IEEE Transactions on Nuclear Science, Vol. 35, No. 4, August 1988

RADIATION DAMAGE EVALUATION ON ALGAAS/GAAS SOLAR CELLS

E. G. Moreno, R. Alcubilla, L. Prat and L. Castañer
Departamento de Electrónica. U.P.C.
Jorge Girona Salgado s/n - Barcelona 08034 - SPAIN

Abstract

A piecewise model to evaluate radiation damage on AlGaAs based solar cells has been developed, which gives complete electrical parameters of the cells in the operating temperature range. Different structures, including graded band gap and double heteroface can be analyzed. The cell structure is sliced into layers of constant parameters, allowing the model to take into account nonuniform damage produced by low energy protons without excess computer time. Proton damage coefficients as well as proton damage ratios can be calculated for energies between 30 and 10^4 keV with only two adjustable parameters. In addition, coirradiation experiments with different energy protons can be simulated, by improving the conventional method of degradation computering.

Introduction

Gallium Arsenide solar cells are considered as especially suitable for space purposes because of their high efficiency and radiation resistance. The use of GaAs solar cells in space power systems scheduled for 7 years of operating lifetime [1] requires prediction capabilities of the expected solar cell degradation. This work must include both laboratory test measurements and simulation work for better understanding of the underlying phenomena as well as to develop tools to facilitate cell design.

The common method to predict solar cell degradation in space is to relate the damage produced by any kind of particles, to damage produced by particles of reference, usually 1 MeV electrons or 10 MeV protons, and to calculate the total equivalent fluence [2]. Although the equivalence damage method has been extensively used, cases of failure when GaAs solar cells are concerned have been detected, mainly due to the different degradation behaviour of these cells in comparison with Silicon cells, in particular if coirradiation with low and high energy protons is considered [1].

In the work reported here the focus is placed on the electrical behaviour of the solar cell in the presence of harmful radiation environment assumed to concentrate its effects in the minority carrier lifetime degradation. It has been found that many of the experimental data of degradation of electrical characteristics may be explained by assuming a minority carrier lifetime deepness- dependent from the surface on which particles are impinging. The shape of the lifetime inside the sample, will be obviously dependent on the type and energy of the particles, as well as on the kind of irradiation, i.e. if the particles have normal or isotropic incidence.

Manuscript received on February 5, 1988

A very first interest of the work is to provide a tool to calculate the expected degradation of solar cells in any kind of irradiation environment, by simply knowing the experimental results after normal irradiation with a monoenergetic particle fluence at 1 MeV electrons and 10 MeV protons. Damage produced by these particles is easily measured in earth laboratories. The model should be capable to explain the failure of conventional prediction models when co-irradiation with different energy protons is concerned.

Solar cell model

Complete simulation of solar cells requires solving a set of non linear differential equations including Poisson, transport and continuity equations for both carrier types. The solution needs complicated and time consuming numerical methods. Simpler models assume constant value parameter in each region of the cell then finding analytical solutions. However they are not able to explain adequately the cell degradation by low energy protons, because the non uniformity of the damage.

These previous analytical models of GaAs cell degradation, either calculate the mean value of carrier lifetime in each region cell as a function of particle fluence and energy, or if they takes into account the non uniformity of the damage, they are only able to calculate the short circuit current reduction [3].

Alternatively, cell degradation after ominidirectional radiation can be computed from the experimental degradation curve after normal radiation, by calculating the total damage in the cell [4]. Again, the non uniformity of the damage is neglected.

The model here presented is based on a piecewise approach taht divides the cell structure in an adaptative number of slices. Inside a particular slice the semiconductor parameters are constant, consequently, it is easy to find an analytical solution of the semiconductor transport equations with suitable boundary conditions for the interfaces with the adjacent slices.

More specifically, the boundary conditions applied for current continuity are related to interface recombination velocities, S, and the boundary conditions applied to minority carrier concentration are for a P type region given by

$$\frac{n(i+1)}{n(i)} = \exp\left[\frac{E_c(i+1) - E_c(i)}{kT}\right] \frac{N_{imp}(i+1)}{N_{imp}(i)} \, \frac{m^*(i)}{m^*(i+1)} \qquad (1)$$

where n is the electron concentration in p-type slice and E_c is the conduction band energy level, N_{imp} the dopant concentration and m^* the electron effective mass.

The selected procedure to perform the

0018-9499/88/0800-1067$01.00 © 1988 IEEE

cell structure division is shown in Figure 1. The emitter, base and depletion regions are sliced into layers when the dopant Aluminium concentration are constant. This method is able to accomodate structures with AlGaAs layers at the top or the botton of the cell as well as to consider variable gap structures.

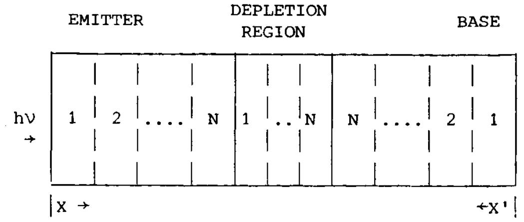


Fig. 1 Division of solar cell structure into slices.

As it will be shown later, the radiation is expected to create very sharp lifetime variations in the semiconductor bulk. For this reason, a selection of the slices and spacial distribution must be performed in order to place a greater number of slices in the semiconductor region where sharper variations in the lifetime are present.

Finally, the computer program that has been developped calculates the total I(V) characteristics by adding the contributions of the emitter, base and space charge regions under AMO illumination conditions. Spectral response is, of course, an output of the program. All the parameters of the model are analytically related to the temperature, composition of the semiconductor (Aluminium concentration) and dopant concentration (N_{imp}). Table I shows the definition of parameters and the dependeces considered in the model. Analytical expressions have been given elsewhere [5].

Table I. Electrical Parameter

Band energy	E^G, E^L, E^X (X_{AL}, Temp)
Effective mass	m_n^*, m_p^* (X_{AL})
Intrinsic conc.	n_i (Band energy, m^* ,Temp)
Carrier mobility	μ_n μ_p (N_{imp}, m^* , Temp)
Carrier lifetime	τ_n τ_p (N_{imp}, m^* , Temp)
Dielectric constant	ε (X_{AL}, Temp)
Absortion coeficient	α (λ, Band energy)
Reflectivity	R (λ, ARC)

Radiation effects

It is well known that the electron and proton radiation creates defects in the semiconductor bulk that acts as recombination centers for carriers. There are several types of recombination centers, each one characterized by the capture cross section and the situation in the gap. These recombination centers modify the carrier lifetime as follows

$$\frac{1}{\tau} = \frac{1}{\tau_0} + \sum_i N_i \sigma_i v_{th} \tag{2}$$

where

τ_o is the minority carrier lifetime before irradiation (BOL)

σ_i is the capture cross section of the i type center

N_i is the desity of the i type center

v_{th} is the thermal velocity

For sake of simplicity we will take only one type of center, placed at the center of the gap, with the same capture cross section for both types of carriers.

Because the range of the 1 MeV electrons is much greater than the thickness of the GaAs cell, it is commonly assumed that the recombination center density is uniform through the cell structure. In that case the minority carrier lifetime, after an electron fluence of Φ_e 1 MeV e^-/cm^2 can be related to the Begining Of Life lifetime as follows

$$\frac{1}{\tau} = \frac{1}{\tau_0} + K_e \Phi_e v_{th} \tag{3}$$

where K_e is the lifetime degradation constant, taking into account the capture cross section of the center and the proportionality between the defects and the density of recombination centers.

The irradiation with protons leads to a more complex situation, on the one hand because the range value is comparable to the cell depth and, on the other hand because of the nonuniform distribution of the defects along the range. More precisely, the number of primary collisions of a proton, with instantaneous energy E, is the reciprocal of the mean free path, l(E), [6]

$$\frac{1}{l(E)} = \sigma(E) N_t \tag{4}$$

where $\sigma(E)$ is the nuclear stopping cross section, and N_t is the atomic density. Each primary collision produces a certain number of atomic displacements, v(E), related to the instantaneous energy through the Kinchin and Pease theory. The total number of atomic displacements produced by the proton per unity path legth is

$$\xi(E) = \frac{v(E)}{l(E)} \tag{5}$$

To relate the instantaneous energy, E, of a proton with incident energy E_o to the penetration, x, we have fitted the range data, $R(E_o)$, of Andersen and Ziegler [7] obtaining

$$R(E_0) = 0.77*E_0^{0.5} + 1.25*10^{-4}*E_0^{1.64} \tag{6}$$

$$E = \frac{175*(R-x)^2}{1 + .67*(R-x)^{1.39}} \tag{7}$$

For isotropic irradiation the function $\xi(R-x)$ has to be averaged for all the incident angles as follows

$$\xi_{iso} = \int_0^1 \xi(R - \frac{x}{\cos\theta}) \, d(\cos\theta) \tag{8}$$

Hence the lifetime value after a proton fluence of Φ_p p^+/cm^2 is

$$\frac{1}{\tau} = \frac{1}{\tau_0} + K_p \xi \Phi_p v_{th} \tag{9}$$

where K_p acts for the protons as K_e for the electrons. Both constants, K_p and K_e, are used to adjust the model to the experimental results.

To take into account the coverglass effects on the distribution function $\xi(E_o,x)$ the coordinate origin is displaced to a deepness of x_o from the surface. x_o is calculated as the GaAs thickness needed in order to have the same stopping power as the coverglass.

Once the function $\tau(\tau_o,x)$ has been calculated, a discretization procedure follows, concerning the whole cell structure. The discretization is automatically performed according to the value of the incident energy and the irradiation type.

Figure 2 shows the results of such a discretisation for irradiations with a fluence of 10^{11} cm^{-2} directional and isotropic, at two different energies. As expected, the shape of the discretization is smoother in the isotropic case.

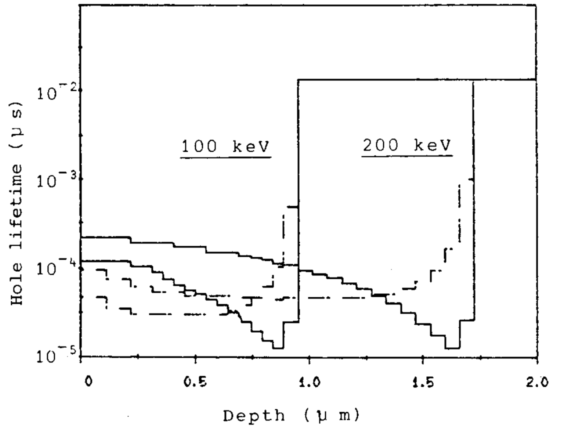


Fig. 2 Hole lifetime reduction after 10^{11} 10 MeV proton/cm^2 irradiation. — normal - - isotropic.

Results

The model has been used to simulate the electrical behaviour of an heteroface AlGaAs solar cell reported in the literature |1|,|8|, in order to check its capabilities. These cells have been qualified by the NASDA for space use, so its behaviour under irradiation are well known.

The main physical parameters and the electrical performance BOL at 28°C are listed in Table II. Series and shunt resistences, and intrinsic carrier lifetime are chosen to match experimental results |8| at this temperature. Figure 3 shows the short circuit current, open circuit voltage, and maximum power plotted as a function of the temperature. Experimental points reported in reference 8 are also superposed.

To calculate the behaviour under irradiation we start setting the values of K_e and K_p. This is done in order to fit the experimental results after normal irradiation by 1 MeV electrons and 10 MeV protons respectively. The former is shown in Figure 4 with experimental points taken from |8|.

Figure 5 shows the spectral response BOL, after 1 MeV electron normal irradiation at a fluence of 5 10^{15} cm^{-2}, and after combinated normal irradiation with 1 MeV electron and 10 MeV proton at fluences of 5 10^{15} cm^{-2} and 5 10^{12} cm^{-2}, respectively.

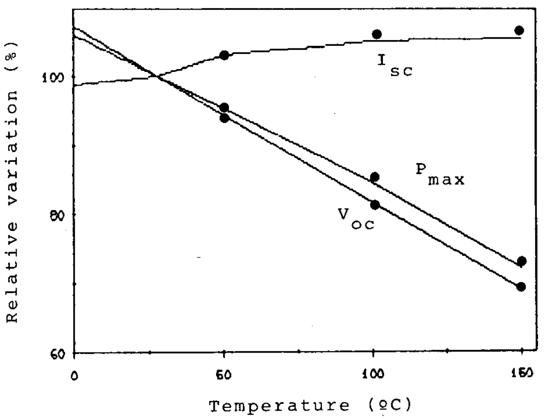
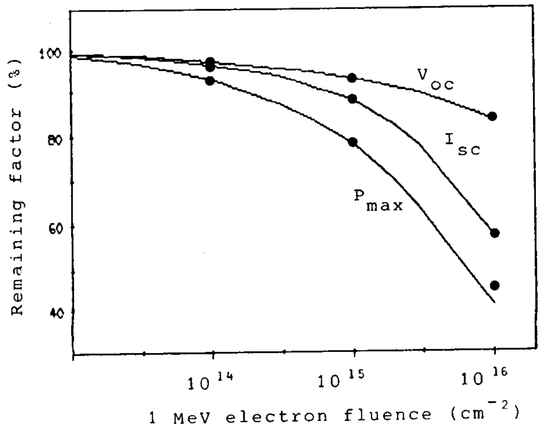


Fig. 3 Temperature characteristics of P_{max}, I_{sc}, V_{oc}.



Remaining factor of V_{oc}, I_{sc}, P_{max} normalized to the initial value [illegible] 1 MeV electron fluence.

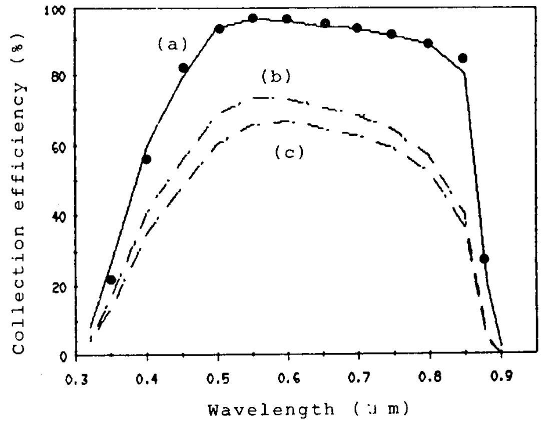


Fig. 5 Spectral response of solar cell (a) before irradiation (b) after $5\cdot10^{15}$ cm^{-2} 1MeV electron irradiation (c) after $5\cdot10^{15}$ cm^{-2} 1MeV electron and $5\cdot10^{12}$ cm^{-2} 10MeV proton irradiation.

These previous adjustements allow us to calculate the degradation of the solar cell performances after proton irradiation of arbitrary energy and fluence, isotropic or directional. Figure 6 shows the efficiency degradation as a function of proton energy for several fluences. Two early conclusions can be given, first there is an energy that produces maximum degradation, around 200 keV, and second, for high energy protons isotropic irradiation produces worse damage.

Table II. Cell parameters

Emitter p-type	AlGaAs layer	Thickness (µm) 0.2 Impurity concentration (cm^{-3}) 10^{18} Aluminium concentration (cm^{-3}) .86 Surface rec velocity (cm/s) 10^6
	GaAs layer	Thickness (µm) 0.5 Impurity concentration (cm^{-3}) 10^{18} Interface rec velocity (cm/s) 10^4
Base n-type	Active layer	Thickness (µm) 6.0 Impurity concentration (cm^{-3}) 4.10^{16}
	Substrate	Thickness (µm) 200 Impurity concentration (cm^{-3}) 10^{18} Back surface rec velocity (cm/s) 10^{10}
General	Size (cm^2) 2 x 2 Contact surface covered (%) 3 ARC Si_3N_4 Series resistence (Ω) 0.4 Shunt resistence (Ω) 250	
Electrical charact	Isc (mA) 125. Voc (V) 0.97 Fill Factor 0.77 Pmax (mW) 94.8	

Moreover, we can calculate the degradation of the cell in any kind of radiation environment by calculating the defects accumulated at each dept. This allows us to predict the cell lifetime in a given orbit.

Damage coefficients

Damage coefficients are defined as the fluence of 10 MeV protons required to reduce one electrical cell parameter (usually I_{sc}, V_{oc}, or P_{max}) at temperature T by r percent, divided by the fluence of protons of energy E required to have the same reduction in the chosen parameter, at the same temperature.

Proton damage ratios are defined in a similar way to the damage coefficients, but taking 1 MeV electrons as reference particles. Both parameters are extensively used to predict the useful life of photovoltaic arrays in space for a given orbit, converting the total irradiation in an equivalent fluence of reference particles. However, this method has some drawbacks.

First, the damage coefficients are not uniquely defined for a given energy. They depend on the irradiation kind (normal or isotropic) and on percent degradation considered. So there are several value tables and their handling is difficult.

Second, damage coefficients depend strongly on the physical structure of the cell considered. Extrapolation to another cell type, even similar, is not possible. For this reason they are not suitable for purposes of optimization structures.

Moreover the method applies superposition to the damage produced by the different particle types to calculate the total equivalent fluence. Errors produced by this assumption can be important, mainly when low energy protons is concerned. Co-irradiation experiments with several energy protons have been performed showing this mismatch |1|.

The method proposed in this work, based on the use of a powerful simulation model fitted both experimental results BOL, and after 1 MeV electron and 10 MeV proton irradiation, can overcome the above mentioned drawbacks.

As an example, degradation produced by combinated irradiation with several energy protons has been calculated. Firstly the proton damage coefficients have been obtained from the curves of Figure 6, for r = 20 % of P_{max}, and they are shown in Figure 7. These results closely agree with those reported in

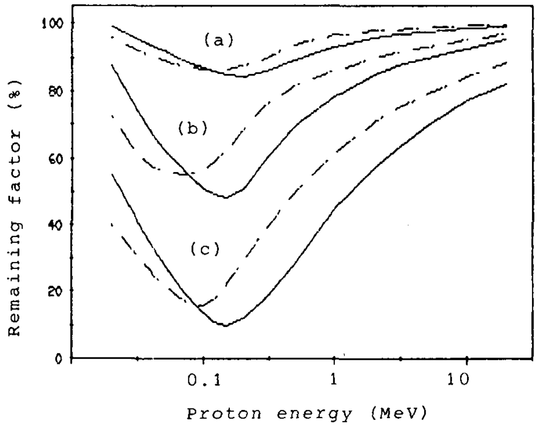


Fig. 6 P_{max} degradation versus proton energy for (a) 10^{10} cm^{-2} (b) 10^{11} cm^{-2} and (c) 10^{12} cm^{-2} fluences. — — normal —— isotropic.

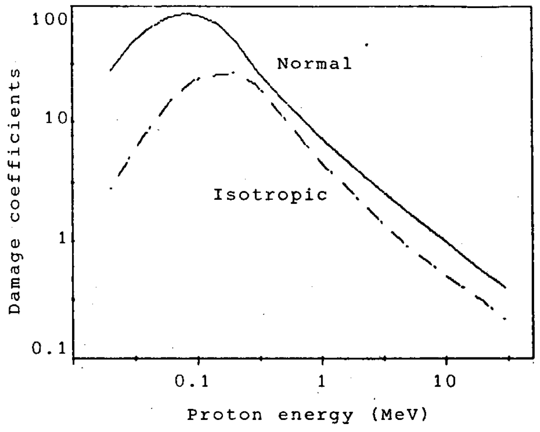


Fig. 7 20% P_{max} damage coefficients.

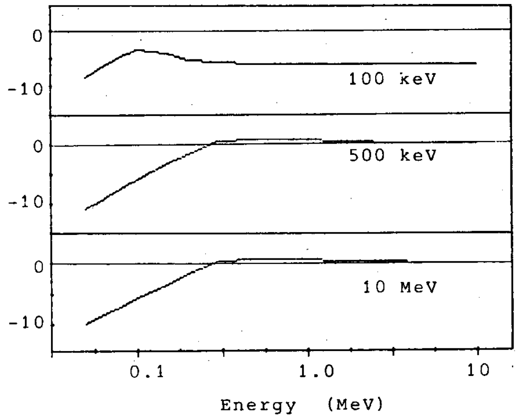


Fig. 8 Differences between remaining P_{max} calculated through the PDM method and by the model. Coirradiation of several energy protons and (a) 100 KeV, (b) 500 KeV and (c) 10 MeV protons. All the fluences causes 20% P_{max} degradation.

reference 4. After that, degradation produced by co-irradiation with 0.1, 0.5 and 10 MeV protons and protons of different energies at fluences which causes 20 % P_{max} degradation has been calculated (a) by the conventional equivalent damage method, and (b) by direct calculation of carrier lifetime degradation. The difference between both methods is shown in Figure 8. As we can see, these differences are more important for co-irradiation with low energy and high energy protons.

Conclusion

We have developed a mathematical model for GaAs solar cells. This model is able to predict electrical performance degradation after proton or electron irradiation of low and medium energies.

This informatic tool allows us to overcome the main disadvantages of the conventional method of prediction, i.e. the damage coeffient method. Moreover, only two parameters are necesary to adjust the model to experimental values, K_e and K_p, both easily measureable in earth laboratories, with 1 MeV electron and 10 MeV protons irradiation, for instance.

The ability of the model to fit experimental results for monoenergetic particle fluence on heteroface AlGaAs solar cells has been proved. Results of co-irradiation experiences with several energy particles has been also presented. The program can be now used to perform studies of irradiation hardness with another AlGaAs cell types like graded band gap or double heteroface cells.

References

[1] N. Takata, K. Toriyama et al., "Energy dependence of proton irradiation damage in GaAs solar cells and effects of combinated radiation on them". 5th Europ. Symp. Phot Gen. in Space. 1986. pp. 425-433.

[2] H.Y. Tada, J.R. Carter Jr., B.E. Anspaugh and R.G. Downing, "Solar Cell Radiation Handbook" 3rd Edition, JPL Publication 82-69, November 1982.

[3] J.Y. Young, "A model for proton damage in Silicon and GaAs solar cells". 17th IEEE Phot. Spec. Conf. 1984. pp. 1084-1087.

[4] B.E. Anspaugh and R.G. Downnig, "Radiation effects in Gallium Arsenide solar Cells using isotropic and normally incident radiation". 17th IEEE Phot. Spec. Conf. 1984. pp. 23-30.

[5] L. Prat, E.G. Moreno and L. Castañer, "Heteroface Gallium Arsenide solar cells induced degradation. Analytical model". IEEE Trans. on Nuc. Sci., Vol. NS-33. No 3. 1986. pp. 1058-1065.

[6] Yu. V. Bulgakov and M.A. Kumakov,"Spatial distribution of radiation defects in materials with beams of monoenergetic particles". Soviet Physics Semicond. Vol. 2 No 11. 1969. pp. 1334-1337.

[7] H.H. Andersen and J.F. Ziegler, "Hidrogen stopping powers and ranges in all elements". Vol. 3. Pergamon Press Inc. 1977.

[8] S. Matsuda, M. Otoda et al., "Developement of AlGaAs/GaAs solar cells with space qualifications". 17th IEEE Phot. Spec. Conf. 1984. pp. 97-102.