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ORIGIN OF THE DEGRADATION OF TRIPLE JUNCTION SOLAR CELLS AT LOW TEMPERATURE

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ABSTRACT

The degradation of solar cells under irradiation by high energy particles (electrons, protons) is the consequence of the introduction of defects trapping minority carriers, which are then not collected by the junction. However, at low temperature, defects located in the space charge region can also induce a tunneling current that results in an apparent decreases of the maximum power. The degradation produced by this tunneling current can depend on temperature, since the concentration of defects created by an irradiation is usually temperature dependent, and can be larger than the degradation associated with carrier recombination. For instance, as we shall see below, an irradiation with 1 MeV electrons at 120 K with a fluence of 3.0 x 10^{15} /cm^2 induces a decrease of less than 10 % in the short-circuit current (I_{SC}) and open-circuit voltage (V_{OC}) of triple junction (TJ) cells, but a decrease of about 40 % in the maximum power (P_{MAX}), which implies that more than half of the total degradation of P_{MAX} should be assigned to another loss mechanism, tunneling in this case. In this work, we demonstrate that this additional degradation must indeed be ascribed to a tunneling process and we investigate the variation of the tunneling current versus fluence induced by electron irradiation in TJ cells, in order to tentatively ascribe the tunneling components to specific sub-cells.

1. INTRODUCTION

Gallium-Arsenide (GaAs) based TJ solar cells, made of three sub-cells: Gallium-Indium-Phosphide (GaInP), Gallium-Arsenide (GaAs) and Germanium (Ge), are state-of-the-art solar cells for powering satellites [1]. These cells are also selected for deep space missions [2-4]. In this respect, it is necessary to determine the temperature dependence of their electrical characteristics, in particular following electron and proton irradiations. This study deals with TJ solar cells developed by AZUR SPACE Solar Power GmbH for the planned Jupiter ICy moons Explorer (JUICE) mission of the European Space Agency (ESA). To investigate the performances of these cells, the corresponding environmental conditions: temperature around 120 K, weak sun light intensity (3.7 % AM0), high energy electron and proton irradiations, have to be reproduced in the laboratory. The work consists of simulating these specific conditions and to monitor the changes induced by irradiation of key parameters, such as short-circuit current (I_{SC}), open-circuit voltage (V_{OC}), maximum power (P_{MAX}), fill factor (FF), and conversion efficiency (η).

2. EXPERIMENTAL CONDITIONS

In order to reproduce the irradiation conditions of a mission to Jupiter, the cells are placed in a liquid nitrogen cryostat whose chamber is connected to the accelerator beam through a thin stainless steel foil. The solar simulator satisfying the specific solar spectrum (equivalent to 3.7 % AM0) has been realized by a combination of a Xenon (Xe) and Quartz Tungsten Halogen (QTH) lamps separated by a cold filter. The adjustment of the simulator has been realized by secondary working standards which have been derived from reference standards assuming a linear dependence of I_{SC} and light intensity. TJ solar cells have a size of 4 cm^2 and a thickness of 80 or 140 μm. The electron irradiation has been carried out at 1 MeV using the SIRIUS facility of LSI (Laboratoire des Solides Irradiés) in Ecole Polytechnique. The cell temperature during irradiation was set at 123 K and three fluences were used: 7.5 x 10^{14}, 1.5 x 10^{15}, and 3.0 x 10^{15} cm^{-2}.

3. ELECTRON IRRADIATION OF TRIPLE JUNCTION SOLAR CELLS

In the course of irradiation, we noticed at low temperature the appearance of an apparent "shunt" effect decreasing P_{MAX} significantly, compared to the decrease expected from the changes of V_{OC} and I_{SC} values. Fig. 1 shows the relative variations of I_{SC}, V_{OC}, and P_{MAX} values versus electron fluence. As expected I_{SC}, V_{OC}, and P_{MAX} decrease as the fluence increases. After a fluence of 3.0 x 10^{15} cm^{-2}, P_{MAX} has been degraded up to about 60 % of the original value. However, I_{SC} and V_{OC} have decreased to 92 % and 95 %, respectively. The amount of degradation observed for P_{MAX} is therefore much larger than expected from the degradation of I_{SC} and V_{OC}.

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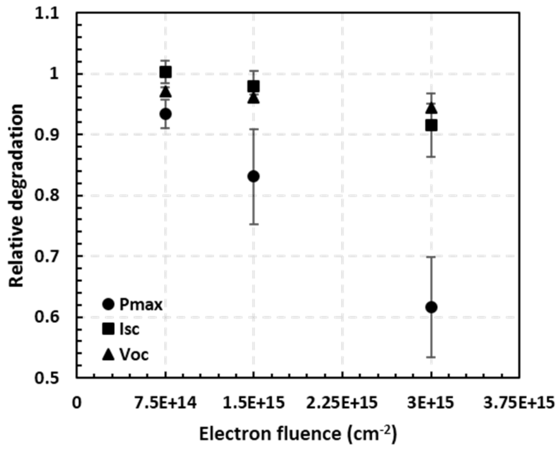

Figure 1. Relative degradation of I_{SC}, V_{OC}, and P_{MAX} measured at 123 K directly after 1 MeV electron irradiation. All values have been divided by BOL values and shown with standard deviations.

As illustrated in Fig. 2, this large degradation correlates with a decrease of the current under light illumination as the voltage increases. The Beginning of Life (BOL) current-voltage (I-V) characteristics under illumination exhibits a fill factor FF of about 90 %. However, after electron irradiation, the End Of Life (EOL) I-V characteristics drops clearly starting from 1 V, resulting in a strong decrease of FF down to 65 %.

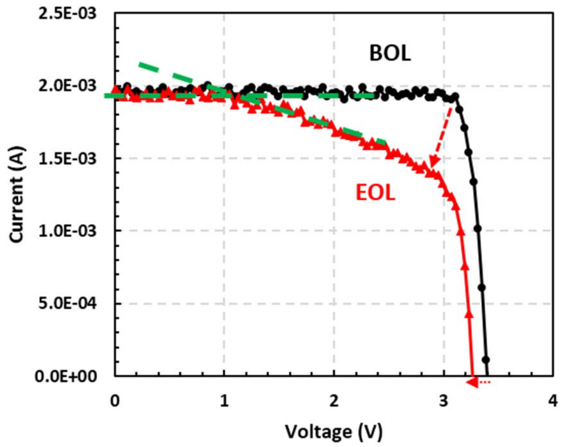

Figure 2. Light I-V characteristics of a TJ solar cell at 123 K before and after 1 MeV electron irradiation (1.5 x 10^{15} /cm^2).

Fig. 2 also shows that EOL light I-V characteristics are not linear. The slope of I-V curve increases at 1 V resulting in a significant loss of power generation. This decrease of current as voltage increases cannot be ascribed to a normal shunt effect. As shown in Fig. 3, the subtraction of the EOL light currents from BOL light currents also shows a non-linearity. This demonstrates that the change of I-V characteristics does not come from a shunt resistance. In the dark I-V characteristics (see Fig. 4), it is clearly observed that, after irradiation, the dark current increases abruptly from 0.5 V. This increase can be correlated with the drop of the photo current in the light I-V characteristics starting at 1 V. This correlation between the degradation of P_{MAX} and the increase of the dark current (I_{Dark}), which we label now excess current, after the irradiation has been quantitatively verified by plotting P_{MAX} versus the value of I_{Dark}, at 2 V.

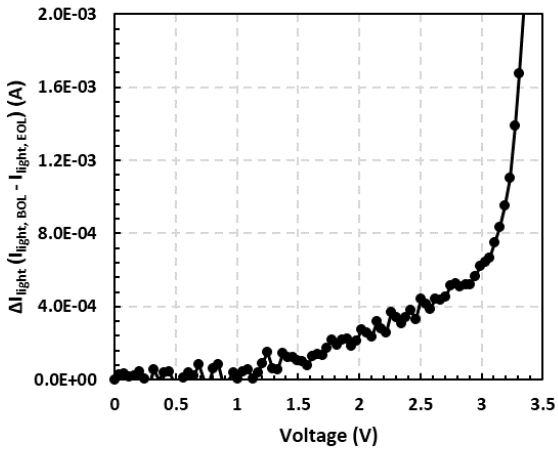

Figure 3. Difference of currents under the illumination: subtraction of EOL light I-V values from BOL light I-V values (linear scale) of a TJ solar cell at 123 K before and after 1 MeV electron irradiation (1.5 x 10^{15} /cm^2).

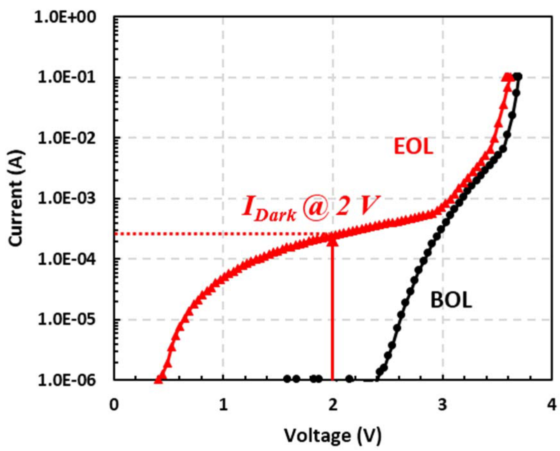

Figure 4. Dark I-V characteristics (log scale) of a TJ solar cell at 123 K before and after 1 MeV electron irradiation (1.5 x 10^{15} /cm^2).

Fig. 5 shows indeed that there is a decreasing tendency of P_{MAX} as I_{Dark} increases. The data in the figure are labelled in order to illustrate their dependence on the fluence: as the fluence increases, I_{Dark} increases, which in turns leads to higher P_{MAX} degradation. It remains to understand the origin of this excess current at low voltage in the dark I-

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V characteristics. For this, we studied the dependence of this current versus temperature and fluence.

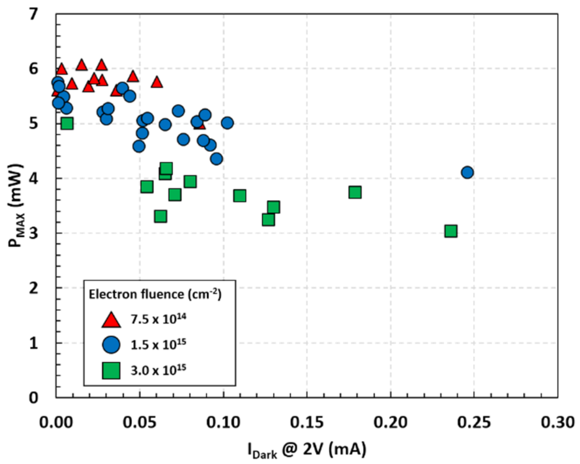

Figure 5. Relationship between P_{MAX} and I_{Dark} at 2 V.

4. VARIATION OF THE DARK CURRENT VERSUS FLUENCE AND TEMPERATURE

In order to reveal the relationship between the decrease of P_{MAX} and the dark current, we have irradiated a TJ cell at low temperature with increasing fluences. As the fluence, i.e. the defect concentration, increases, the threshold voltage at which the excess dark current starts to appear decreases. (Fig. 6)

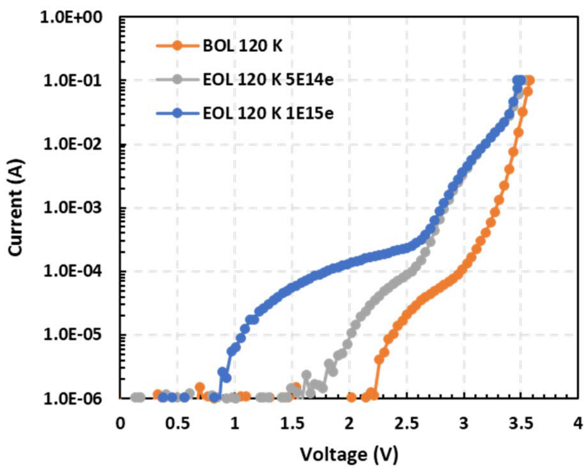

Figure 6. Dark I-V characteristics of a TJ cell after two accumulative fluences.

Thus, the existence of this excess current is directly related to the presence of defects. Then, we tried to determine which part of the cell is responsible for this excess current. For this, we investigated component cells, i.e. cell structures in which only one of photovoltaic pn junctions (top, middle and bottom) is active, in order to determine from which subcell the excess current originates.

The results are shown in Fig. 7: clearly, before irradiation, the excess current comes from the Bottom (Ge) subcell. Following irradiations, top and bottom cells exhibit excess current while the middle cell does not.

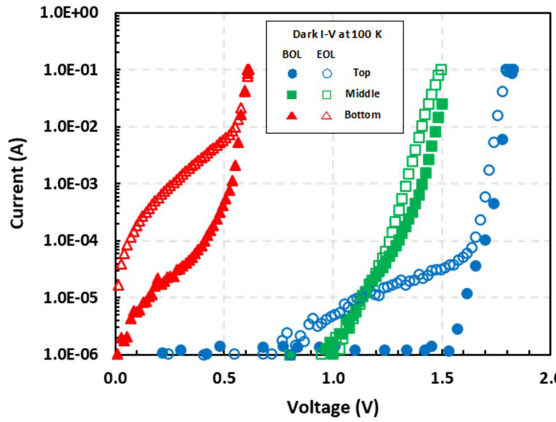

Figure 7. Dark I-V characteristics of top, middle and bottom component cells at 80 K before irradiation and after 1 MeV electron irradiation (3.0 x 10^{15} /cm^2).

We finally investigated the temperature dependence of the excess current in the bottom cell. The result described in Fig. 8 shows that the excess current is temperature independent. The dark current increases faster as the temperature increases, due to the temperature dependence of the barrier height of the junction. In fact, the current which changes depending on the temperature is the thermal current regime; the other part of the current, the excess current, (see the red dotted line in Fig. 8) is not modified by changing the temperature.

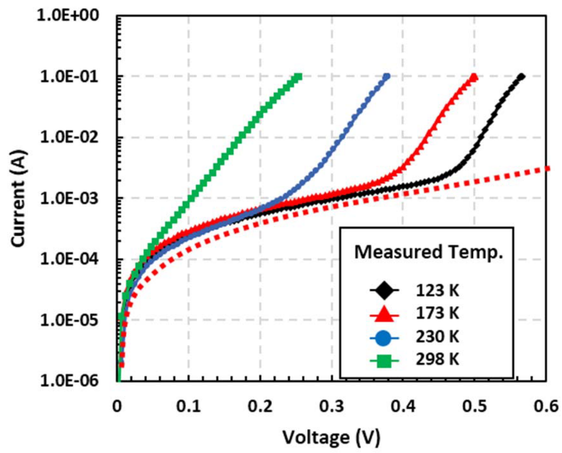

Figure 8. Dark I-V characteristics of a Ge bottom cell at various temperatures after 1 MeV electron irradiation and annealing at 123 K.

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5. ORIGIN OF THE EXCESS CURRENT

Because the excess current is not temperature dependent and because its amplitude increases (to some extent) with the defect concentration, we ascribe it to a tunneling effect [4-5]. Fig. 1 in [5] presents a typical dark I-V characteristics of a Ge tunnel diode. Depending on the range of applied bias, and on the concentration of defects, two dark currents mechanism can appear. At low voltage, the current flows by direct band to band tunneling. As the voltage increases, one starts to see the excess current induced by tunneling through defects in the forbidden band. At higher voltage, the dominating current is due to band to band thermal excitation. In our case, the current we observe is the excess current induced by the defects created by the irradiation. The dark current of a Ge bottom cell increases as the temperature increases. This increase is due to the temperature dependence of the barrier height of the junction. In fact, in Fig. 8, the step-like increase of the current results from thermoionic emission (thermal regime) which is the function of temperature, whereas the red dotted line is temperature-independent which is the sign of tunneling mechanism [6]. Thus the variation of the dark current versus fluence, its temperature independence and the shape of the I_{Dark} (V) suggest that the excess current at low voltages in the TJ cells is related to a tunneling regime. It corresponds to carrier tunneling from a band state to a defect state located in the gap before decaying to the other band on the other side of the junction.

6. CONCLUSION

We irradiated TJ solar cells with electrons to study the influence of irradiation on the performances of the solar cell at low temperature in conditions corresponding to the Jupiter environment. After irradiation, the degradation of P_{MAX} was significantly higher than what was expected from the degradation of I_{SC} and V_{OC}. The reason is the existence of an apparent “shunt effect”. We demonstrate that this phenomenon is directly related to an increase of the dark current after the irradiation, resulting in the decrease of P_{MAX}, induced by a tunneling current taking place in the top and bottom sub-cells. In conclusion, at low temperature a large fraction of the degradation of P_{MAX} originates from carriers tunneling in some of the junctions of TJ cells.

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