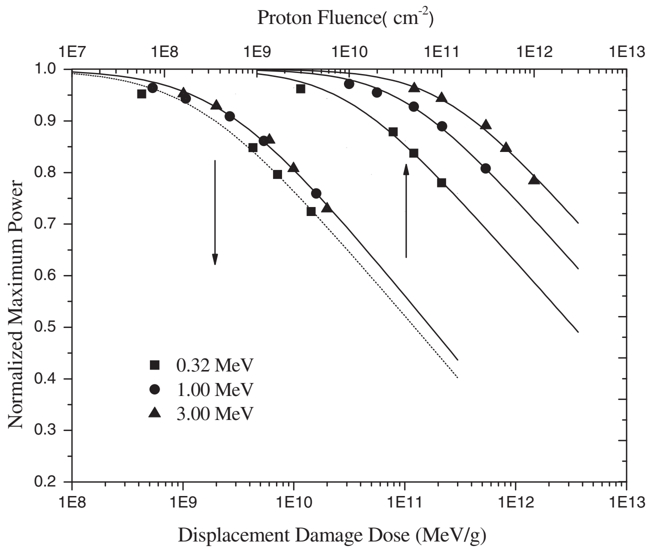

Fig. 1. The set of curves on the right is the original data plotted against fluence, while the curves on the left is plotted against D_d.

the respective proton NIEL, and is plotted versus D_d using the lower abscissa. From the curve on the left, correlation of data occurs for these energies except the lowest, i.e. 0.32 MeV. SRIM [5] analysis shows that 0.32 MeV protons stop in the GaAs middle cell of the 3J solar cells.

Typical changes in QE of the top and middle cell due to proton irradiation with 0.32 and 3.00 MeV at a fluence of 1×10^{11} cm^{-2} are shown in Fig. 2. Since the short circuit current of the Ge bottom cell is much larger than that of the two others, its QE was not plotted [6]. In Fig. 2, it should be noted that the QE mainly drops in wavelength from 650 to 900 nm for the middle GaAs cell after irradiation with different energies, and that the QE degradation of the longer wavelength region from 750 to 900 nm is more significant than that of the shorter wavelength in the middle GaAs cell, which indicates the damage mainly occurring at the middle cell base region [7,8]. Nevertheless, the QE hardly decreases in the wavelength range from 350 to 650 nm for the top GaInP cell. Thus, proton irradiation degrades the QE of the middle GaAs cell more than that of the top GaInP cell.

3. Derivation of adjusted NIEL

Owing to the series of connections in 3J solar cells, their radiation resistance is dominated by the worst performing layer. GaInP top cell is more radiation-resistant than GaAs middle cell due to a greater level of defect annealing in GaInP than in GaAs [9], and the radiation resistance of the Ge bottom cell is much better than that of GaAs middle cell [10]. Furthermore, SRIM [5] analysis and the QE data show that 0.32 MeV protons can penetrate beyond the GaInP top cell and mainly damage the base region of the GaAs middle cell. Therefore, 3J cell degradation will be primarily controlled by the GaAs middle cell, and it is also reasonable to assume anti-reflection layer and the GaInP top cell to be a shield layer for the calculation of NIEL values.

Fig. 3 shows that the vacancies production rates for protons on 3J solar cells as a function of depth, calculated by SRIM [5]. A non-uniform vacancies production rate distribution occurs at the end of the tracks. Since the Bragg damage peak of 1.00 and 3.00 MeV protons are far from the active region of the middle cell, the distribution of displacement damage can be assumed to be uniform in the active region. However, 0.32 MeV protons create more vacancies in the GaAs middle cell, so they result in more degradation of the solar cells.

In Ref. [3], the SRIM-derived NIEL is calculated by dividing the total deposited energy by the width of the active region of the GaAs middle cell, and the total deposited energy here can be estimated by numerically integrating the SRIM-derived NIEL over the particle track. In the process of numerically integrating, the active region is equally divided into n thin layers where the NIEL is constant. But the layer is not thin enough with the proton energy decreasing, which means the assumption that the NIEL values in the thin layer do not change is no longer valid. Because the track lengths of incident protons from different angles in the thin layer are different from each other, NIEL values for a relative longer track length is not also considered as a constant. According to this principle, it is proposed what we call the adjusted NIEL. Firstly, as shown in Fig. 3, the thickness of a thin layer is defined as the difference of range when proton energy changes from E_j to E_{j+1}, where E_j is equal to $0.99^j E_0$ and E_0 is proton energy in the surface of the middle cell, ($j = 0,1,2,\ldots n$). Obviously, the thin layer gradually gets smaller and smaller with the decreasing of proton energy. Secondly, based upon the data given by Messenger [2], NIEL values in each thin layer for protons in the GaAs middle cell are obtained by cubic

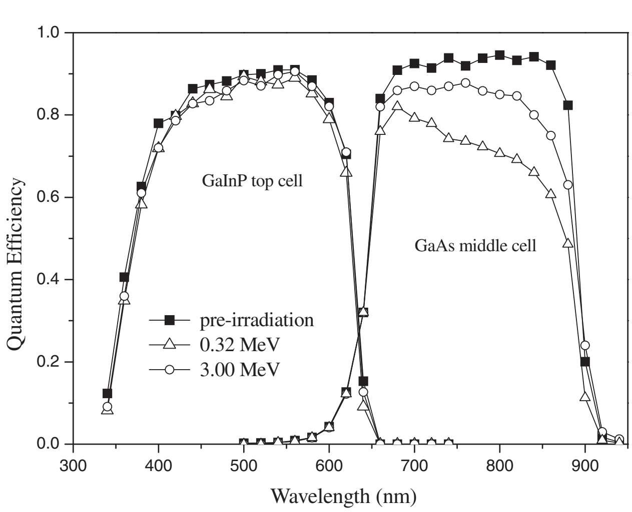

Fig. 2. Typical changes in QE of the top and middle cell in 3J solar cells due to proton irradiation at 0.32, 3.00 MeV at a fluence of 1×10^{11} cm^{-2}.

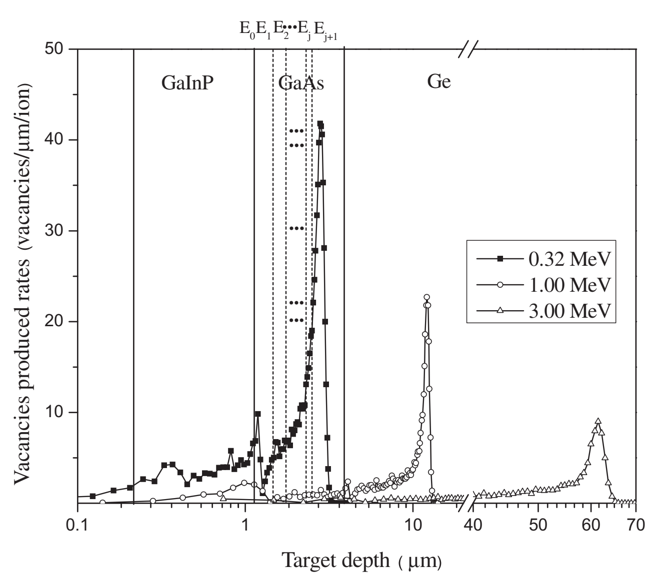

Fig. 3. Vacancies production rate for protons in GaInP/GaAs/Ge 3J solar cells.

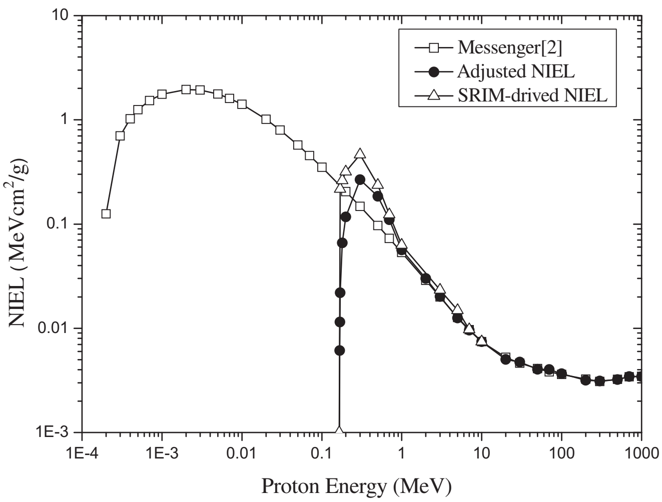

Fig. 4. Comparison of the energy dependence of the adjusted NIEL for protons in GaAs middle cell with SRIM-derived NIEL. The squares show that the NIEL values for protons in GaAs is given by Messenger.

spine interpolation. Furthermore, adjusted NIEL is expressed as follows:

$$\mathrm{NIEL}_{\mathrm{Adjusted}}(E_0,\theta) = \frac{\sum_{E_j=E_0}^{E_n} \mathrm{NIEL}(E_j)\left[R(E_j)\ \text{-}\ \mathrm{R}(E_{j+1})\right]}{d} \quad (1)$$

where d is the thickness of the active region, R is the range of protons in GaAs materials, θ is the angle between incident direction and the normal to the surface at the point of incidence, E_n is cutoff energy. If $R(E_0) \leqslant d/\cos\theta$, $E_n = 0.0002$ MeV (the minimum energy shown in Fig. 4), else $E_n = R^{-1}[R(E_0)\text{-}d/\cos\theta]$ the energy of proton passing through the active region of solar cell). The results of adjusted NIEL and SRIM-derived NIEL are shown in Fig. 4.

The results of the adjusted NIEL deviate from SRIM-derived NIEL. The major reason lies in a fact that the NIEL values derived from SRIM for protons in GaAs [11] are greater than those given by Messenger, especially at low energy. Moreover, since the thin layers gradually get smaller in our method, the total deposited energy in the active region calculated by numerically integrating is more accurate.

4. Application of displacement damage dose method

The adjusted NIEL shown in Fig. 4 can also be employed to condense the data in Fig. 1 by determining the displacement damage dose associated with the degradation of solar cell parameters. The result, when the adjusted NIEL is used as calculated above, is shown in Fig. 5. The proton data from Fig. 1 is condensed to a single characteristic curve and the method is effective in applying adjusted NIEL to predict the damage of solar cells. The correlation between the degradation of $P_{\max}$ and the displacement damage dose can be fitted by the following simple analytic function:

$$\frac{P_{\max}}{P_{\max 0}} = 1 - k\log\left(1 + \frac{D_{\mathrm{d}}}{D_{\mathrm{x}}}\right) \quad (2)$$

where $P_{\max 0}$ and $P_{\max}$ are the maximum power of solar cells before and after irradiation respectively, D_{d} is the displacement damage dose and k and D_{x} are fitting parameters. The parameters k and D_{x} fitting for the experimental data are 0.25 and 2.25×10^9 MeV/g, respectively.

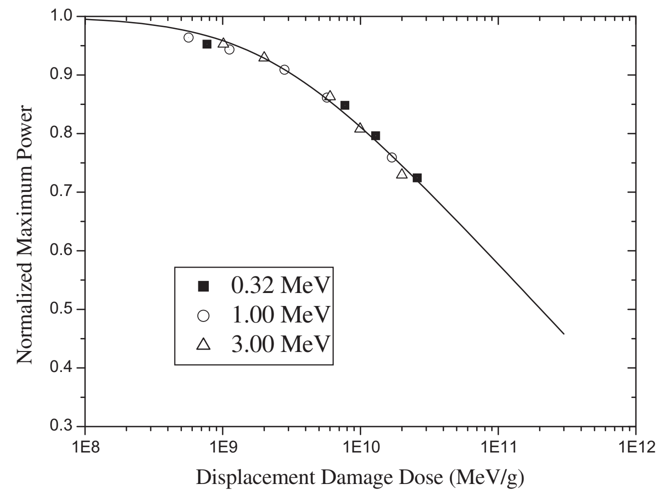

Fig. 5. Normalized maximum power GaInP/GaAs/Ge space solar cells as a function of displacement damage dose. NIEL values is adjusted NIEL values.

5. Conclusions

To sum up, a new method is proposed to modify NIEL which can be used to calculate the corresponding displacement damage dose. It is demonstrated that the data of proton irradiations for different energies including the lowest one are well correlated with the displacement damage dose. The degradation of GaInP/GaAs/Ge 3J space solar cells is investigated successfully by the D_{d} approach. In addition, adjusted NIEL with the incidence angle is extended from normal incidence protons to an omnidirectional spectrum of protons. Thus, the method can be expediently applied to analyze the degradation of the solar cells in true space radiation environments.

Acknowledgments

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