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Proton Damage in GaAs Solar Cells

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Abstract—A simplified model for the short-circuit current reduction caused by proton-induced radiation damage is described. The model accounts for the nonuniformity of defect production within heteroface GaAs shallow junction solar cells. The results from the model show agreement with the strong energy dependence observed in proton radiation damage experiments.

INTRODUCTION

GALLIUM ARSENIDE solar cells irradiated with protons exhibit a reduction in short-circuit current. For shallow junction (0.5 μm) cells, the magnitude of the short-circuit current reduction is strongly dependent on the proton energy with maximum damage at about 150 keV [1], [2]. Such strong proton energy dependence of the short-circuit current is apparently related to spatial nonuniformity in defect production. This requires a damage model in which spatial variations are accounted for explicitly. Earlier models for electron radiation damage assumed defects to be produced uniformly throughout the cell and modeled cell performance in terms of cell-averaged minority-carrier diffusion lengths [3], [4]. In the present paper, cell performance is evaluated in terms of the cell-averaged minority-carrier recombination probability during carrier diffusion to the cell junction. The average of the minority recombination probability over the cells' active region weighted according to the solar-average photoabsorption rate is used to estimate the proton-induced decrease in the short-circuit current.

THEORY

Atomic displacements caused by proton impact with atomic nuclei result in a variety of crystal defects which serve as recombination centers for minority carriers within the crystal. The formation rate of these defects is related to Rutherford's cross section and the threshold for displacement formation [5]. The defect cascade is treated according to the theory of Lindhard, Scharff, and Schiott [6]. The proton's energy deposited within the cell is partitioned between electronic and nuclear displacement using the recent data of Andersen and Ziegler [7]. The total number of displacements formed along the path of a proton of initial energy E (keV) is

$$D(E)=\begin{cases} 0, & E<0.64 \\ 12.4+350.4(1-0.8236E^{0.016})\log E, & 0.64\leqslant E\leqslant 20 \\ 47.83+20.48(1+0.003246E^{0.721})\log E, & 20\leqslant E \end{cases} \tag{1}$$

assuming that the threshold energy for displacement formation is 9.5 eV.

Let $D_v(x)$ be the volume density of defects due to a fluence of protons ϕ of energy E_0 incident on the face of the cell where x is the distance into the cell. If σ_r is the recombination cross section, then the fractional loss of electron-hole pairs in moving from depth x to the junction at depth x_j along a direction defined by μ is

$$f(\mu)=\begin{cases} 1-\exp\left(-\int_{x_j}^{x}\sigma_r D_v(x)\sqrt{6}\,dx/\mu\right), & x>x_j \\ 1-\exp\left(-\int_{x}^{x_j}\sigma_r D_v(x)\sqrt{6}\,dx/\mu\right), & x<x_j. \end{cases} \tag{2}$$

Here the factor $\sqrt{6}$ is the rule of thumb relation between diffusion length and the rms distance traveled [8]. Averaging the fractional loss over all directions toward the junction

$$F(x)=\int_0^1 f(\mu)\,d\mu \tag{3}$$

and noting that

$$\int_x^{x_j} D_v(x')\,dx'=\phi[D(E_x)-D(E_j)] \tag{4}$$

results in

$$F(x)=\begin{cases} 1-E_2\{\sqrt{6}\,\sigma_r\phi[D(E_x)-D(E_j)]\}, & x<x_j \\ 1-E_2\{\sqrt{6}\,\sigma_r\phi[D(E_j)-D(E_x)]\}, & x>x_j. \end{cases} \tag{5}$$

Here E_x is the energy of the proton if it penetrates to depth x, E_j is the energy if it penetrates to the junction, and $E_2(Z)$ is the second-order exponential integral. Multiple scattering effects can be included by the appropriate average of E_x and E_j [9].

The photoabsorption density is proportional to

$$\rho(x)=\frac{1}{\lambda}e^{-x/\lambda} \tag{6}$$

where the solar-average absorption length is 0.714 μm. The rate at which electron-hole pairs are normally collected at the junction is

$$i_{sco}=K\int_0^t \eta_c(x)\,\rho(x)\,dx \tag{7}$$

where $\eta_c(x)$ is the normal collection efficiency, K is the photon flux in the spectral band, and t is the depth of the active

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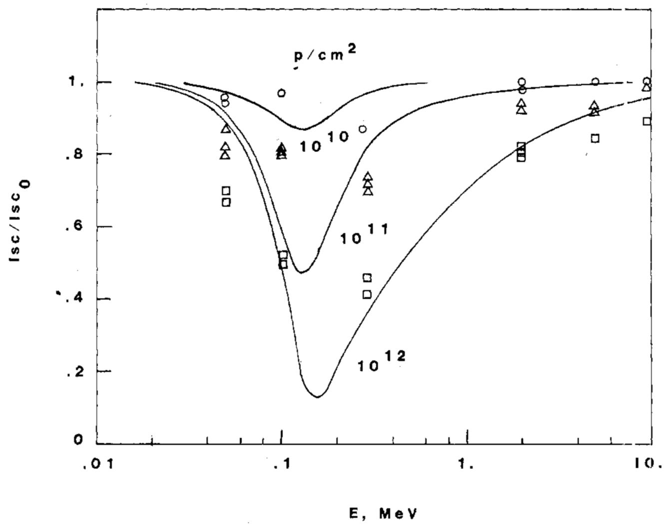

Fig. 1. Comparison with experimental short-circuit current changes in proton-damaged GaAs shallow junction solar cells as a function of proton energy.

region. Subtracting from (7) the electron-hole pairs which are lost due to radiation damage yields

$$i_{sc} = K \int_0^t \eta_c(x)\,\rho(x)[1 - F(x)]\;dx \tag{8}$$

from which

$$i_{sc}/i_{sc0} = 1 - \int_0^t \eta_c(x) F(x)\,\rho(x)\;dx \Big/ \int_0^t \eta_c(x)\,\rho(x)\;dx. \tag{9}$$

To simplify the present calculation without serious error, we take $\eta_c(x) \approx 1$ in (9) with results shown in Fig. 1.

RESULTS

The cells used in the experimental test had windows of 0.2 to 0.6 μm and junction depths of 0.4 μm. The change in collection efficiency was evaluated by (9) for several values of σ_r and an appropriate average over-window thickness. The results for $\sigma_r = 6.1 \times 10^{-14}$ cm^2 are shown in comparison to experimental measurements of short-circuit current in Fig. 1. Although the comparison is less than perfect due to scatter in the experimental data, a qualitative understanding is achieved. The value of σ_r used in the comparison is in fair agreement with values obtained by deep-level transient spectroscopy [10] for which the average is $\sigma_r \simeq 10^{-13}$ cm^2.

With the present success of this model, one is able to consider a host of questions concerning the performance and testing of these cells for space applications. Since the spatial distribution of the damage can be unambiguously related to cell performance, the effects of isotropic angular incidence and the spectral composition of space protons may now be evaluated. The model will soon be extended to electron damage so that relative importance of these two space radiation components may be evaluated. In addition, the concept of equivalent electron flux may be tested on the basis of the model especially with regard to preflight radiation testing. The whole concept of additivity of electron and proton exposure can be examined on the basis of the model.

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