Application of Displacement Damage Dose Analysis to Low-Energy Protons on Silicon Devices

Scott R. Messenger, Edward A. Burke, Geoffrey P. Summers, and Robert J. Walters

***Abstract*—Past work has shown that the degradation of GaAs solar cells in space radiation environments can be described with a single curve for all incident particle energies. This greatly simplifies the prediction of the performance of solar cells exposed to complex particle spectra. A similar approach has not been applied to silicon solar cells because the large diffusion length in silicon means that protons with relatively high energies lose a significant fraction of their energy in the active region of the cell. The proton energies are, therefore, not well defined in the device. In this paper, we show how the Monte Carlo code SRIM can be used to extend the displacement damage dose concept to cases where this occurs. The approach described can be used to analyze the response of complex device structures in the space environment.**

I. INTRODUCTION

THE CONCEPT of displacement damage dose, D_d, has been very useful in enabling the prediction of GaAs solar cell response in space radiation environments. D_d is the product of the particle fluence and the respective nonionizing energy loss (NIEL) in the material under investigation. It was found that a large amount of experimental data could be condensed into a single curve showing the loss of maximum power and other photovoltaic parameters as a function of D_d [1], [2]. This condensed data could be fitted by a simple analytic function. With the aid of NIEL calculations as a function of energy, the results could be transformed into the fluence that would produce a given degree of degradation at a specific proton energy. The extension to reducing the effect of a proton energy spectrum to a single value of D_d is also readily obtainable. The method not only simplified the representation of extensive radiation data sets, but it also showed how experiments could be optimized for new cell types while conserving time and reducing costs. GaAs solar cell response for several space missions was also predicted successfully using the D_d approach [1], [2].

The approach works well when the particle energy can be assumed to be constant across the active region of the device. This is the case for GaAs-based cells, where the active region can be considered thin for proton energies $> \sim 0.1$ MeV. In these cases, the energy dependence of the NIEL and the relative damage coefficients (RDC) are similar [1]. However, this is not true for

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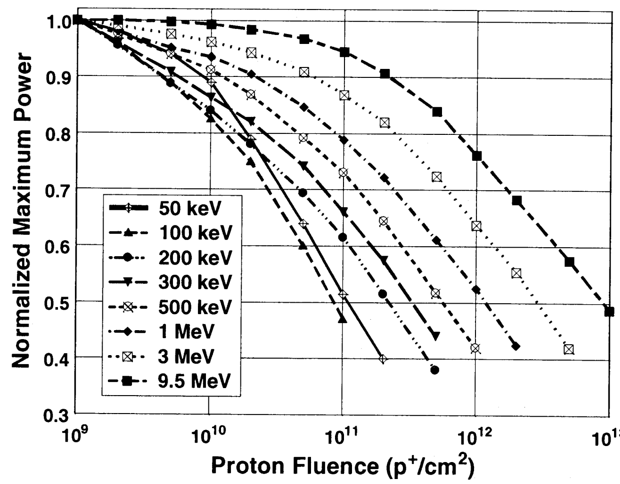

Fig. 1. The degradation of the maximum power point of gallium arsenide solar cells due to proton irradiation [3], [4]. The measurement conditions were 1 sun, AM0, 25 °C. The points on the curves are used for identification only.

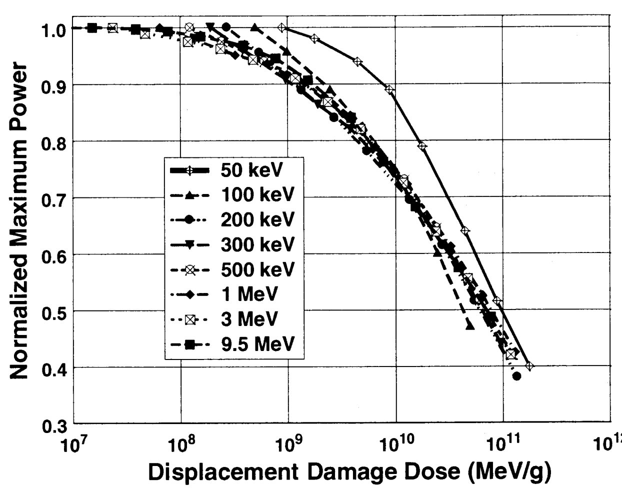

Fig. 2. Application of the displacement damage dose (D_d) approach [1], [2] to the data in Fig. 1. D_d is obtained by multiplying the fluences by the appropriate NIEL values for protons in gallium arsenide. The data for proton energies of 200 keV and higher collapse onto a single curve. The data for 50- and 100-keV protons deviate from the "characteristic" curve because they stop in the active layer of the device. The points on the curves are used for identification only.

very low-energy protons incident on uncovered GaAs cells, and deviations between the energy dependence of the NIEL and the RDCs are observed [1]. Figs. 1 and 2 show the results for maximum power degradation in GaAs solar cells [1]–[4]. Fig. 1 shows the data as a function of proton fluence, whereas Fig. 2 shows the transformation of the fluence (ϕ) to D_d using the appropriate NIEL (S) $(D_d = S\phi)$. We can see in Fig. 2 that correlation of the data occurs for all energies except the lowest, i.e., 50 and 100 keV. Protons with these energies stop in the active region of the cell.

For Si cells, where the active region in typical cells is 100 times greater than is the case for GaAs, the problem is exacerbated. In GaAs cells, the sensitive region is typically on the order of 1 μm, as opposed to 100 μm for silicon. This means that protons with relatively high energy will slow down significantly or reach the end of their tracks in critical silicon cell regions more so than is the case in GaAs cells. The slowing-down effects complicate the analysis. What is more, experiments show that, for normally incident protons of a given energy, the damage per incident proton is a maximum when the particle track terminates in the active device region [3]–[6]. Whereas for GaAs [3], [4], the energies where this is a problem exist only for protons below a few hundred keV; it extends to several MeV in the case of silicon [5], [6].

In a paper recently presented by Abbey *et al.* [7], the effect of low-energy protons on silicon EPIC-MOS charge coupled devices (CCDs) was addressed. They showed that, even though the MOS CCD cameras on the XMM-Newton X-ray satellite were surrounded by aluminum shielding having a thickness of 3 cm, the radiation spectrum that both penetrates the shielding and is scattered by mirrors was responsible for a gradual degradation of the charge transfer efficiency of the MOS CCDs. The proton energy spectrum of concern was for energies below 900 keV.

In this paper, we show that the response of silicon solar cells to protons with energies below several MeV can be quantitatively modeled by taking into account the total energy deposited in the active region as the proton slows down. If we divide the total deposited energy by the width of the active region, we obtain what we call the adjusted NIEL. The adjusted NIEL values can then be used to derive a condensed displacement damage dose response curve just as was done for GaAs.

In the following, the method used to derive the adjusted NIEL is described. The results are then applied to obtain the relative damage as a function of proton energy throughout the energy regime, where damage is a maximum and proton tracks terminate. A displacement damage dose response curve is then generated and compared with available experimental data. The method described here can be applied to a wide range of devices in addition to solar cells, e.g., nuclear radiation detectors [7].

II. Application of Displacement Damage Dose Method to Silicon Solar Cells

Fig. 3 shows the degradation of the maximum power point of silicon solar cells as a function of particle fluence due to irradiation with protons of different energies [5], [6]. The current–voltage characteristics of these silicon cells (10 Ωcm) were measured under 1 sun, AM0, 25 °C solar illumination conditions. If we multiply the fluence at a given energy by NIEL to obtain the associated D_d, Fig. 4 shows that a single curve does not result as it did for GaAs (see Fig. 2).

An alternative comparison of experimental results is shown in Fig. 5. Here the relative damage coefficients (RDCs) for maximum power degradation in silicon cells [5], [6] are compared with NIEL [8] as a function of energy, normalized at 10 MeV. In

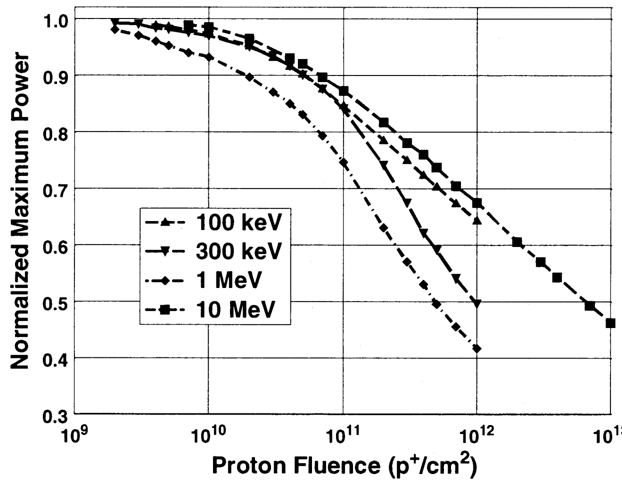

Fig. 3. The degradation of the maximum power point of silicon solar cells as a result of proton irradiation [5], [6]. The measurement conditions were 1 sun, AM0, 25 °C. The points on the curves are used for identification only.

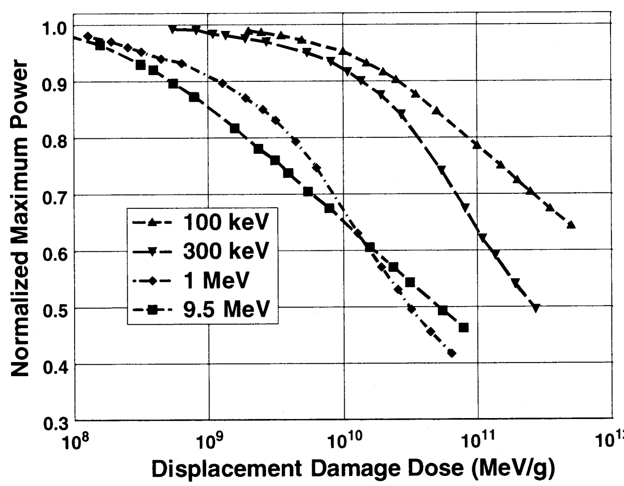

Fig. 4. Application of the displacement damage dose (D_d) technique [1], [2] to the data in Fig. 4. The data do not collapse onto a single curve as found, for example, for GaAs solar cells (see Fig. 2). This is because protons having $E < 6$ MeV are slowing down in the active region of the silicon device. Typical active regions for Si devices extend to the order of 100 μm in silicon as opposed to a few microns for GaAs devices. The points on the curves are used for identification only.

Fig. 5, it can be seen that the energy dependences of the NIEL and the RDCs differ dramatically for energies less than about 6 MeV. The RDCs have a peak value at an energy around 2 MeV (rising well above the NIEL curve) and fall dramatically below the NIEL curve at energies below 1 MeV. The difference between the RDCs and NIEL at energies greater than 10 MeV has been previously addressed, resulting in better agreement with NIEL [9], [10]. The motivation for this study initially arose from the differences between the RDCs and NIEL below 6 MeV.

III. Derivation of Adjusted NIEL

At relatively high proton energies (>6 MeV for silicon), SRIM [11] results show that for normal incidence, the proton energy and, hence, NIEL is essentially constant throughout the solar cell active region. The width of this region in the

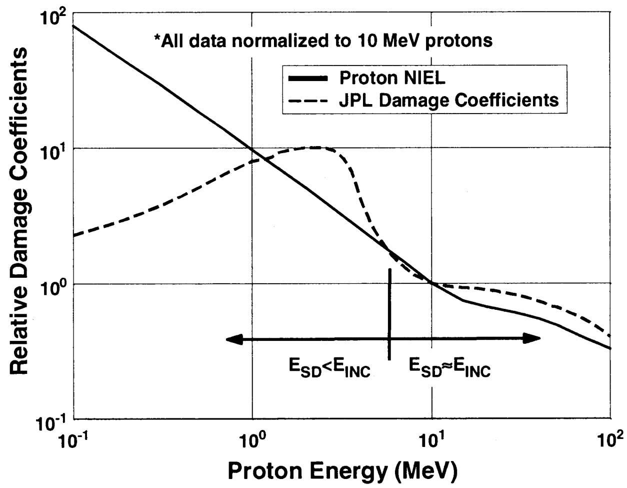

Fig. 5. Comparison of proton NIEL [8] with the relative damage coefficients for maximum power degradation in silicon solar cells [5], [6]. A marked difference exists for proton energies < 6 MeV. For such incident energies, the protons produce nonuniform damage as function of depth [as the slowed-down energy (E_{SD}) is less than the incident energy (E_{INC})]. The damage coefficients display a peak near 2–3 MeV and dramatically fall below the NIEL curve (thereby showing less damage) for lower energies.

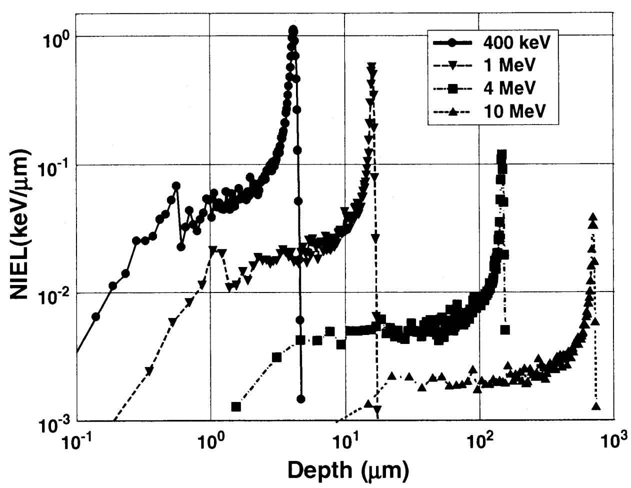

Fig. 6. SRIM-derived NIEL for protons on silicon [2]. A nonuniform NIEL distribution occurring at the end of the tracks results from a nonuniform vacancy production [11].

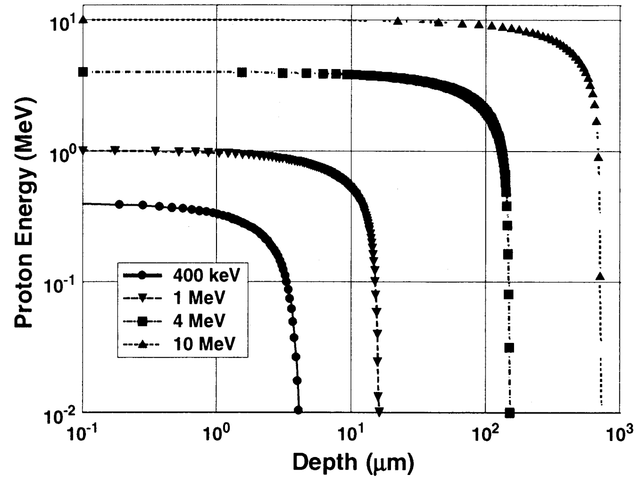

Fig. 7. SRIM [11] results for proton stopping in silicon. Not until proton energies reach about 6 MeV will they lose little energy in traversing 100 μm in silicon.

cells used in the present example had been estimated from data given in [5] and [6] to cover the range from 0.8 to 80 μm below the front surface. For protons having $E < 6$ MeV, the assumption that the proton energy does not vary is no longer valid and the NIEL varies markedly with the decrease in energy throughout the active region. However, the variation in NIEL can be determined from the SRIM [11] Monte Carlo program for all proton energies of interest [2]. Fig. 6 shows the results of SRIM-derived NIEL for protons on silicon as a function of silicon depth.

The SRIM studies show that, at energies below about 3 MeV, the proton stops within the active region (see Figs. 6 and 7). The simplest approach to quantitatively account for the spatial nature of the damage is to assume that the relative damage coefficient changes in direct proportion to the total damage produced within a minority carrier diffusion length of the junction. The energy deposited to displacements at low energies can be estimated by numerically integrating the SRIM-derived NIEL over the particle track. The adjusted NIEL is then calculated by dividing the total deposited energy by the width of the active region (80 μm).

At high energies, where the protons traverse the cell with little change in energy, the damage factor is assumed to be proportional to the displacement damage energy deposited. This is given by the product of NIEL and the width (approximately 80 μm). The NIEL for 10-MeV protons in silicon is given as 7.885×10^{-3} MeVcm^2/g in the Appendix to the 1993 paper [8]. This can be expressed as 1.829×10^{-3} keV/μm or 3.33×10^{-2} vacancies/μm [2]. The latter units are convenient for direct comparison to SRIM results, which are usually expressed as vacancies/μm. The low-depth tail of the 10-MeV SRIM-derived NIEL indeed agrees with the analytical value obtained in [8].

The results obtained by applying this procedure (and normalizing at 10 MeV) are given in Fig. 8 and are compared with the data given in [6]. Inspection of Fig. 8 shows reasonable agreement of the calculated adjusted NIEL and the data from [6]. The general shape of this curve for silicon is not very sensitive to the exact value used for the diffusion length. As shown in Fig. 8, an active depth value of 100 μm does not alter the shape or the relative values of the curve in a significant way.

It is important to emphasize that this is a key result of the calculations described here. From this basic curve, a family of curves can be generated for different amounts of shielding in the isotropic space radiation environment. A detailed description of how this is done is given in [3]–[6]. The performance of silicon cells can then be predicted for any defined space radiation environment.

Performing the same procedure on GaAs solar cells produces the results displayed on Fig. 9 [8]. The active region in this case was varied from 0.5 to 5 μm. Reasonable agreement is obtained for active regions having thicknesses of about 1 μm. The energy dependence of the SRIM-derived RDCs again rises above the NIEL for GaAs, as was the case for Si (Fig. 8). However, the energy dependence of the experimentally determined RDCs [3],

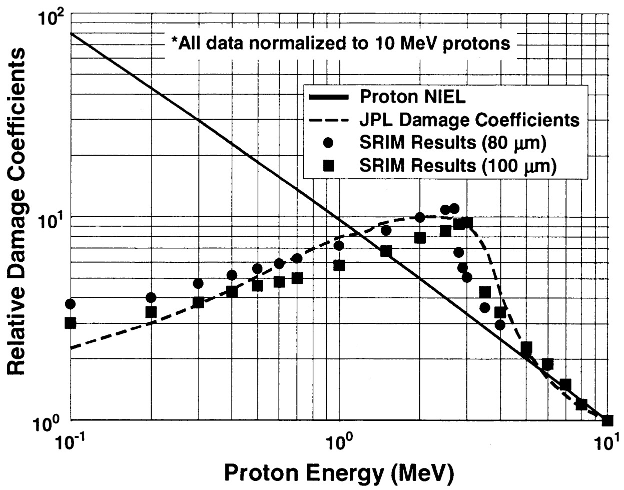

Fig. 8. SRIM-derived relative damage coefficients for maximum power degradation in silicon solar cells. The solid line represents the JPL experimentally determined damage coefficients (see Fig. 5), whereas the data points represent the results of the calculation outlined here. An integration depth of 80 μm seems to give a good fit.

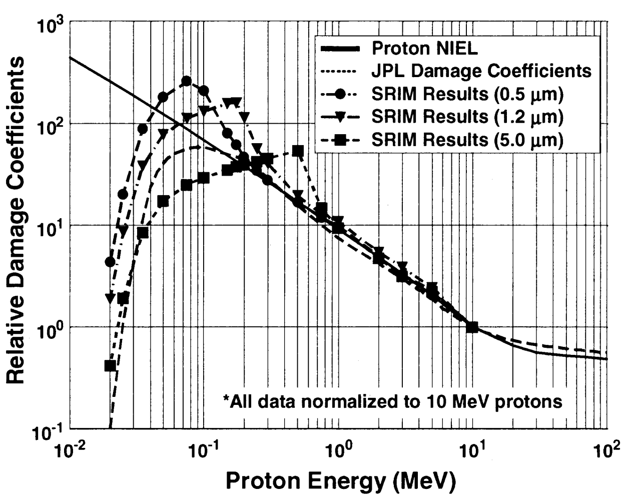

Fig. 9. SRIM-derived relative damage coefficients for maximum power degradation in GaAs solar cells [3], [4]. The dashed line represents the JPL experimentally determined damage coefficients, whereas the data points represent the results of the calculation outlined here. The solid line is the proton NIEL. An integration depth of about 1 μm seems to give the best fit.

[4] follows the NIEL more closely until energies get less than about 100 keV. Defect annealing may be an issue here.

IV. Application to the Space Environment

A test of the applicability of the adjusted NIEL results shown in Fig. 8 is to compare them with results obtained using actual relative damage data for silicon as given in [6]. The most severe test is to assume an unshielded cell where the low-energy part of the spectrum is dominant. In [12], an analytical expression for a differential energy spectrum ($d\phi/dE$, in units of $p^+/\text{cm}^2/\text{MeV}$) of a large solar proton event is given as

$$\frac{d\phi}{dE} = ak\phi_o E^{a-1} \exp\left(-kE^a\right), \tag{1}$$

where a, k, and ϕ_o are fitting parameters. The variables a and k are dimensionless, relating to the spectrum hardness, whereas ϕ_o has units of p^+/cm^2 and is related to the magnitude of the event. As an example, we take $a = 0.2815$, $k = 2.115$, and $\phi_o = 1.32 \times 10^{12}$, corresponding to the October 19, 1989 solar proton event [12]. The cumulative relative damage can be determined by integrating over the product of the adjusted NIEL as a function of energy and the differential spectrum, e.g.,

$$D_{dcum} = \int_{E_{\min}}^{E_{\max}} N(E)\left(\frac{d\phi}{dE}\right) dE, \tag{2}$$

where D_{dcum} is the cumulative relative displacement damage dose over the energy interval $E_{\min}$ to $E_{\max}$, $N(E)$ is the experimental or theoretical relative damage, and $d\phi/dE$ is given by (1). Equation (2) can be integrated numerically. The results show that the energy range 0.1–1 MeV contributes over 56% of the total displacement damage dose for unshielded cells. Furthermore, the spectrum below 10 MeV contributes 99% of the total dose. The difference between the results obtained with the experimental and theoretical models was less than 2%. The addition of shielding would markedly reduce the displacement damage dose. However, the end-of-track effects observed at low energies are still present when high-energy protons slow down in the shield and enter the active device region as low-energy particles. They must be accounted for in a damage calculation.

It is important to note that the relative dose curve must be transformed from the normally incident case to that for an isotropic environment. We have found that for conventional cell shielding, the isotropic correction as outlined in the 1982 JPL Handbook [6] can be used. Although low-energy protons in the space environment are stopped by modest amounts of shielding, the effects of low energy protons are important. This is because high-energy protons are slowed down in the shield and enter the sensitive cell regions at low energies. Cell response to these low-energy slowed-down protons must be taken into account. That is, in fact, what is achieved with the JPL isotropic corrections to the RDCs shown in Fig. 8.

V. Application to Displacement Damage Dose Analysis

The adjusted NIEL shown in Fig. 8 can also be used to condense the available data by determining the displacement damage dose associated with the degradation of solar cell parameters. The data used as an example here was reported in [6] and is plotted in Fig. 3. The result when the adjusted NIEL, as calculated above, is used is shown in Fig. 10. This is the analog to similar results obtained with GaAs, as reported in [1], [2]. The line labeled "FIT" in Fig. 10 is based on the formalism given in [3] and [6]. In the silicon case, the width of the band formed by the experimental results is much greater than is the case with GaAs [1], [2], but the variation is still within about 10%. Such variation is observed in the original data taken from [6]. The displacement damage dose method not only allows a representation of the experimental data with a relatively simple analytic function, but it also permits estimates to be made where little experimental data exist.

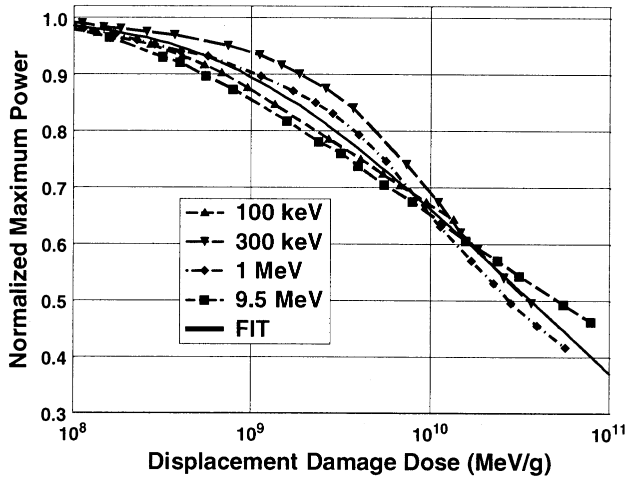

Fig. 10. Result of applying the adjusted NIEL approach obtained using the procedure here. The curve labeled "FIT" is based on the standard solar cell degradation curve [3], [5]. The points on the curves are used for identification only.

VI. Conclusions

In summary, we have described a relatively simple method for applying the damage dose concept to low-energy protons incident on silicon where the device response is dominated by "end-of-track" effects. The method brings damage calculations into agreement with the experiment, as shown in Fig. 8. We have shown how the SRIM Monte Carlo code can be used to derive a curve that provides the normal incidence relative damage coefficients as a function of proton energy when the proton slows down in the active region of the cell. The only variable needed is an estimate of the minority carrier diffusion length. This curve is basic to predicting solar cell response in space radiation environments where the proton energies can vary over many decades and their energy spectra exhibit wide variations. From this normally incident derived curve, the extension to omnidirectional spectra can be readily performed. This can mean, as has been found for GaAs, that future experimental studies can be optimized to select proton energies most critical to the prediction of device response in space radiation environments, thereby reducing costs and expediting the evaluation of new technologies.

The Monte Carlo code SRIM can be used to expand existing calculations [3]–[6] to a wider variety of device structures and complex shielding types. It, in combination with the displacement damage dose and NIEL concepts, markedly amplifies analysis capabilities for future devices.

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