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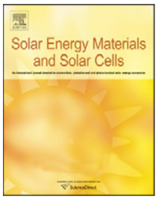

Modelling of solar cell degradation in space

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ABSTRACT

We present a method for modelling the degradation of solar cells in space, induced by electron or proton irradiations. It applies to modern cells, single, double or triple junctions made of GaInP, GaAs and Ge materials. It is based on classical semiconductor equations, after the values of all the various material parameters involved, as well as the electronic characteristics of irradiation induced defects, which act as recombination centers, have been experimentally determined. Because the nature of the irradiation induced defects in GaAs and GaInP is independent of the concentration and nature of the native defects and doping impurities, the method does not introduce empirical parameters and is valid for all types of cells. Modelling the degradation of 3J cells, as well as the associated top and middle subcells, of two origins (Emcore and Azurspace), has been performed and the results are confronted successfully with experimental data for the case of 1 MeV electron irradiation. Modelling has also been performed for several types of GaAs and GaInP, n/p and p/n, single cells, using the same electronic characteristics for the irradiation induced defects. The fits with experimental data are correct in all cases, thus illustrating the generic character of the method.

1. Introduction

The use of a solar cell in space requires knowledge of the degradation of current–voltage (*I–V*) characteristics under light illumination. This degradation is illustrated by the decrease of the maximum power P_m, short-circuit current J_{SC} and open-circuit voltage V_{OC} induced by the interaction with energetic particles present in space. This degradation is the result of the introduction of non-radiative recombination centers, the result of displacements of atoms induced by their collisions with these energetic particles. The recombination centers reduce the minority carrier lifetime and, consequently, the collection of electrons and holes generated by photon absorption.

The way to evaluate the degradation induced by a given fluence φ of irradiation is in principle straightforward: it consists of computing the *I–V* characteristics of the cell using values of the lifetimes τ in the emitter and base, calculated to take into account the concentrations N_t of the non-radiative centers introduced by the irradiation:

$$1/\tau = 1/\tau_0 + N_t \sigma_t v_{th} \qquad (1)$$

where τ_0 is the value of the lifetime prior to irradiation, the so-called BOL (for beginning of life) value, v_{th} the thermal velocity of the carriers (electrons or holes) and σ_t the cross-section for minority carrier capture on the irradiation induced recombination centers. Hence, modelling of the degradation requires the knowledge of N_t, i.e. of the introduction rate k of the defects that act as recombination centers:

$$N_t = k\varphi \qquad (2)$$

and of their associated capture cross-section σ_t. Although simple in principle, the computation of degradation has not yet been performed quantitatively for an obvious reason: the "degradation parameters": k and σ_t were unknown because the non-radiative recombination centers introduced by irradiation were not identified.

The determination of these degradation parameters is complicated because several different defects are usually created by irradiation and it is difficult to sort out those that act as non-radiative recombination centers and to measure their associated minority carrier capture cross-section with correct accuracy. Other defects trap free carriers and therefore reduce the apparent doping levels in the base and the emitter. However, in space irradiation, they play a negligible role because their concentration is usually small compared with the doping concentration. For instance, an equivalent fluence of 10^{16} cm^{-2} 1 MeV electrons, which corresponds to a typical space condition, introduces a total of 10^{16} cm^{-3} defects in GaAs (1) while the emitter and base of a cell are doped at a level of several 10^{17} cm^{-3}. Systematic studies, combining measurements of *I–V* characteristics in dark and under illumination, electroluminescence, time resolved photoluminescence (TRPL) and deep level transient spectroscopy (DLTS) performed on single GaAs and GaInP junctions, have allowed us

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to identify, characterize and measure the concentrations and the introduction rates (for 1 MeV electrons only) of the native and irradiation induced defects acting as non-radiative recombination centers in these two materials [1–8].

Until recently, solar cells used in space were made of Si, a material in which the nature and concentration of the defects induced by irradiation depend on many parameters such as natures and concentrations of doping impurities, natures and concentrations of residual impurities (in particular oxygen) and temperature (for a review on this question see for instance Ref. [9]. Thus, despite numerous studies, only a qualitative understanding has been reached, which is not sufficient to allow a quantitative prediction of the degradation for a cell made of a specific Si material. As a result, ways to evaluate the degradation have been based on empirical methods. The first, original one considered irradiating of each cell of a given type with variable fluences φ of electrons and protons of various energies E and tabulating, versus E and φ, the corresponding degradation rates of P_m, I_{SC} and V_{OC} [10]. Subsequently, in order to reduce the number of irradiations tests, the concept of relative damage coefficient (RDC), or of equivalent fluence, was introduced by the Jet Propulsion Laboratory (see in Ref. [11]). An RDC coefficient relates the fluence φ at a given energy E which produces the same degradation as the fluence φ_0 at a standard energy E_0:

$$\varphi(E) = RDC(E)\varphi_0(E_0) \tag{3}$$

This concept is valid in the cases of GaAs and GaInP cells [12] because: (i) the defects created by energetic electrons and protons are the same, since they result directly from the transmission of energy to the "primary knock-on atom" and (ii) the displaced atoms, which are stable at room temperature, are separated by an average distance larger than the extension in space of their wave functions in the case of proton irradiation so that they are isolated, like in case of electron irradiation. This is not true for Si because the primary defects, interstitials and vacancies are mobile at room temperature and form complexes with impurities (doping or native) and between themselves. The most frequent and most extensively studied defects are the vacancy–oxygen complex (A center), the vacancy–doping impurity (E center) and the divacancy (for a comprehensive review, see Chapter 8 in Ref. [13]).

Then, a degradation curve describing the variation of cell characteristics (P_m for instance) versus fluence, corresponding to irradiation at energy E, can be deduced (by translation along the abscissa when P_m is plotted versus the logarithm of φ) from the degradation curve at the standard energy E_0 when RDC(E) is known. More elaborate empirical methods, such as the one based on "displacement damage dose", a concept proposed by the Naval Research Laboratory, have been introduced later [14] with the aim of reducing further the number of irradiation tests (for a detailed comparison between these two approaches see Ref. [15]). Within this picture, the degradation follows the following empirical law:

$$P_m/P_{m0} = 1 - C\ln(1+\varphi/\varphi_0) \tag{4}$$

where P_m/P_{m0} is the normalized maximum power after irradiation; C and φ_0 are empirical constants, whose values are different for electron and proton irradiations and for each parameter (V_{OC}, I_{SC} and P_m), i.e. they are specific to a given cell and a given type of irradiation.

With the advent of multijunction (MJ) solar cells to improve power dissipation in satellites, the question of prediction of their degradation arose again [16,17]. The empirical techniques of prediction previously developed for single cells are then of little use because MJ cells contain a variety of new materials (Ge, GaInP, GaInAs, GaAs and probably others in the future) and each individual cell composing a MJ cell (a subcell) degrades differently from others. Consequently, the actual empirical techniques adapted to single cells cannot be applied directly.

In this work, we propose an "ab initio" method, i.e. a method in which the values of all the parameters involved have been measured by independent experimental techniques. Thus, the characteristics of irradiation induced non-radiative centers have been measured in each material composing each cell. This is possible for cells made of GaAs and GaInP (but not of Si, see above) because the natures and concentrations of the defects introduced by irradiation in these two materials do not depend on the nature and concentration of the impurities, native or irradiation induced, they contain [1,18–20].

GaAs and GaInP materials are now at the heart of modern space solar cell technology because they allow building of MJ cells, from GaInP/GaAs/Ge structures, characterized by large efficiency (actually 28%). The method for predicting their degradation, based on the computation of I–V characteristics of each subcell they contain, is described briefly in Section 2. Since it is a classical subject, only the difficulties encountered in the quantitative evaluation of these characteristics are described. The method is first applied to single GaAs and GaInP cells and then extended to triple junctions (3J) cells. The predicted results are successfully confronted with experimental data for different types of cells originating from different manufacturers and the correct prediction obtained in all cases illustrates the power of the method.

2. Principle of the modelling

The equations describing the I–V characteristics of a cell under illumination are given in textbooks (see for instance Ref. [21]). The short circuit current J_{SC} is the sum of three components, the photocurrent currents J generated in the emitter (e), the base (b) and the space charge region (z):

$$J_{SC} = J_e + J_z + J_b \tag{5}$$

whose expressions are

$$J_e = q\varphi\frac{\alpha L_e}{1-\alpha^2 L_e^2}e^{-\beta d_w}e^{-\alpha d_e} \times\left[\alpha L_e - \frac{(S_eL_e/D_e+\alpha L_e)e^{\alpha d_e} - ((S_eL_e/D_e)\mathrm{ch}(d_e/L_e)+\mathrm{sh}(d_e/L_e))}{\mathrm{ch}(d_e/L_e)+(S_eL_e/D_e)+\mathrm{sh}(d_e/L_e)}\right] \tag{6}$$

$$J_z = q\varphi e^{-\beta d_w}e^{-\alpha d_e}(1-e^{-\alpha w}) \tag{7}$$

and

$$J_b = q\varphi e^{-\beta d_w}e^{-\alpha d_e}\left[\frac{1}{\alpha L_b}\frac{\mathrm{ch}(d_b/L_b)-e^{-\alpha d_b}}{\mathrm{sh}(d_b/L_b)} - 1\right] \tag{8}$$

The parameters entering these expressions are as follows: d_b, d_e and d_w are the thicknesses of the base, emitter and window, respectively, w is the thickness of the depletion region (which is calculated from the doping concentrations N_e and N_b in the emitter and base, respectively), $\alpha(\lambda)$ and $\beta(\lambda)$ are the absorption coefficients of the cell material and of the window, respectively and S_e is the recombination velocity at the emitter interface. The diffusion lengths $L_{e,b,}$ are related to the diffusion coefficients $D_{e,b}$ characteristics of the recombination centers by the Einstein relation:

$$L_{e,b}(\phi) = \sqrt{D_{e,b}\tau_{e,b}} \tag{9}$$

where

$$D_{e,b} = \frac{k_bT}{q}\mu_{e,b} \tag{10}$$

$\mu_{e,b}$ being the mobilities of the minority carriers.