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10 MeV proton irradiation effects on GaInP/GaAs/Ge concentrator solar cells and their component subcells

M. Ochoa[a,*], E. Yaccuzzi[b,c], P. Espinet-González[a], M. Barrera[b,c], E. Barrigón[a], M.L. Ibarra[b,d], Yedileth Contreras[a], J. García[b,c], E. López[a], M. Alurralde[b], C. Algora[a], E. Godfrin[b], I. Rey-Stolle[a], J. Plá[b,c]

[a] Instituto de Energía Solar – Universidad Politécnica de Madrid, Av. Complutense 30, 28040 Madrid, Spain
[b] Departamento Energía Solar - Gerencia Investigación y Aplicaciones - CNEA, Av. General Paz 1499, 1650 San Martín, Argentina
[c] Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Av. General Paz 1499, 1650 San Martín, Argentina
[d] Universidad Nacional de General San Martin, Martín de Irigoyen 3100, 1650 San Martín, Argentina

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ABSTRACT

In this paper, the experimental results of a 10 MeV proton irradiation on concentrator GaInP/GaAs/Ge lattice-matched triple-junction solar cells and their corresponding subcells are examined. Electro-optical characterization such as external quantum efficiency, light and dark I-V measurements, is performed together with theoretical device modeling in order to guide the analysis of the degradation behavior. The GaInP (on Ge) and Ge cell showed a power loss between beginning of life and end of life of about 4% while the GaInP/GaAs/Ge and GaAs solar cells exhibited the highest damage measured of 12% and 10%, respectively for an irradiation fluence equivalent to an 8-years satellite mission in Low Earth Orbit. The results from single-junction solar cells correlate well with those of triple-junction solar cells. The performance of concentrator solar cells structures is similar to that of traditional space-targeted designs reported in literature suggesting that no special changes may be required to use triple junction concentrator solar cells in space.

1. Introduction

Because of the radiation belts surrounding our planet, satellites in Low Earth Orbits (LEO) operate in a harsh radiation environment. Taking into account the relative motion between the satellite and the bombarding particles, we can consider that proton and electron irradiation inside the inner Van Allen belt have an isotropic incidence. Most part of the damage produced is due to protons with energies ranging from a few keV to hundreds of MeV. Moreover, the satellite is unprotected from cosmic radiation hitting with several kinds of energetic particles. Accordingly, among the key goals of space power engineering are to understand and develop photovoltaic devices that can perform well in this severe environment.

In the past decade, the lattice-matched GaInP/GaAs/Ge triple-junction solar cell (3JSC) has been chosen for space power generation in spacecrafts and satellites mainly as a result of its high efficiency (~30% at AM0), relatively high power-to-mass ratio and good radiation hardness [1–3]. Other existing multijunction solar cell architectures capable of achieving higher efficiencies than the conventional 3J – namely, inverted metamorphic (IMM) solar cells, solar cells including dilute nitride subcells, multijunction devices fabricated through wafer bonding, among others– have not yet fully demonstrated a radiation hardness comparable to the 3JSC case (see for instance Ref: [2]).

Despite the good properties of the GaInP/GaAs/Ge 3JSC at beginning of life (BOL), its electrical performance gets degraded when exposed to charged particles in space such as protons and electrons. Obviously, such radiation damage has a deleterious impact on the electrical performance of the cells (mainly via the degradation of their minority carrier properties [4]) and hence the analysis of solar cell performance emulating the conditions found in real space missions is a must in order to envisage the optimum configuration of the devices and predict their operation in space.

Although extensive literature exists about radiation damage of 3JSCs [1,5–7], the radiation degradation analysis of these cells remains a topic of great scientific interest and debate, as a result of the high complexity of the multijunction structure. Besides, most of the works related to proton damage in multijunction solar cells analyze separately either single junction cells or triple-junction solar cells [8,9]. The analysis of each subcell inside a triple-junction has also been studied indirectly by using different irradiation particle energies to control the

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[*] Corresponding author.
E-mail address: mario.ochoa@ies-def.upm.es (M. Ochoa).

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depth and thus the subcell to be damaged [9,10] and by using electroluminescence characterization techniques capable of reconstructing the electrical characteristics of each subcell [11,12]. Even though this indirect technique gives excellent results, it does not provide a direct access to the radiation damage in each subcell. Another motivation to increase the number of degradation studies in conventional 3JSCs is that such structure is the baseline of the so-called 4-junction lattice matched multijunction solar cell which inserts a 1 eV dilute-nitride cell between the GaAs and Ge subcells [13,14].

In this work we expand the experimental data available to understand the degradation in space of GaInP/GaAs/Ge triple junction solar cells and, in particular we do so by analyzing the radiation resistance of devices whose semiconductor structure has been designed to operate under concentrated light. Space applications of this type of devices would also range from near sun missions [15] to alternative space solar panel designs where concentrators are used to reduce the total weight of the panels and increase their efficiency [16]. It should be stressed that devices tested in this work were designed to operate under concentration at about 1000 suns, and this is probably beyond the actual spacecraft tracking accuracy for space concentrator systems. This fact would imply that larger devices should be used for potentially practical applications. Anyway, it is expected that results obtained here will at least hold, given the influence of perimeter recombination in our tiny devices could be considered as not the optimum case for current practical applications.

In this study, we combine degradation experiments of concentrator triple-junction solar cells (GaInP/GaAs/Ge) together with their corresponding component subcells in the same experiment and report on the effects of 10 MeV proton irradiation on these cells. The solar cells have been experimentally characterized in situ –i.e. inside the irradiation chamber– by dark and light I-V measurements and *ex-situ* by deep level transient spectroscopy, and quantum efficiency. Technology Computer Aided Design (TCAD) from Silvaco tools has been used to simulate the solar cells and analyze the experimental findings.

2. Experimental and modeling

2.1. Experimental design and setup

10 MeV proton energy is the standard energy used to simulate a space irradiation. The selected fluence represents the fluence received during a space mission in a LEO during 8 years and it was determined using the method previously developed at DES [17]. This method considers the equivalence between space proton spectrum and the 10 MeV monoenergetic proton fluence based on the primary knock-on atoms (PKA) obtained using the TRIM (transport of ions in matter) software [18] for a simplified semiconductor structure representative of each sample. The details for the application of this method are published elsewhere [17,21]. The spatial damage was simulated using a total spatial dose of 1.23×10^{12} proton cm^{-2} calculated for III-V devices using the SPENVIS facility (see Ref. [8]). The resulting fluence calculations for all devices were used to design the experiment. Accordingly, to emulate the radiation damage suffered in orbit, III-V solar cells were irradiated by a 10 MeV proton beam produced by the tandem Van de Graaff accelerator of CNEA (Tandar). All experiments were performed under high vacuum using a specially developed chamber installed in one of the experimental lines of the accelerator (for details see also [17–21]). In order to spread the beam, a 10 µm-thick aluminum foil was installed intercepting the beam path about 6 m before the chamber. The resulting beam intensity uniformity at the target position was determined prior to the experiment by using an array of 9-Faraday cups (FC) installed a few centimeters from the sample holder. The beam current in each FC was measured using a Keithley 6514 electrometer. The overall beam uniformity was better than 5% over the whole target area (diameter ~ 9 cm).

During the experiments the samples were positioned in place of the central FC (FC1). Fluence integration and corrections were applied in each case using a calibration factor between a reference FC and FC1 obtained in the previous beam distribution measurement. To observe the degradation of the devices during irradiation, the beam was interrupted at four different stages for each solar cell, allowing the in-situ measurement of dark and light I-V curves to take place.

The samples were mounted on a rotatable sample holder able to move without breaking the vacuum to irradiate all of them (i.e. they were sequentially moved to the position of FC1 where they were irradiated one by one). In order to reduce the radiologic activation of the copper holders (see next section), they were shielded by aluminum masks (individual collimators), and thick enough to stop the beam, but featuring appropriate holes just in front of the solar cells for the irradiation. All cells received four accumulated fluences reaching a final total fluence of about $5\cdot10^{11}$ p/cm^2.

2.2. Device fabrication

For this study we grew and manufactured lattice-matched GaInP/GaAs/Ge 3JSCs as well as component cells for each subcell type, namely, single junction GaAs and Ge solar cells and GaInP/Ge solar cells with active Ge subcells cells (see Table 1). The layer design (in particular, the tunnel junctions and top cell emitter) was adapted to concentrator operation. The active germanium subcell was formed by phosphorous diffusion from a GaInP nucleation layer. For further details on the growth see Refs. [22,23].

Solar cell epiwafers were processed into small area solar cell devices (see Table 1) following a procedure very similar to that described in [3]. Photolithography was employed to define the front grid, with inverted square symmetry and a shadowing factor of around 4%. The front (AuGe/Ni/Au) and back (Au) metal contacts were deposited by thermal evaporation. The wet mesa etching process applied to isolate the devices consisted of an optimized sequence of etching steps using acid and basic solutions. No anti-reflection coating (ARC) was deposited onto the samples. Finally, solar cells were individually encapsulated by soldering each of them with Sn/Ag or indium paste to a copper plate (which acted both as the rear contact and the heat sink for the device). The front contact was made using Al wire bonding to a PCB.

2.3. In situ and ex situ device characterization

The cells were characterized ex situ before and after irradiation by quantum efficiency measurements, deep level transient spectroscopy and light I-V measurements. External quantum efficiency (EQE) has been measured with a setup using a Xe-lamp as white light source which goes through a Horiba TRIAX 180 monochromator and an external filter wheel. The light is chopped and a monitor cell is used to compensate for any intensity fluctuations coming from the Xe-lamp. Light I-V measurements were performed in situ before and after each proton fluence using a Sciencetech solar simulator with AM0 filter coupled to the irradiation chamber through a borosilicate window and a source measure unit (SMU) Keithley 2602 A with four-wire configuration to avoid cable losses. In addition, *ex situ* light I-V measurements were carried out under standard test conditions at BOL and end

Table 1
Solar cell structures subjected to 10 MeV proton irradiation. The GaAs solar cell was grown on a highly doped p-type GaAs substrate while the other solar cells were grown on Ge substrates. Two different devices have been irradiated for each solar cell and their corresponding fluences are shown in the last two columns.

Junctions	Active area (cm^2)	Final fluences (10^{11} p/cm^2)	
GaInP/Ge	0.01	3.35	3.81
GaAs	0.01	2.93	4.99
Ge	0.1	3.59	3.6
GaInP/GaAs/Ge	0.01	3.76	4.78

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