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# Equivalent Electron Fluence for Space Qualification of Shallow Junction Heteroface GaAs Solar Cells

JOHN W. WILSON AND L. V. STOCK

*Abstract*—It is desirable to perform qualification tests prior to deployment of solar cells in space power applications. Such test procedures are complicated by the complex mixture of differing radiation components in space which are difficult to simulate in ground test facilities. Although it has been shown that an equivalent electron fluence ratio cannot be uniquely defined for monoenergetic proton exposure of GaAs shallow junction cells, an equivalent electron fluence test can be defined for common spectral components of protons found in space. Equivalent electron fluence levels for the geosynchronous environment are presented.

## INTRODUCTION

IT IS DESIRABLE to perform qualification tests prior to deployment of solar cells in space power applications. Such test procedures are complicated by the complex mixture of different radiation components in space which are difficult to simulate in ground test facilities.

A recent simplified model of radiation damage in GaAs shallow junction cells [1] shows good predictive capability for monoenergetic normal incident proton and electron exposures [2], [3]. On the basis of this model and the supporting experimental data it was shown that an equivalent electron fluence ratio cannot in general be uniquely defined [3] for monoenergetic normal incident protons. It was further noted that this result arises from the spatial dependence of defect production of low energy protons within the active region of the cell [3].

The model of [1] is extended to combine electron and proton produced defects in the crystal and includes factors related to spatial composition and angular distribution appropriate to the space environment. The equivalent fluence ratio depends on the thickness of cover glass used to protect the cell. In addition to the complexity of space radiation components, other factors such as exposure rate and cell temperature during and post irradiation are important in determining cell damage at any given time since annealing of displacement damage is a diffusion process. Short-term room temperature exposures seem to display little annealing. In distinction, long-term space exposure especially at high solar concentration should show considerable annealing. Recommendations for electron irradiation test procedures for space qualification of 0.5-μm $Al_{0.9}Ga_{0.1}As$ window heteroface cells for geosynchronous missions of specific durations are discussed.

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### *Theory of Equivalent Electron Fluence*

It is customary in protection from mixed radiation environments to develop concepts under which effects of radiations of different quality may be combined to ascertain the total effect on device performance [4]. From an electronic device point of view, the equivalent electron fluence is usually employed to determine the combinational rule. The equivalent electron fluence is defined as that fluence of electrons of fixed energy (usually 1 MeV) which produces the same effect on the device performance as a particle fluence of a particular type, energy, and fluence. Therefore, the fluence of electrons $\phi_e$ equivalent to a fluence of protons $\phi_p(E_p)$ of energy $E_p$ is given by

$$R_p\ [\phi_p(E_p)] = R_e\ [\phi_e] \tag{1}$$

where $R_p$ and $R_e$ are the device response functions for proton and electron damage. If (1) is satisfied, the equivalent fluence ratio may be defined as

$$r(E_p) = \phi_e/\phi_p(E_p) \tag{2}$$

and the usefulness of the concept requires $r(E_p)$ not to be dependent on the magnitude of $\phi_p(E_p)$. The combined effects of electron and proton exposure are then taken as

$$R_{Tot}\ [\phi_p(E_p), \phi_e] = R_e\ [\phi_e + r(E_p)\, \phi_p(E_p)] \tag{3}$$

where $\phi_e$ and $\phi_p(E_p)$ are the mixed environmental components. The understanding (3) comes from recognition of the role of minority carrier diffusion length as it relates to defects within the cell as

$$L^{-2} = L_0^{-2} + K_e\, \phi_e + K_p(E_p)\, \phi_p(E_p) \tag{4}$$

from which the equivalent fluence ratio is

$$r(E_p) = K_p(E_p)/K_e. \tag{5}$$

Implicit in (4) is the assumption that the cell averaged diffusion length $L$ is sufficient to define the cell response.

Experimentally it is observed that the performance of proton-irradiated cells are strongly energy dependent at low proton energies [5], [6]. This energy dependence was shown to arise from nonuniformity in the damage to the cell [7]. We now question the validity of concepts derived on the basis of cell-averaged quantities such as (4) and (5).

### *Short-Circuit Current Reduction*

We assume herein that the radiation damage to the cell is mainly due to change in the bulk of the cell and ignore the re-

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combination at the window interface [8]. The radiation produces a displacement density within the cell $D_v(x)$ of which the distribution in position $x$ is determined by the particle types and energies. The displacement density for protons is calculated using Rutherford's cross section for the initial displacement, while the McKinley-Feshbach cross section is used for electrons [9]. The recoil cascade is treated using the theory of Lindhard, Scharff, and Schiott [10]. The threshold displacement energy for GaAs is taken as 9.5 eV [11].

It is assumed that these displacements form recombination centers for the electron-hole pairs formed by photoabsorption. The fraction of the pairs lost in diffusion from their point of production at depth $x$ to the junction at depth $x_j$ is given by [1], [3]

$$F(x) = 1 - E_2 \left[ \sqrt{6}\, \sigma_r \left| \int_x^{x_j} D_v(x')\, dx' \right| \right] \tag{6}$$

where $\sigma_r$ is the recombination cross section, to be estimated by comparing with experimental data and $E_2$ $(Z)$ is the exponential integral of order 2. Note that (6) is written in different but equivalent form compared to [1] and [3]. The $D(E)$ of [3] is the number of displacements formed by a particle of energy $E$ in coming to rest and is related to the local density of displacements as

$$D_v(x) = \left| \frac{dD(E)}{dE} \right| S(E)\, \phi(E)$$

where $S(E)$ is the local stopping power and $\phi(E)$ is the fluence of particles [12]. The fractional change in short-circuit current using (6) is

$$\frac{\Delta i_{sc}}{i_{sc_0}} = \int_0^a \rho(x)\, F(x)\, dx \Big/ \int_0^a \rho(x)\, dx \tag{7}$$

where $\rho(x) \approx \lambda^{-1} \exp(-x/\lambda)$, with $\lambda \simeq 0.714\ \mu$m, and $a$ is the depth of the active region of the cell. The fractional short-circuit current remaining after 1-MeV electron irradiation is shown as a function of electron fluence in Fig. 1. The recombination cross section was taken as $\sigma_r = 4 \times 10^{-14}$ cm$^2$ and calculations were made for two junction depths, namely 0.5 and 0.8 $\mu$m. Also shown are corresponding experimental data [13], [14]. The agreement appears within the scatter of the experimental data (note inconsistency of the data at $\phi_e = 10^{14}$/cm$^2$).

The short-circuit current was likewise calculated for the three proton fluence levels of $10^{10}$, $10^{11}$, and $10^{12}$ protons/cm$^2$ with comparison to experimental results shown in Fig. 2. The best estimate of recombination cross section was found from comparing to the data to be $\sigma_r = 6 \times 10^{-14}$ cm$^2$ which is in fair agreement with the above value for electron produced defects.

*Equivalent Electron Fluence*

The short-circuit current change was evaluated as a function of proton energy and fluence. The equivalent fluence ratio was calculated using (1) and (2) for 1-MeV electron fluence levels corresponding to $\Delta i_{sc}/i_{sc_0}$ equal to 0.2, 0.5, and 0.8 representing the fluence levels $\phi_e$ of $1.7 \times 10^{15}$, $6.8 \times 10^{15}$, and $2.3 \times 10^{16}$/cm$^2$, respectively, for junction depth $X_j = 0.5\ \mu$m. The resulting values of $r(E_p)$ for normal incident protons and electrons are shown in Fig. 3 for each of the three fluence levels. The usefulness of the equivalent fluence concept requires the three curves to coincide at all proton energies as they do above 0.5 MeV. However, on the proton energy range 0.05-0.5 MeV where the cell is extremely sensitive, the value of equivalent electron fluence ratio depends on the damage level. This has important consequences in terms of radiation testing since generally the mixed environment must be simulated to insure a valid test.

The main limit on the use of equivalent electron fluence arises from the nonuniform production of defects in the cell active region by monoenergetic low energy protons. That such nonuniformity is not characteristic of the space environment results from the broad energy spectrum of space protons as well as their near isotropicity. Calculations have been made to test the equivalence concept for the geosynchronous environment including the possibility of a large solar flare event.

The model was evaluated for the geosynchronous-trapped

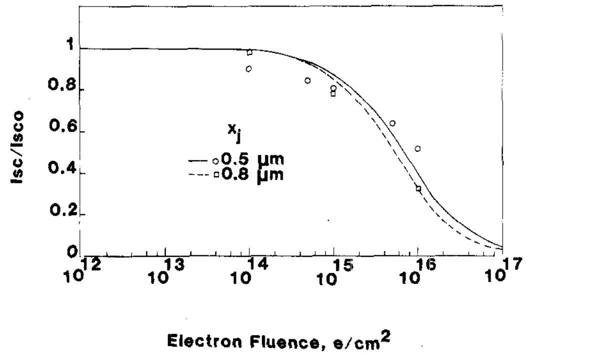


Fig. 1. Comparison of predicted and experimental solar cell damage from 1-MeV electrons for junction depths of 0.5 and 0.8 $\mu$m.

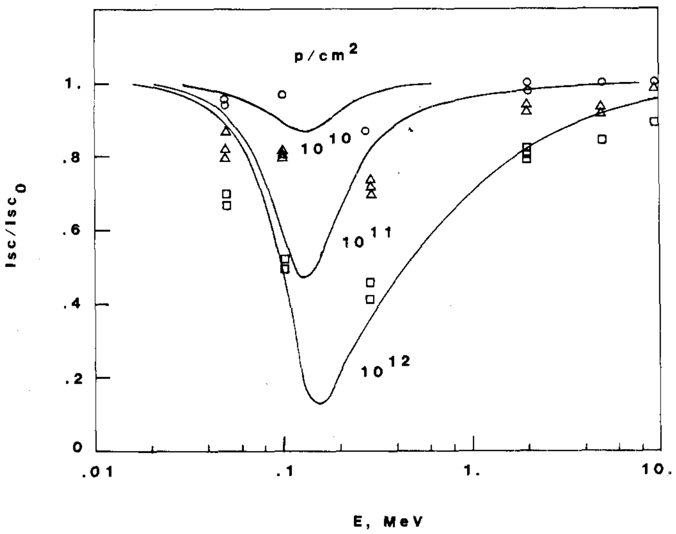


Fig. 2. Reduced short-circuit current for monoenergetics proton exposure at three fluence levels. Experimental data are noted as 0 for $10^{10}$ p/cm$^2$, Δ for $10^{11}$ p/cm$^2$, and □ for $10^{12}$ p/cm$^2$.

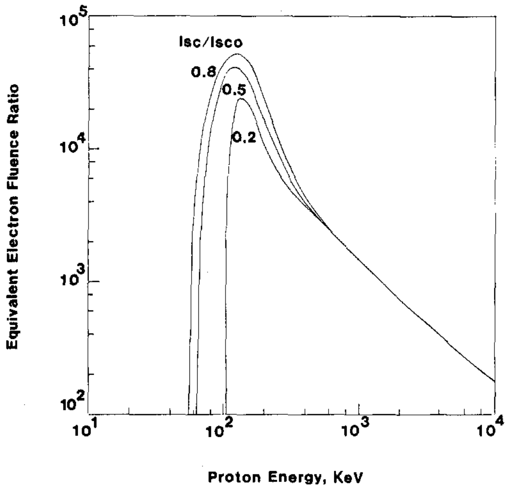


Fig. 3. Equivalent electron fluence ratio for GaAs heteroface solar cells with an 0.4-$\mu$m (GaAl)As window and 0.5-$\mu$m junction depth as a function of proton energy for three different damage levels.

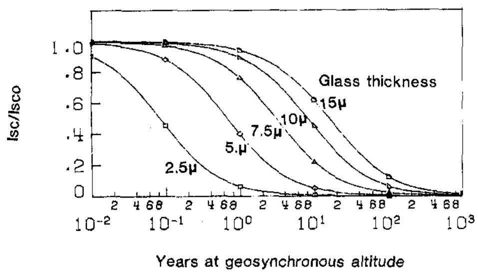


Fig. 4. Fractional short-circuit current reduction as a function of years spent at geosynchronous altitude with various cover glass thicknesses.

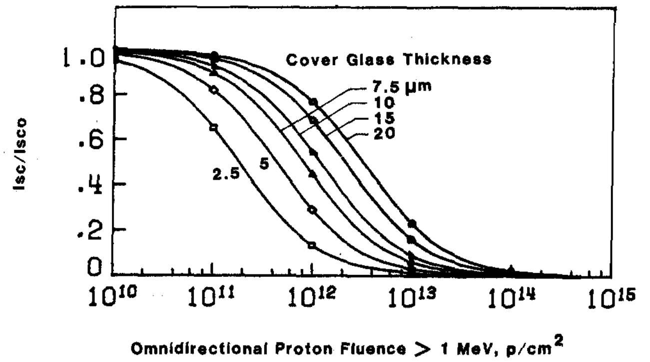


Fig. 5. Short-circuit current remaining after solar cosmic ray exposure for various cover glass thicknesses.

TABLE I
EQUIVALENT ELECTRON FLUENCE LEVELS FOR GEOSYNCHRONOUS ORBITS

| | | Geosynchronous Trapped Radiation | Solar Cosmic Rays |
|---|---|---|---|
| t,μm | Ec,MeV | Φe, Equivalent Electrons per year | Φe, Equivalent Electrons per major event |
| 2.5 | 0.31 | $6.8 \times 10^{16}$ | $1.7 \times 10^{16}$ |
| 5.0 | 0.55 | $8.7 \times 10^{15}$ | $6.5 \times 10^{15}$ |
| 7.5 | 0.75 | $1.9 \times 10^{15}$ | $3.7 \times 10^{15}$ |
| 10.0 | 0.95 | $7.8 \times 10^{14}$ | $2.3 \times 10^{15}$ |
| 15.0 | 1.25 | $3.7 \times 10^{14}$ | $1.4 \times 10^{15}$ |
| 20.0 | 1.55 | $3.7 \times 10^{14}$ | $9.5 \times 10^{14}$ |
| 30.0 | 1.86 | $3.7 \times 10^{14}$ | $5.2 \times 10^{14}$ |
| 40.0 | 2.23 | $3.7 \times 10^{14}$ | $3.1 \times 10^{14}$ |
| 50.0 | 2.42 | $3.7 \times 10^{14}$ | $1.8 \times 10^{14}$ |

$\Phi_e$ in units of e/cm²

radiations (See Fig. 4) for various thicknesses $t$ of cover glass shield over the cell face. The cell used in the calculations has an 0.5-$\mu$m $Al_{0.9}Ga_{0.1}As$ window and an 0.5-$\mu$m junction depth. The thickness of cover glass was included in the model by an equivalent increase in the window thickness. Shown in the figure is the remaining short-circuit current as a function of years in orbit. The cover glass must be greater than 15 $\mu$m to filter most of the low energy protons. The equivalent electron fluence is calculated using Fig. 4 and the 1-MeV normal incident electron cell response shown in Fig. 1. The equivalent electron fluence expressed in units of fluence per year in orbit is given in Table I.

According the Webber [15], the solar cosmic ray omnidirectional proton fluence (p/cm²) per year is approximately

$$\Phi_p\,(>E_p) \simeq 10^{9+0.02S}\,E_p^{-2}$$

where $S$ is the yearly average sunspot number. A detailed study by Foelsche [16] yeilds

$$\Phi_p\,(>E_p) \simeq 5 \times 10^{11}\,E_p^{-1}$$

for the low energy protons during the year 1960. The spectrum of Foelsche is used in the present study.

The short-circuit current was evaluated for the spectrum

$$\Phi_p\,(>E_p) = A/E_p \tag{8}$$

where $A$ is numerically the fluence with energy greater than 1 MeV and is taken as a parameter in the present calculations. The value of $A$ (defined as $\phi_p$ (>1 MeV)) equal to $10^{11}$ - $10^{12}$ represents a major solar event while $A$ less than $10^{10}$ is a small to minor event. Results are shown in Fig. 5 as a function of cover glass thickness. The equivalent electron fluence is found from Figs. 1 and 5 and (1) is determined to be independent of the damage level. The equivalent electron fluence for the solar proton fluence $\Phi_p(>E)$ is

$$\phi_e = \tilde{r}_p\,(E_c)\,\Phi_p\,(>Ec) \tag{9}$$

where $E_c$ is the cutoff energy of the glass cover plate and is shown in Table I. It is found from (1) and Figs. 1 and 5 that

$$\tilde{r}_p\,(E_c) \simeq 1.85 \times 10^4/t^{0.61}. \tag{10}$$

An alternate equivalent fluence ratio defined through

$$\phi_e = r_p\,(E_c)\,\Phi_p \qquad (>1\text{ MeV}) \tag{11}$$

which may be approximated as

$$r_p\,(E_c) \simeq 1.2 \times 10^5/t^{1.38}. \tag{12}$$

This quantity will be used in defining equivalent electron fluence for space testing.

## Space Qualification

In order to test for adequate design of a shielded GaAs solar cell with an 0.5-$\mu$m $Al_{0.9}Ga_{0.1}As$ window, 0.5-$\mu$m junction and thin glass covers ($t < 50\ \mu$m) one may use 1-MeV electrons of normal incidence at a fluence level

$$\phi_e \simeq (3.7 \times 10^{14} + 1.2 \times 10^{18}/t^{3.17})\ T + 1.2 \times 10^5\ A/t^{1.38} \tag{13}$$

where $t$ is the cover glass thickness in micrometers, $T$ is the time duration in years at geosynchronous altitude, and $A$ is the expected solar cosmic ray proton fluence level with energy above 1 MeV. If a severe solar cosmic ray event is to be expected, then $A$ is on the order of $10^{12}$ representing a solar particle fluence above 1 MeV of $10^{12}$ p/cm$^2$.

In addition to the equivalent fluence for test exposure, one must take account of exposure time and temperature since a degree of self healing of the cell is normally present. In this respect one may call to mind the experience with GaAs cells on NTS-2 for which annealing in flight is suspected [17]. When such factors are fully considered a reexamination of electron equivalency must be made since evidence exist which indicates that defect structures produced by proton exposure do not readily anneal [18]. Further study of space radiation damage in which the chemistry of specific defects are included are clearly needed.

## References


[1] J. W. Wilson, G. H. Walker, and R. A. Outlaw, "Proton damage in GaAs solar cells," *IEEE Trans. Electron Devices*, vol. 31, pp. 421–422, Apr. 1984.

[2] J. W. Wilson, G. H. Walker, R. A. Outlaw, and L. V. Stock. "A model for proton-irradiated GaAs solar cells," in *Proc. 1982 IEEE Photovoltaic Specialists Conf.* (San Diego, CA) Sept. 1982.

[3] J. W. Wilson, J. J. Stith, and G. H. Walker, "On the validity of equivalent electron fluence for GaAs solar cells," in *Proc. 1982 IEEE Photovoltaics Specialists Conf.* (San Diego, CA) Sept. 1982.

[4] W. C. Cooley and M. J. Barrett, "Space environmental effects on solar cell power systems," NASA, CR-92675, 1968.

[5] R. Loo, R. C. Knechtli, and G. S. Kamath, "Enhanced annealing of GaAs solar cell radiation damage," in *Proc. Fifteenth IEEE Photovoltaics Specialists Conf.*, 1981, paper 81CH1644-4, pp. 33–37.

[6] G. S. Kamath, "GaAs solar cells for space applications," presented at the Sixteenth Intersociety Energy Conversion Engineering Conf., 1981, paper 81-65380, pp. 416–421.

[7] J. W. Wilson, G. H. Walker, and R. A. Outlaw, "A simple model of proton damage in GaAs solar cells," NASA, TM-84495, 1982.

[8] G. H. Walker and E. J. Conway, in *Proc. 13th IEEE Photovoltaic Specialists Conf.*, 1978, pp. 575–579.

[9] F. L. Vook, *Radiation Effects in Semiconductors.* New York: Plenum 1968.

[10] L. Lindhard, M. Scharff, and H. E. Schiott, "Range concepts and heavy ion ranges," *Dans. Mat. Fys. Medd.*, vol. 36, no. 10, 1968.

[11] R. Bauerlein, "Messung der energie zur verlagerung eines gitter atoms durch elektronenstoss in $A^{III}$-$B^{V}$ verbindugen," *Z. Phys.*, vol. 176, pp. 498–509, 1963.

[12] J. W. Wilson, J. J. Stith, and L. V. Stock, "A simple model of space radiation damage in GaAs solar cells, NASA, TP-2242, Dec. 1983.

[13] G. H. Walker and E. J. Conway, *J. Electrochem. Soc.*, vol. 125, no. 10, pp. 1726–1727, 1978.

[14] R. Loo, L. Goldhammer, B. Anspaugh, R. C. Knechtli, and G. S. Kamath, "Electron and proton degradation in (AlGaAs)-GaAs solar cells," presented at the Thirteenth Photovoltaics Specialists Conf., 1978, pp. 562–570.

[15] W. R. Webber, "An evaluation of the radiation hazard due to solar-particle events," Boeing Co., Report, no. D2-90469, Dec. 1963.

[16] T. Foelsche, "Specific solar flare events and associated radiation doses. Space radiation effects," American Society for Testing and Materials, Special Tech. publ. no. 363, 1963, pp. 1–13.

[17] D. H. Walker, R. L. Statler, and R. J. Lambert, "Solar cell experiments on the NTS-2 satellite," presented at the Thirteenth Photovoltaics Specialist Conf., 1978, pp. 100–106.

[18] B. E. Auspaugh and R. G. Downing, "Damage coefficients and thermal annealing of irradiated silicon and GaAs solar cells, presented at the Fifteenth Photovoltaics Specialists Conf., 1981, pp. 499–505.