Radiation Analysis of InGaP/GaAs/Ge and GaAs/Ge Solar Cell: A comparative Study

Mohammed Bekhti*‡

*Centre for Satellites Development, Algeria

(m_bekhti@yahoo.fr)

‡Corresponding Author; Mohammed Bekhti, Centre for Satellites Development, Po Box 4065, Ibn Rochd, USTO, Oran, 31130, Algeria, +213 663 025 823, m_bekhti@yahoo.fr

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Abstract-Currently in orbit satellite electrical power system demands are doubling every five years, forcing the spacecraft designer to look for options to solve the power availability problem. The need for high performance solar arrays for space applications continues to increase, as the energy budget of satellites becomes ever higher, and power systems become constrained by either total mass or stowed volume. Solar cells industries have stepped up to this challenge by developing new innovative designs that will increase efficiency and decrease cells weight. Two approaches are being pursued to enable higher power levels on satellites systems. The first approach is to increase the efficiency of the solar cells used on state-of-the-art flat panel solar arrays thereby increasing the total power delivered to the payload for a given array size. The second approach is to utilize thin film solar cells that can be efficiently stowed, possess greater radiation hardness, and are lightweight and less costly. Solar cell efficiency is the most significant parameter to optimize in order to achieve minimum mass and volume of the solar cell and therefore the power system. Due to the extreme nature of the low earth orbit environment, solar cells are subject to possible damage; most commonly, a radiation damage, which affects all the cells similarly. Radiation causes a constant slow degradation of a solar cell performance. The probability of damage increases with increased mission time, therefore most of these effects can be discounted for short mission times. In order to use the GaAs/Ge or the InGaP/GaAs/Ge solar cells for space applications more efficiently, it is essential to predict their tolerance to irradiation by high energy electrons or protons.This paper reports on the electron or proton irradiation effects on GaAs/Ge and InGaP/GaAs/Ge space solar cells. The paper compares the electrical properties of GaAs/Ge and InGaP/GaAs/Ge space solar cells regarding electron and proton irradiation. The results for the effects were produced by simulation for different energies over a range of 0.5 to 12 MeV and fluences ranging from (10^9, 10^{10}, 10^{11} to 10^{12} cm^{-2}).

Keywords-GaAs solar cells, InGaP/GaAs/Ge solar cells, protons, electrons, irradiation, fluence, energy.

1. Introduction

The power output of solar cells is severely reduced by damages caused by radiation. The solar panels of a typical satellite in low earth orbit lose 15% of its power generating potential in 5 years. Predicting the degradation of solar cells during a mission can be crucial in determining the length of the mission. Spacecrafts power subsystems are designed to meet the requirements of the end of life (EOL), and as such, it is necessary to provide for the loss of power from the solar cells during the lifetime of the mission. There are experimental data about solar cells degradation according to proton and electron fluences. Therefore, a method for prediction of degradation based on experimental data is desirable.

An approach to the power loss correlation radiation consists of multiplying the calculated non-ionizing energy (NIEL) and the fluences. Power losses related to proton irradiation are a special case due to the linear dependence of the coefficient of damage against the proton NIEL for every solar cell. The electron irradiation, however, does not vary linearly with NIEL and a more general approach is required. This method of characterizing the effects of radiation on solar cells in terms of absorbed dose to removal damage allows the prediction of power losses in the space environment with limited experimental data.

2. Absorbed Dose of Displacement Damage

Damages whether permanent or transitory, are often proportional to the amount of energy lost by the incident particle in the matter through which it passes. In this context, another technique for characterizing the degree of displacement damage was developed, called NIEL (Non Ionizing Energy Loss); it is based on the measurement of the energy associated with the displacement damages. The NIEL hypothesis assumes that any damage induced by an irradiating particle in a semiconductor depends only on the energy lost in a non-ionizing manner; it therefore takes into account the decrease of the substrate atoms. The amount of defects produced is assessed according to the energy deposited in the first collision. The unit of NIEL is: MeV cm^2/g.

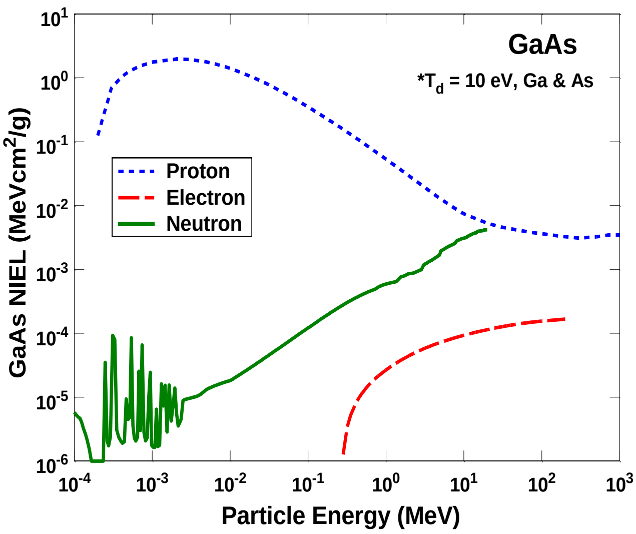

Fig. 1. NIEL curves measured for protons, electrons and neutrons in GaAs.

Figure 1 shows the NIEL curves measured for protons, electrons and neutrons in GaAs. It should be noted that the NIEL allows to match the fault displacement generated by different types of particles with different energies. It is now interesting to understand the impact of these displacement defects on the properties of semiconductors. The absorbed dose across the entire energy spectrum of a particular type of radiation (protons or electrons) for a given mission can be expressed as follows:

$$D_d = t\, S(E_{ref})^{-(n-1)} \int \frac{dF(E)}{dE} S(E)^n \, dE \qquad (1)$$

Where

- F(E) : particles flux,
- t : mission duration.

The concept of damage equivalent to an energy of an electron of 1MeV and to an energy of a proton of 10 MeV is also applicable in the consideration of the effects of non-ionizing energy losses.

3. Damage Produced by Protons

3.1. GaAs/Ge Solar Cells

Figure 16 shows a data plot of the normalised Pmax degradation for GaAs/Ge solar cells. The results represent simulation data for the normalized Pmax degradation against protons fluences for different energies (0.5, 1, 3, and 9.5 MeV).

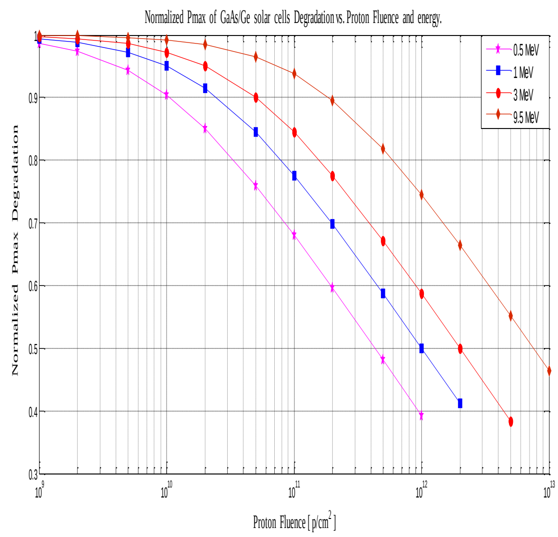

Fig. 2. Normalized Pmax degradation of GaAs/Ge solar cells Vs. proton fluence at different energies.

From the results on figure 2, one can say that for fluences up to $10^{10}cm^{-2}$, Pmax reduces to 90.51, 95.07, 97.3 and 99.22%, respectively for proton irradiation of 0.5, 1, 3, and 9.5 MeV. At a higher proton fluence, 10^{11}cm-2, Pmax is about 68.03, 77.61, 84.47 and 93.77% and at a fluence of $10^{12}cm^{-2}$, Pmax reduces to 39.23, 50.05, 58.75 and 74.48% respectively for proton irradiation of 0.5, 1, 3, et 9.5 MeV.

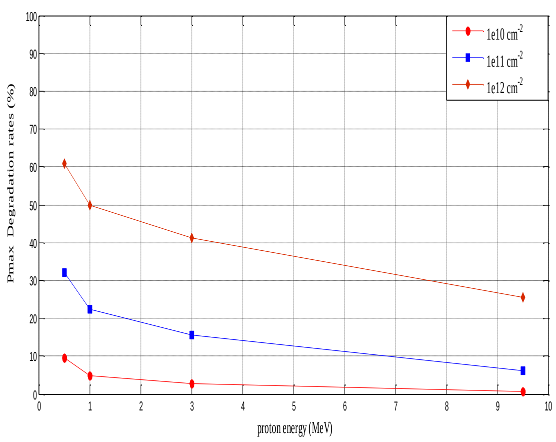

Fig. 3. Degradation rate of Pmax of GaAs/Ge solar cells Vs. protons energy at different fluences.

From equation 2, a curve of damages caused by protons (figure 4) can then be obtained by multiplying the proton fluence, $\varphi(E)$ with the NIEL, S(E), for a given force, E.

That way, data for all energies can be represented by a single characteristic function.

$$D_d = \varphi(E) \cdot S(E) \tag{2}$$

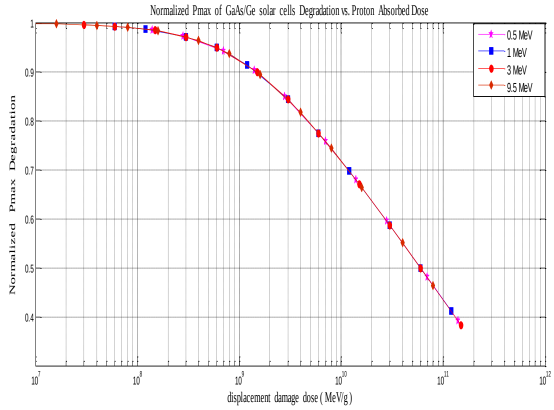

Fig. 4. Pmax of a GaAs/Ge solar cell irradiated with protons Vs. the displacement absorbed dose.

The characteristic curve is produced to model the power loss due to the proton irradiation, and to predict the degradation of a solar cell to displacement defects. Pmax of a photovoltaic cell according to the displacement dose is given by the semi-empirical equation:

$$\frac{P_{max}}{P_{max0}} = 1 - C \, ln \left(1 + \frac{D_d}{D_x}\right) \tag{3}$$

Where:

- P_{max0} and P_{max} represent respectively the maximum power of the solar cells before and after irradiation.
- Dd is the displacement damage dose.
- The parameters C and D_x are constants adapted to experimental data where, C= 0.1295 and D_x = 1.295*10^9 MeV/g for the GaAs/Ge solar cells.

3.2. InGaP/GaAs/Ge Solar Cells

Figure 5 shows the degradation of the normalized Pmax. The results represent simulation data on an InGaP/GaAs/Ge solar cell as a function of protons fluence for different energies (0.3, 1, 2.5, and 10 MeV).

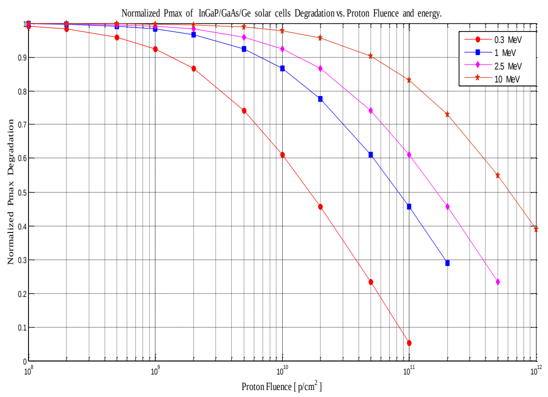

Fig. 5. Degradation of Pmax for a triple junction solar cell Vs. protons fluence for different energies.

From Figure 5, we note that the fluence for the initial Pmax is equal to 4.5 10^9, 2.3 10^{10}, 5 10^{10} and 1.7 10^{11} corresponding to an energy of protons equal to 0.3, 1, 2.5, and 10 MeV respectively. From these results, it appears that there is an increase in the maximum standard fluence with power, but a decrease with an increase of protons energies.

Hence as the degradation of triple junction solar cells GaInP/GaAs/Ge is mainly determined by the displacement in the deterioration of the middle cell GaAs, the NIEL values for protons in the middle cell GaAs were used to calculate the amount of displacement degradation.

Figure 6 shows the correlation of the normalized Pmax of a solar cell InGaP/GaAs/Ge irradiated with protons as a function of the dose of the displacement degradation. The curve produced was calculated from equations 2 and 3 with C = 0.27 and D_x= 9.29*10^8 MeV/g.

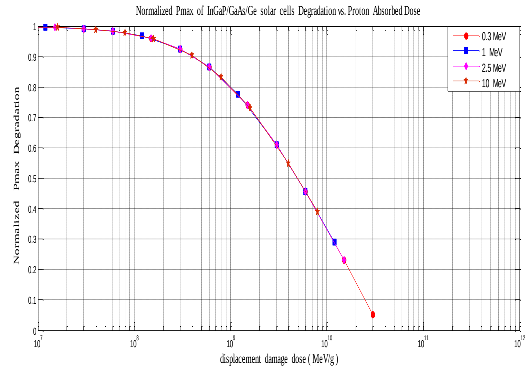

Fig. 6. Normalized Pmax degradation for a triple junction solar cell Vs. protons absorbed dose for different protons energies.

4. Damage Produced by Electrons

4.1. GaAs/Ge Solar Cells

Figure 7 shows the degradation of the normalized Pmax of the solar cell GaAs/Ge as a function of the electrons fluence. The simulation assumed a solar cell irradiated with 0.6, 1, 2.4 and 12 MeV with different electrons fluence ranging from 1×10^{12} to 1×10^{16} cm^{-2}.

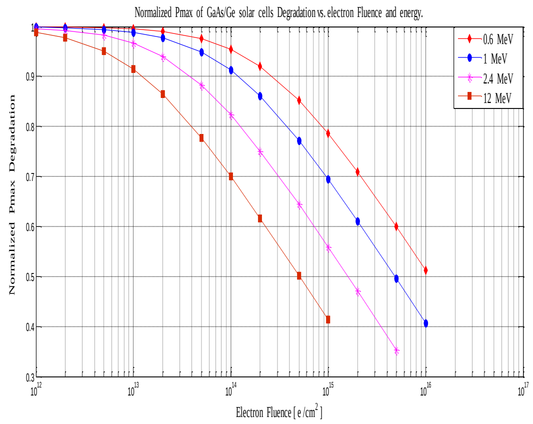

Fig. 7. Normalized Pmax degradation of a GaAs/Ge solar cell Vs. electrons fluence for different energies.

Instead of producing a curve, such as that in figure 4, to compensate for the nonlinear variation coefficients of degradation and NIEL, it is necessary to establish an effective dose of electron energy, Deff. This value is typically chosen equal to 1MeV. Upon irradiation of the solar cells with electrons of energy E, and the fluence is F(E) and S(E) is the NIEL, the actual absorbed dose degradation displacement is given by the following equation:

$$D_{eff} = \varphi(E)\cdot S(E)\cdot\left[\frac{S(E)}{S(E_{ref})}\right]^{(n-1)} \qquad (4)$$

The exponent n is determined experimentally. Its value is 1, for proton irradiation, and (1 <n <2) for the case of electron irradiation, (Eref) is the reference energy for electrons; it is chosen equal to 1MeV for the solar cells.

Figure 8 shows the correlation between the normalized Pmax of a solar cell irradiated with electron and the displacement damage dose, the curve produced was calculated from equations 3 and 4 with n = 1.7, C= 0.1295 and $D_x = 2.7*10^9$ MeV/g.

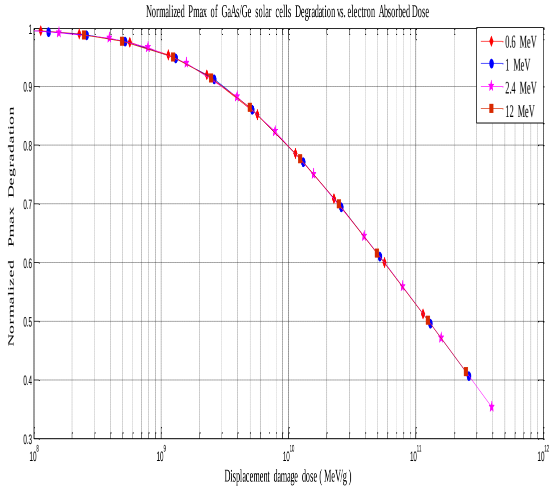

Fig.8. Normalized Pmax degradation of a GaAs/Ge solar cell irradiated with electrons Vs. the displacement dose absorbed.

4.2. InGaP/GaAs/Ge Solar Cells

Figure 9 shows the degradation of the normalized Pmax of the solar cell due to electron irradiation (normalized to its initial value). The simulation results produced here are for a solar cell which was irradiated with 0.8, 1, 2, and 12 MeV at different electrons fluencies ranging from 1×10^{12} to $2\times10^{15}cm^{-2}$.

Note that for a specified level of power degradation, the fluence level decreases with an increase of electrons energy, indicating that higher energy electrons do more damage.

To study the degradation induced by electrons on GaInP/GaAs/Ge solar cells used in space using the displacement dose damage approach, the NIEL curve produced for electrons in GaAs was used to calculate Dd. Figure 1 shows the dependence of the electrons energy and NIEL for GaAs for the energy range of 0.28 to 200 MeV. It should be noticed on figure 1 that the NIEL measured for the electrons increases with energy.

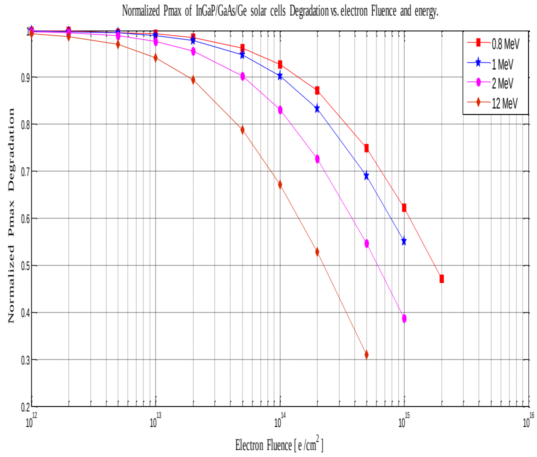

Fig. 9. Normalized Pmax degradation of InGaP/GaAs/Ge solar cell Vs. electrons fluences at different energies.

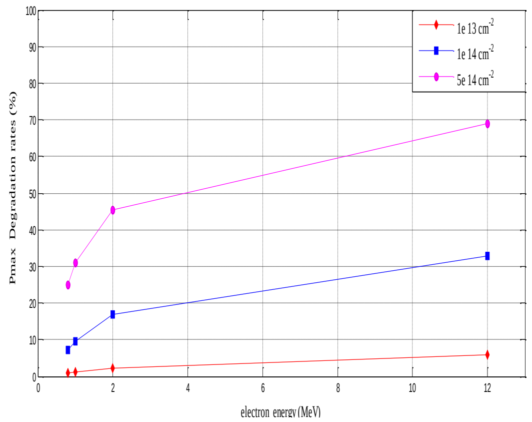

Fig. 10. Pmax degradation rate of the triple junction solar cells Vs. electrons energy at different fluence.

If data in Figure 9 are plotted against the amount of displacement damage by multiplying the fluence by NIEL for a specific energy in solar cells, the curve can be obtained from equation 3 and 4 with n = 1.29, C= 0. 27 et $D_x = 6.06*10^9$ MeV/g as shown on figure 11.

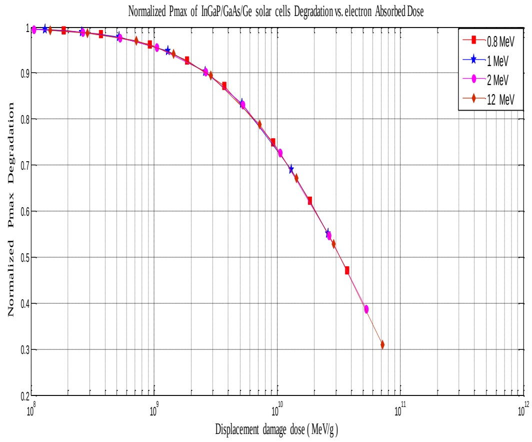

Fig. 11. normalized Pmax degradation of the InGaP/GaAs/Ge solar cell Vs. absorbed dose for different electrons energies.

5. Results and Discussions

On figure 2, we can see that the fluence for the initial values of P_{max} are reduced by 75% to reach 5.5 10^{10}, 1.3 10^{11}, 2.55 10^{11} and 9.5 10^{11} corresponding to proton energies of 0.5, 1, 3, and 9.5 MeV respectively. We easily note the increase in the maximum standard fluence with power, but a decrease with increasing protons energy.

Figure 3 shows the degradation rate of P_{max} as a function of the energy of proton irradiation at different fluencies (10^{10}, 10^{11} and $10^{12}cm^{-2}$). Obviously, the rate of degradation of the electrical parameter P_{max} decreases with the increase of the irradiation energy of the protons. That is to say, the more the energy of the proton radiation is high, the less is the degradation rate of P_{max} at the same protons fluences.

According to the results shown on figure 7, we note that the normalized P_{max} of a GaAs/Ge solar cell increases with the electrons fluence and the energy increase. The degradation energy deposited by the electrons of a given energy is calculated with the use of the equation 2. However, the electron case proves more complicated than the case of proton because the coefficients of degradation vary more linearly with NIEL.

Figure 10 shows the degradation rates of P_{max} as a function of the energy of electrons with different irradiation fluences (1013, 1014 and 5*1014 cm^{-2}). Obviously, the rate of degradation of the electrical parameter P_{max} increases with an increase of the irradiation energy of the electron, i.e., the higher the energy of the electrons, the higher the rate of degradation of Pmax at the same electrons fluence.

6. Conclusion

This study is devoted to the degradation of GaAs/Ge and triple junction solar cells under the effect of different electron and proton fluences. In conclusion, one can say that the electric properties of GaAs/Ge solar cells degrade as proton fluencies increases and the higher the energy of protons the less degradation rates of the electric properties. That is to say, the more the proton energy irradiation is high, the less the degradation rates of P_{max} at the same protons fluencies.

For triple junction InGaP/GaAs/Ge solar cells, it was noted that for a specified level of power degradation, the fluence level decreases with an increase of electrons energy, indicating that higher energy electrons do more damage.

Finally, data from figures 3 and 10 can be used to predict the irradiation behaviour of GaAs/Ge and InGaP/GaAs/Ge solar cells in space conditions.

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