

THE USE OF DISPLACEMENT DAMAGE DOSE TO CORRELATE DEGRADATION
IN SOLAR CELLS EXPOSED TO DIFFERENT RADIATIONS

Geoffrey P. Summers
U.S. Naval Research Laboratory
Washington, DC

Edward A. Burke, Philip Shapiro, Richard Statler,
and Scott R. Messenger
SFA, Inc.
Landover, Maryland

and

Robert J. Walters
U.S. Naval Research Laboratory
Washington, DC

SUMMARY

It has been found useful in the past to use the concept of "equivalent fluence" to compare the radiation response of different solar cell technologies. Results are usually given in terms of an equivalent 1 MeV electron or an equivalent 10 MeV proton fluence. To specify cell response in a complex space-radiation environment in terms of an equivalent fluence, it is necessary to measure damage coefficients for a number of representative electron and proton energies. However, at the last Photovoltaic Specialist Conference (ref.1) we showed that nonionizing energy loss (NIEL) could be used to correlate damage coefficients for protons, using measurements for GaAs as an example (ref.2). This correlation means that damage coefficients for all proton energies except near threshold can be predicted from a measurement made at one particular energy. NIEL is the exact equivalent for displacement damage of linear energy transfer (LET) for ionization energy loss. The use of NIEL in this way leads naturally to the concept of 10 MeV equivalent proton fluence. The situation for electron damage is more complex, however. In this paper it is shown that the concept of *displacement damage dose* gives a more general way of unifying damage coefficients. It follows that 1 MeV electron equivalent fluence is a special case of a more general quantity for unifying electron damage coefficients which we call the *effective 1 MeV electron equivalent dose*.

INTRODUCTION

The most common way of specifying radiation environments for solar cells is in terms of their response to a fluence of 1 MeV electrons. The Solar Cell Radiation Handbook (ref.3) for example is full of such tables and figures showing the degradation of key photovoltaic parameters in a variety of space orbits. Although the effect of an electron or a proton *fluence* is the way displacement damage is generally determined, the *absorbed dose* is the parameter used to describe ionization effects in biological and microelectronic systems. Absorbed dose, which measures the energy deposited per unit mass as a result of ionization, was found to be so useful in comparing the effect of different radiations that a special unit was introduced to measure it. The original unit was the rad, but this has been superseded by the Gray (1 J/kg). Presumably the reason for determining displacement damage in terms of fluence originated in the way dosimetry is performed at particle accelerators. Conversely x-ray and γ -ray dosimetry is performed using techniques such as thermoluminescent emission, the magnitude of which is determined by the absorbed energy or dose. Unlike absorbed dose, fluence cannot be used to correlate the effect of different radiations. However, the product of fluence and NIEL gives the displacement damage

equivalent of absorbed dose, which we will show gives a sound physical basis for correlating both electron and proton displacement damage coefficients. The concept of equivalent fluence then follows in a straightforward way under certain conditions. In other cases it is necessary to introduce the concept of an effective 1 MeV electron equivalent dose in order to correlate electron damage coefficients.

DAMAGE CORRELATIONS USING ABSORBED DOSE

1. PROTONS

Figure 1 shows experimentally measured curves of the normalized power degradation for p/n GaAs solar cells produced by increasing fluences of incident monoenergetic protons with energies of 0.5, 1.0, 3.0, and 9.5 MeV. The data points plotted in figure 1 are taken from the original line figure given by Anspaugh in reference 2 and the lines are shown only to guide the eye. The displacement damage dose for each data point was then calculated from the product of the NIEL in GaAs $S(E)$ and the respective fluence $\phi(E)$ for the particular proton energy E , using the NIEL values given in reference 4. The data were replotted as shown in figure 2, where the abscissa is now the absorbed displacement dose given in units of MeV/g. As can be seen the data for all proton energies when plotted in this way collapse on to a single, universal line. This line, which represents the complete response of GaAs cells to protons of all energies, can be produced using protons of any single energy. Conversely, if degradation data exist for any one energy the experimental line for another energy such as 10 MeV protons could be readily obtained using the equation:

$$\text{Absorbed Dose} = \phi_1(E_1) \cdot S_1(E_1) = \phi_2(E_2) \cdot S_2(E_2) \quad (1)$$

Equation (1) leads naturally to the concept of 10 MeV proton equivalent fluence, which is widely used to simulate the effect of a complex proton environment given in terms of a differential proton spectrum $d\phi_p(E)/dE$. The 10 MeV proton equivalent fluence is calculated from the integral of the proton NIEL over the proton spectrum, divided by the NIEL for 10 MeV protons, i.e.,

$$\phi_p(10) = [1/S_p(10)] \int S_p(E) \cdot [d\phi_p(E)/dE] dE \quad (2)$$

It is usual to take damage correlation further than Eq.(2) by specifying radiation effects in terms of the effect of a 1 MeV equivalent electron fluence. This requires first reducing the 10 MeV equivalent proton fluence to 1 MeV equivalent electron fluence and then adding the result to the 1 MeV electron fluence equivalent to the total electron environment present. However, because of complexity in the way some semiconductors respond to electrons, such calculations require using the concept of equivalent damage dose in a modified way as we now show.

2. ELECTRONS

It has been found that a linear dependence of photovoltaic parameter change on absorbed dose as shown in figure 2 is always found for relatively high NIEL particles such as protons and helium ions. A linear dependence is also found for low NIEL particles such as electrons incident on n-type Si, GaAs and possibly other semiconductors. In these cases, Eq.(1) can be used directly to convert a 10 MeV proton fluence to a 1 MeV electron fluence from a ratio of the respective NIELs. Similarly, a 1 MeV equivalent electron fluence can be defined for an electron environment in the same way as discussed above for the 10 MeV proton equivalence, Eq.(2), by simply substituting the appropriate symbols.

However, for devices with p-type active regions electron-induced changes are often found to vary in a way which depends on the square of the NIEL of the electrons. This finding is analogous to the different response found for some biological systems to high and low LET ionizing radiations, which leads to the concept of the "quality factor, Q" of the radiation. The quality factor expresses the relative effect of a given radiation to the effect of x-rays, for which $Q = 1$. In the displacement damage case we will show

below that we can define a quantity called the “effective 1 MeV electron equivalent dose”, which is obtained by multiplying the absorbed dose for electrons of energy E_j , i.e., $S(E_j) \cdot \phi(E_j)$, by the ratio $S(E_j)/S(1.0)$, where 1.0 refers to 1 MeV. This ratio is the displacement equivalent of the quality factor. The reason for the choice of normalizing energy is that the response to 1 MeV electrons is the traditional way of comparing the behavior of different kinds of solar cells.

As an example we consider the data of Yamaguchi and Amano (ref.5) for changes in minority carrier diffusion length in p-type GaAs irradiated with 0.8, 1.0, 2.0, and 4.0 MeV electrons and with Co^{60} gamma rays. The data were derived from in-depth profiles of short-circuit current changes measured in the emitter of a p/n GaAs cell using the EBIC method. The difference between the reciprocal square of the post- and pre-irradiation diffusion lengths, L_ϕ and L_0 , respectively is given by

$$1/L_\phi^2 - 1/L_0^2 = K(E) \cdot \phi \quad (3)$$

where $K(E)$ is the diffusion length damage coefficient for electrons of energy E . The NIELs for electrons in GaAs with energies of 0.8, 1.0, 2.0, and 4.0 MeV are 21.4, 26.5, 44.2, and 63.2 eV.cm²/g, respectively. The data points from figure 4 of reference 5 has been replotted in figure 3. The line for 4.0 MeV electrons is a least squares fit to the data. The other lines are calculated from this reference line using the ratio of the squares of the NIELs for the respective energies. Co^{60} gamma rays produce a spectrum of mostly Compton electrons and the average NIEL assuming a linear dependence on electron energy is 9.40 eV.cm²/g. Assuming a quadratic dependence gives 155.0 (eV.cm²/g)². Details of these calculations, which are somewhat complicated, have been discussed briefly in reference 3. As an example of the magnitude of the difference associated with the effect of a linear or a quadratic dependence on NIEL consider the data for 4.0 MeV electrons and Co^{60} gamma rays. With a linear dependence the 4.0 data would be calculated to shift to the right by a factor of $63.2/9.40 = 6.72$, which clearly would not coincide with the experimental data for Co^{60} . A quadratic dependence gives a shift of 45.2 and the agreement with the data can then be seen in figure 3 to be excellent.

The quadratic dependence of NIEL means that Eq.(1) must be modified for electrons on p-type GaAs to give.

$$\phi_1(E_1) \cdot [S_1(E_1)]^2 = \phi_2(E_2) \cdot [S_2(E_2)]^2 \quad (4)$$

which can be rearranged to give

$$\phi(E_1) \cdot S(E_1) = \phi(E_2) \cdot S(E_2) [S(E_2)/S(E_1)] \quad (5)$$

where the subscripts 1 and 2 for different types of particles has now been dropped because the discussion applies to electrons only. Eq.(5) can be written

$$\text{Dose}(E_1) = \text{Dose}(E_2) \cdot [S(E_2)/S(E_1)] \quad (6)$$

Eq.(6) shows how an effective 1 MeV electron equivalent dose can be defined, i.e.,

$$\text{Dose}(1.0) = \text{Dose}(E_2) \cdot [S(E_2)/S(1.0)] \quad (7)$$

Figure 4 shows the data in figure 3 replotted using Eq.(7) to calculate the effective 1 Mev electron equivalent dose for each point. As can be seen in figure 4, when plotted in this way, all the data collapses on to a single line. This line represents the general response of GaAs solar cells to electrons of all energies.

DISCUSSION

The results presented here show that the concept of displacement damage dose gives a more fundamental way of comparing the radiation response of solar cells to irradiation than the more commonly used particle fluence. A question that comes immediately to mind in comparing the radiation response of cells, however, is the cause of the general linear dependence of damage coefficients on NIEL found for protons in contrast to the quadratic dependence found for electrons on p-type Si, GaAs and possibly other semiconductors. This question is more complicated than is at first apparent because clearly there is a point at which a plot of the coefficients for p-type cells versus NIEL for protons and electrons, when extrapolated, must coincide. At this "critical" point a linear dependence would presumably be found, assuming there is a particle that actually has the corresponding value of NIEL. The answer to the question must lie in the nature of the stable defects caused by different particles. Higher LET particles such as protons produce defect cascades that have a tree-like structure with dense defect concentrations at the end of branches containing isolated defects (ref.6). Lower LET particles such as low energy (<~50 MeV) electrons produce mostly isolated point defects. It is the details of the formation mechanism of the point defects affecting the electrical properties of the solar cell that determine the dependence on NIEL. The "critical" value of the NIEL appears to correspond to the value at which the tree-like cascade structure becomes dominant.

REFERENCES

1. Summers, G.P., Burke, E.A., Walters, R.J., Shaw, G.J., Shapiro, P., Statler, R.L., and Messenger, S.R.: A General Method for Predicting Radiation Damage to Solar Cells in the Space Environment. IEEE 23rd Photovoltaic Specialists Conference, 1993, pp. 1426-1431.
2. Anspaugh, B.: Proton and Electron Damage Coefficients for GaAs/Ge Solar Cells. IEEE 22nd Photovoltaic Specialists Conference, 1993, pp. 1593-1598.
3. Tada, H.Y., Carter, J.R., Anspaugh, B.E., and Downing, R.G.: Solar Cell Radiation Handbook, 3rd edition. JPL Publication 82-69, 1982.
4. Summers, G.P., Burke, E.A., Shapiro, P., Messenger, S.R., and Walters, R.J.: Damage Correlations in Semiconductors Exposed to Gamma, Electron and Proton Radiations. IEEE Trans. in Nucl. Sci., vol., 1993, pp. 1372-1379.
5. Yamaguchi, M. and Amano, C.: Co⁶⁰ Gamma Ray and Electron Irradiation Damage of GaAs Single Crystals and Solar Cells. J. Appl. Phys., vol. 54, 1983, pp. 5021-5029.
6. Wood, S., Doyle, N.J., Spitznagel, J.A., Choyke, W.J., More, R.M., McGruer, J.N., and Erwin, R.B.: Simulation of Radiation of Damage in Solids. IEEE Trans. in Nucl. Sci., vol.28, 1981, pp. 4107-4112.

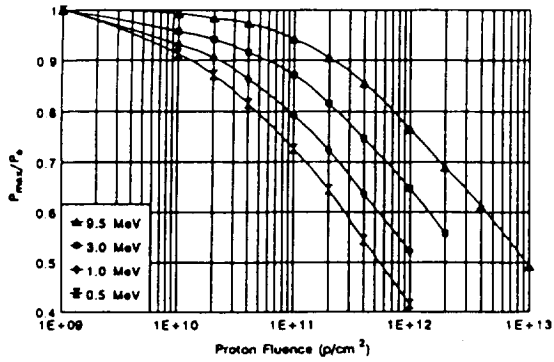


Figure 1-- Power loss of GaAs/Ge solar cells versus proton fluence from reference 2.

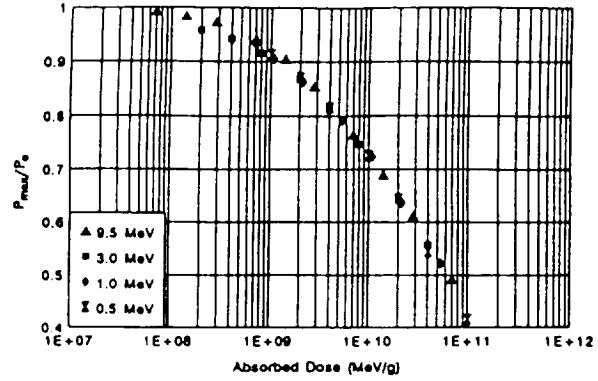


Figure 2-- Power loss of GaAs/Ge solar cells versus displacement damage absorbed dose using data from figure 1.

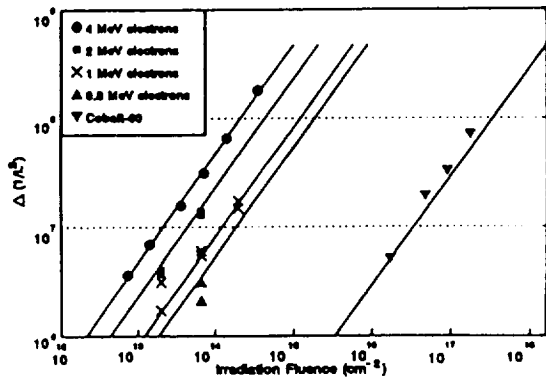


Figure 3-- Diffusion length damage coefficients versus electron fluence from reference 5. The line through the 4.0 MeV data is a least squares fit. The other lines are calculated from the 4.0 MeV line assuming a quadratic dependence on NIEL.

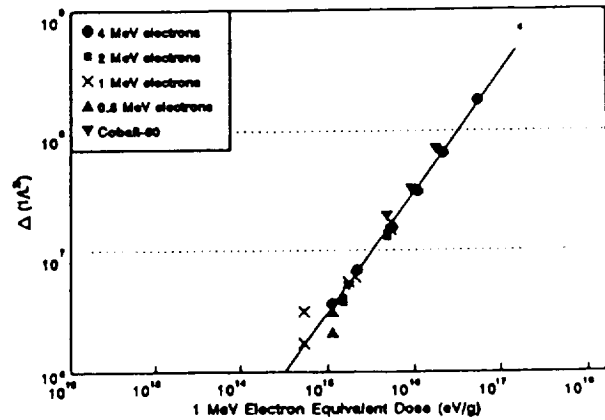


Figure 4- Diffusion length damage coefficients versus 1 MeV electron equivalent dose using the data from figure 3.

