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Evaluation of the degradation of solar cells in space

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Abstract

We discuss the limit of validity of the procedure which is used to predict the End Of Life (EOL) performances of a solar cell in space. This procedure consists to measure the performances of a cell after it has been irradiated at the EOL fluence during a time very short compared to the lifetime in space, i.e. with a considerably larger flux. We demonstrate that this procedure is not valid when the defects created by the irradiation anneal during the irradiation. This is for instance the case of GaInP cells, which are at the heart of the modern high efficiency multijunction space solar cells. To illustrate the effect of injection annealing during irradiation, we model the time dependence of the concentration of the irradiation induced defects in GaInP in different practical situations.

Keywords

Solar cell; Degradation; Irradiation; End of life; Defect.

INTRODUCTION

Solar cells are the mean to deliver energy to spacecrafts. These cells are submitted to irradiation with energetic particles *(electrons and protons)* present in space, and these particles produce atomic displacements in the crystalline structure of the cells. Some of the defects resulting from these displacements act as so-called recombination centers, i.e. trap free carriers induced by the solar illumination, thus reducing their collection by the junction of the cell, and consequently degrading its electrical performances. This degradation, increasing with time, limits the cell lifetime and it is therefore necessary to evaluate it for a given mission (*characterized by a duration, a temperature and a flux of particles*), i.e. to get the knowledge of its end of life (EOL) performances.

The aim of this communication is to describe neither the mechanisms for defect creation nor the role of these defects on the cell performances, these questions being already extensively documented (*see for instance refs. 1, 2*). It is to examine the validity of the technique of prediction made to evaluate this degradation and to illustrate its limit for situations where it clearly leads to misleading results.

ANALYSIS OF THE PROCESS OF DEGRADATION

The standard technique for evaluating the degradation of a solar cell in space consists in performing an irradiation with a flux of specific particles of a given energy in a time t_e very short compared to the duration D of the mission (*for practical reasons*), at a fluence F (*particle flux I times duration D of the mission: F = D I*). To obtain the same fluence than in space, the flux of irradiation in the lab must be: $I' = I\, D/t_e$, i.e. large compared to the flux I encountered during the space mission. The irradiation is followed by an electrical characterization (*usually a measurement of the Current-Voltage characteristics*) giving a measure of the degradation.

The assumption made, but never verified, is that the defects created by the irradiation remain stable during the irradiation. This is the case of Si solar cells designed to operate at room temperature (*on earth satellites*) because irradiation at 300K induces defects some of which have been annealed quasi instantaneously while others are stable. When this assumption is not fulfilled, namely when defects are created and annealed simultaneously, it can happen for a long enough time t_s that the rate of annealing, because increasing linearly with the defect concentration C(t), becomes of the order of the rate of defect creation. Then, when the rate of annealing balances the rate of creation, C(t) saturates.

Under the flux I, the concentration of created defects C_c varies versus time t as:

$$C_c(t) = K_0 I t \quad (1)$$

where K_0 is the so called defect introduction rate (*number of defects created per unit length of path of the irradiating particle*), which depends on the nature of the material, the nature and energy of the particle.

The concentration C_a of the defects which anneal, varies as:

$$C_a(t) = C(t) \exp(-A t) \quad (2)$$

where the rate A is characterized by an activation energy E_a:

$$A = A_0 \exp(-E_a/kT) \quad (3)$$

The resulting defect concentration at the saturation time t_s, $C(t_s)$, is smaller than the value $C_c(t_s)$ expected if no annealing had taken place: the degradation evaluated by the standard technique is then overestimated. The difference $C_c(t_s) - C(t_s)$ depends on parameters related to the material (*through A_0, E_a*), the irradiation (I, D) and external conditions (*T and eventually –see below- the density of injected carriers*).

When the annealing is induced by the injection of minority carriers (*as we shall see below, this injection can be induced by the ionization produced by light illumination or irradiation*), the parameter A_0 depends on the density of injection J. Then, A must be replaced by:

$$A_i = A_{oi} J^2 \exp(-E_i/kT) \quad (4)$$

where the activation energy E_i is such that $E_a - E_i$ is the energy released by carrier trapping on the defect site. The differential equation describing C(t):

$$dC(t)/dt = K_0 I + (A C(t) - dC(t)/dt) \exp(-At) \quad (5)$$

is solved numerically. Annealing decreases $C_c(t)$ when the associated time constant A^{-1} becomes smaller than D.

We illustrate in Figure 1 the T and J dependences of A for GaInP when the annealing is induced by carrier injection, as we describe in the next sections.

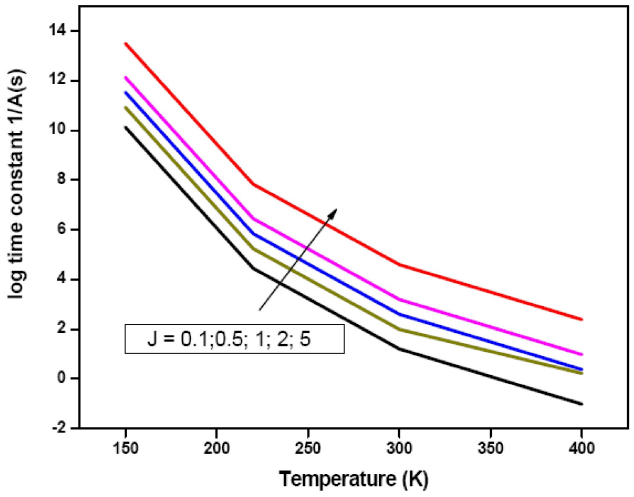

Figure 1 : Temperature dependence of the time constant of injection annealing in GaInP for different levels of illumination (in AM0 unit) inducing this injection.

Hence, for instance, a significant saturation of C(t) is expected at 300K, with an illumination intensity of 5 AM0, for times t longer than 16 s (*$\log A^{-1} = 1.2$*). The degree of this saturation, which depends on t for a given value of J, is calculated section III for specific cases.

Eventually, C(t) saturates when:

$$dC_a/dt = dC_c/dt \quad (6)$$

i.e. for a time t_s given by:

$$K I = \exp(-At_s) (dC(t_s)/dt - A C(t_s)) \quad (7)$$

The defect concentration at t_s being smaller than the value expected if no annealing had occurred, the degradation evaluated with the standard technique is therefore overestimated. This overestimation is dependent on the material parameters (A_0, E_a), the irradiation (K_0) and external conditions (*T, J, D*).

ILLUSTRATIONS FOR SPACE MISSIONS

This situation is not unusual in practice: irradiation produces several types of defects in the materials used for space solar cells (*Si, GaAs, GaInP*), some of which being mobile below room temperature, while the irradiations are usually performed at 300 K. This question never appear up to now because tests were performed at 300 K, exclusively on Si, GaAs and GaInP cells, i.e. on materials in which the defects produced at this temperature are stable. However, as we examine below, defect annealing can be enhanced by the ionization produced either by the irradiation itself, or by light illumination and be significant even at low temperature if this ionization is large enough. We discuss here this case of injection annealing.

It was suggested in the seventies to explain observations such as the impossibility to detect interstitials in

Si or any defect in p-type Ge[3], even after irradiation at 4 K, that the energy released by a minority carrier, when it is trapped on a defect site, could enhance the migration of this defect[4-6]. Later, annealing of irradiation induced defects produced by injection of minority carriers in a junction has been observed and quantitatively analyzed, first in GaAs[7] and subsequently in GaInP[8,9], allowing to derive the parameters which define this injection annealing (*the cited references contain all the authors having worked on this question*).

To illustrate the potential importance of injection annealing on the evaluation of the degradation, we consider the case of GaInP because this material is used to make the subcell limiting the performances in the 28% three junctions cells actually produced for space applications (*earth satellites as well as deep space missions*). We calculate the time dependence C(t) for a variety of solar illuminations (*0.03 to 7 AM0*) and temperatures (*120 to 400 K*), in order to examine the limit of validity of the standard technique for evaluating the degradation in each case. We do not take into account a possible thermal annealing. We illustrate for four cases, corresponding to specific situations (*the indicated temperatures are approximate since depending on the distance to the planet*), with figures 2 to 5:

a) around Jupiter (*120 K, 0.03 AM0*) for an irradiation fluence of 10^{14} electrons cm^{-2} during two months,
b) around Earth (*300 K, 1 AM0*) for an irradiation fluence of 10^{14} electrons cm^{-2} during one year,
c) around Venus (*320 K, 2.25 AM0*) for an irradiation fluence of 10^{13} cm^{-2} during one week,
d) around Mercury (*370 K, 6.25 AM0*) for an irradiation fluence of 10^{13} cm^{-2} during one week.

In this case, A is far larger than the duration of the mission and the annealing effect is negligible. In EOL condition, the defect concentration (*5 10^{14} cm^{-3}*) and consequently the degradation, is the one predicted by the standard test.

Then, owing to the length of the mission, the annealing time constant is shorter than the duration of the mission and a saturation occurs: the defect concentra-

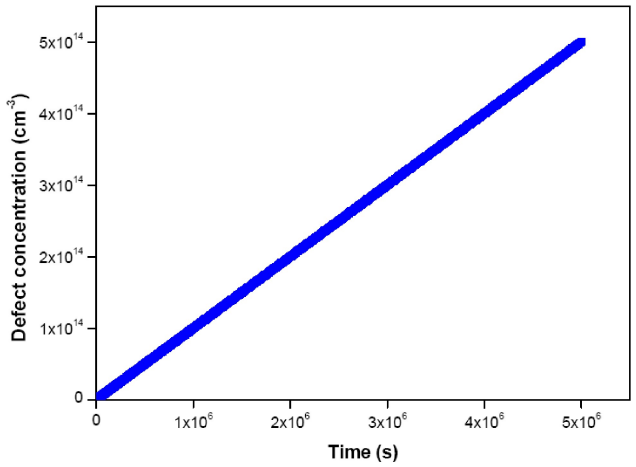

Figure 2 : Concentration of defects versus time in GaInP induced at 120 K by 1 MeV electrons (case a: 120 K, 0.03 AM0) for an irradiation fluence of 10^{14} electrons cm^{-2} during $5x10^6$ s.

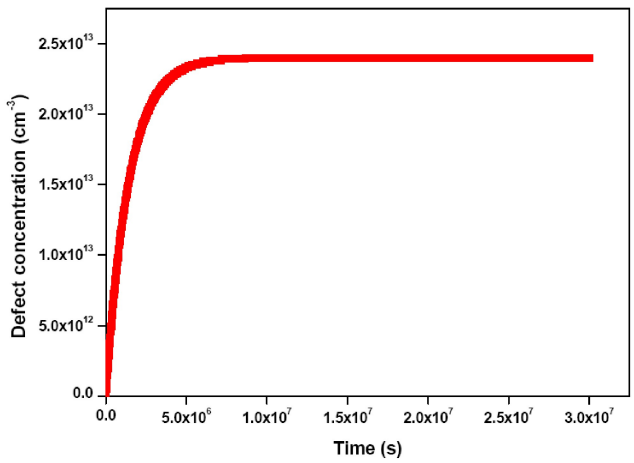

Figure 3 : Concentration of defects versus time in GaInP induced at 300 K by 1 MeV electrons (case b: 300 K, 1 AM0) for an irradiation fluence of 10^{14} electrons cm^{-2} during $3x10^7$s.

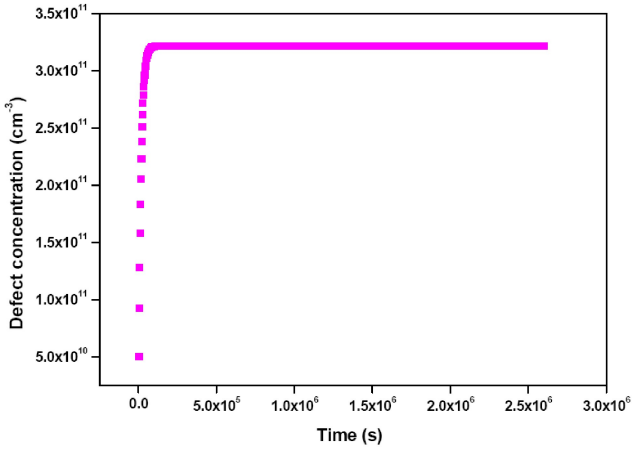

Figure 4 : Concentration of defects versus time in GaInP induced at 320 K by 1 MeV electrons (case c: 320 K, 2.25 AM0) for an irradiation fluence of electrons 10^{13} cm^{-2} during $6x10^5$ s.

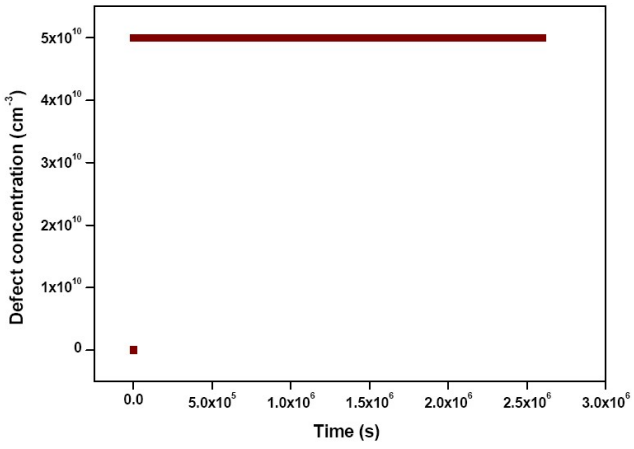

Figure 5 : Concentration of defects versus time in GaInP induced at 370 K by 1 MeV electrons (case d: 370 K, 6.25 AM0) for an irradiation fluence of 10^{13} electrons cm^{-2} during $6x10^5$ s.

tion reaches a maximum ($2.4x10^{13}$ cm^{-3}) more than 10 times smaller than the value ($7x\ 10^{14}$ cm^{-3}) foreseen if no injection annealing had occurred.

Finally, in both cases c and d described in figures 4 and 5, A is short and all the created defects are annealed quasi instantaneously. It remains a very small concentration of defects, equal to the concentration created by the irradiation within the annealing time constant.

TEST OF DEGRADATION

Injection annealing can also have strong consequences on the result of an irradiation test which is undertaken to predict the EOL degradation of a cell. Indeed, as already mentioned, a test irradiation is performed in a duration short compared to the duration of the mission, i.e. with a far larger intensity of irradiation and thus with a far larger injection level. Consider again the case of GaInP irradiated at 300 K for an EOL fluence of 10^{14} electrons of 1 MeV per cm^2. When the duration of the test is larger than 1000 s (Figure 6), the intensity of the irradiation beam induces a low concentration of minority carriers, injection annealing is negligible and the created defect concentration is the expected one. However, for shorter (*perhaps unrealistic but good for illustration*) durations (*see* Figures 7 and 8), the injection level increases enough to induce annealing. Then, the defect concentration measured after the test is completed is smaller than the value expected if no annealing had occurred. Of course, the effect will be similar for longer durations if the temperature is larger.

Consequently, the result of a test depends critically on the test conditions (*temperature, fluence and duration*) which are different from the conditions of the mission. Prediction with the test procedure and actual degradation in space can give quite different results.

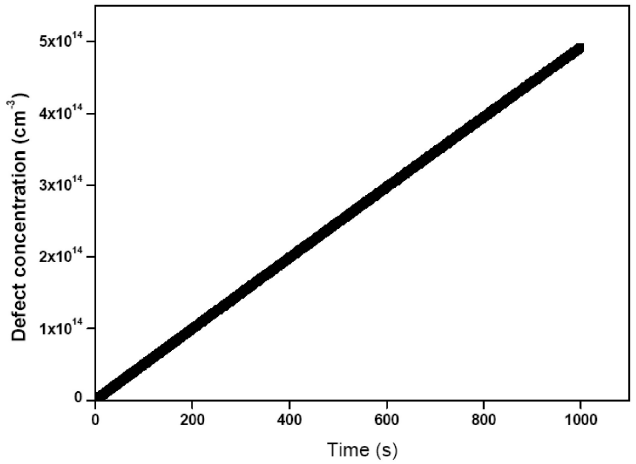

Figure 6 : Time dependence of the defect concentration induced in GaInP by 1 MeV electron irradiation at 300 K at a rate of 10^{11} $cm^{-2}.s^{-1}$. The test is conducted for an irradiation fluence of 10^{14} electrons cm^{-2} during 10^3 s

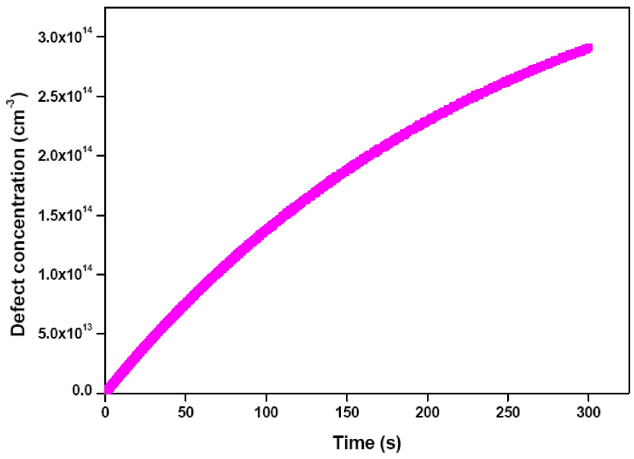

Figure 7 : Time dependence of the defect concentration induced in GaInP by 1 MeV electron irradiation at 300 K at a rate of 3 10^{11} $cm^{-2}.s^{-1}$. The test is conducted for an irradiation fluence of 10^{14} electrons cm^{-2} during 300 s

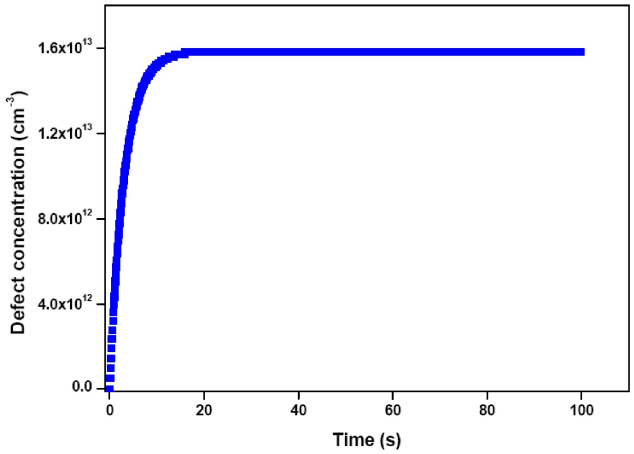

Figure 8 : Time dependence of the defect concentration induced in GaInP by 1 MeV electron irradiation at 300 K at a rate of 10^{12} $cm^{-2}.s^{-1}$. The test is conducted for an irradiation fluence of 10^{14} electrons cm^{-2} during 100 s

CONCLUSION

When the defects created by an irradiation with energetic particles anneal at the same time they are created, which is a common case for the materials used to produce solar cells for spatial applications, then the procedure which is used to measure the End of Life performances of these cells is not valid.

We illustrated the effect of such annealing, taking as example the annealing induced by minority carrier injection in a GaInP cell which constitutes the limiting subcell in the actual high efficiency multijunction space cell. In case of a multijunction cell this analysis should be extended to the GaAs and Ge subcells and to the effect of thermal annealing already documented[10-12].

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